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ABSTRACT

We use moderate-resolution, moderate signal-to-noise ratio spectroscopy to derive Li abundances for six F and G stars in the young (few Myr) cluster NGC 2264. These are combined with consistently determined abundances of five NGC 2264 G and K stars having published Li data. The mean non-LTE abundance, calculated with photometric temperatures, is log $N(\mathrm{Li}) = 3.27 \pm 0.05$. This is essentially identical to the meteoritic value, providing no evidence of Galactic Li enrichment over the past 4.6 Gyr—at least to the extent that the meteoritic value represents a typical "cosmic" value at that time. The scatter of 0.16 dex is well within the expected uncertainties and does not indicate any unexpected differential Li depletion. Our mean Li abundance is 0.2–0.3 dex larger than that in the hotter stars of IC 2602 (30 Myr) and the Pleiades (100 Myr), which have consistently determined abundances. This might indicate prior modest differential enrichment, very recent Galactic Li enrichment that is not a global process, or the increasing effect of Li depletion at the young ages of these clusters; such depletion cannot be satisfactorily understood in terms of extant standard or rotational stellar models. Li is not overabundant in the cluster short-period binary W134, a result consistent with the predictions of tidal theory and rotational stellar models. The flatness of Li with T_{eff} (mass) persists to 4000 K ($\sim 0.5\ M_{\odot}$), a morphology in agreement with both standard and rotational stellar models having ages $\lesssim 4$ Myr. We note that some spectral type–based T_{eff} scales lead to Li abundances in all of the five cooler cluster stars that are 0.3–0.8 dex larger than abundances in the six hotter stars. Interestingly, such behavior also is inferred for the near-initial Li-T_{eff} (mass) morphology of IC 2602 and the Pleiades when model depletion factors are mapped onto their observed current abundances. No physical origin of such an abundance pattern, which might suggest an initial cluster Li abundance over a factor of 2 larger than meteoritic, is identified. Rather, we believe that it is caused by lingering deficiencies in the model depletion predictions and errant spectral type–based relative T_{eff} values; comparison of independent spectral classifications and the effects of their differences on the derived Li abundances provide direct support for the latter. This underscores the need for accurate relative spectroscopic T_{eff} values derived for a larger number of cluster stars from higher quality data. Finally, radial velocities are derived for our NGC 2264 stars. Our heliocentric estimate of 24 km s^{-1} is in fine agreement with recent determinations from early-type cluster stars, but shows ample scatter. Some candidate pre–main-sequence spectroscopic binaries are noted, including a multiple-lined star not included in the Li study.

Key words: binaries: spectroscopic — open clusters and associations: individual (NGC 2264) — stars: abundances — stars: evolution — stars: pre–main-sequence

1. INTRODUCTION

Li abundances of very young stars in the solar neighborhood can provide useful constraints on both stellar evolution and Galactic chemical evolution. If the present-day Li abundance were significantly larger than the meteoritic value of log $N(\mathrm{Li}) = 3.3$ (Anders & Grevesse 1989), this might suggest Li production over the past 4.6 Gyr; such Li production might also have cosmological implications. Interesting evidence of isolated Li production has been put forth by Martín et al. (1992), who detected Li in the secondary of the black hole binary V404 Cyg and suggested that (for a system age significantly older than the Pleiades) there was Li production in this system. Such a conclusion might be affected, though, if (in contrast to standard stellar models) tidal interactions play a role in inhibiting Li depletion in such systems.

Observational evidence supporting such a notion does exist. The well-known Li depletion in open cluster F stars (Boesgaard & Tripicco 1986), the large solar Li depletion (Muller, Peytremann, & de la Reza 1975), the dispersion in Li abundances of otherwise identical cool dwarfs and subgiants in open clusters (Soderblom et al. 1993a; Deliyannis, King, & Boesgaard 1997), and Li/Be ratios in Population I F dwarfs (Stephens et al. 1997) indicate that standard stellar models provide an incomplete description of stellar Li processing. Recent theoretical and observational work suggests that rotationally induced mixing may play a significant role in explaining these phenomena, and direct evidence of such a role is provided by observed Li abundances in short-period binaries in a variety of stellar populations (Ryan & Deliyannis 1995). That some such binaries are relative preservers of photospheric Li compared with otherwise similar single stars can be understood, in principle anyway, by the combination of rotational stellar models (e.g., Charbonnel, Vauclair, & Zahn 1992; Pinsonneault, Kawaler, & Demarque 1990, hereafter PKD90) and tidal theory (Zahn & Bouchet 1989).

Li abundances in very young stars may also present some fundamental challenges to such models, however. Possible Li abundance spreads have been inferred for stars of similar mass in the young clusters/associations Taurus-Auriga (Strom et al. 1989), IC 2602 (Randich et al. 1997, hereafter RAPPS), Orion (Cunha, Smith, & Lambert 1995; King 1993), and the Pleiades (Duncan & Jones 1983). While no monotonic correlation between Li abundance and (projected) rotation velocity is seen, several of these studies suggest that the lowest Li abundances are preferentially found in the slowest rotators, perhaps suggesting some sort of extra-mixing mechanism operating prior to the age of the Pleiades (~ 100 Myr). At the young ages of these stars, rotational stellar models seem hard-pressed to account for such dispersions (particularly in stars with $M \gtrsim 1.0\ M_\odot$) and abundance-rotation relations. However, rigorous membership determinations and, e.g., the adequacy of model atmospheres used in the abundance analyses remain problematic issues.

Here we use spectra obtained as part of another project to derive Li abundances for several stars in the young cluster NGC 2264, which has an estimated age near ~ 5 Myr (Walker 1956; Makidon et al. 1997). Our goals are twofold. First, we wish to consider how our F and G star abundances compare with the NGC 2264 K dwarf Li abundances from Magazzù, Rebolo, & Pavlenko (1992, hereafter MRP), and with other young Population I stars. The mean non-LTE (NLTE) abundance of these authors' three NGC 2264 stars is log $N(\mathrm{Li}) = 3.58$; here we examine whether such a supermeteoritic value can be confirmed by more stars. Second, we wish to examine abundances in NGC 2264 stars having masses bracketing those of the components of the NGC 2264 short-period ($P = 6.35$ days) binary W134 (Padgett & Stapelfeldt 1994, hereafter PS94). If our abundances are significantly lower than those of these binary components, this might suggest that substantial Li depletion occurs even in massive ($M \gtrsim 1.4\ M_\odot$) stars of very young age; this would conflict with the predictions of both standard stellar models and those incorporating prescriptions of rotationally induced mixing.

2. OBSERVATIONAL DATA, RADIAL VELOCITIES, AND BINARITY

Spectra of seven NGC 2264 pre–main-sequence (PMS) stars were kindly provided by G. Herbig, who acquired them at the coudé focus of the Lick Observatory 3 m telescope in 1986 March, November, and December as part of another program. The details of the observations, reductions, and measurements can be found in King (1993). The data quality is similar to the spectra used there—i.e., resolution of ~ 1.0 Å and typical signal-to-noise ratio (S/N) of 50–100. Spectra of our NGC 2264 objects W84 (with Hα emission), W190, and V20 are shown in Figure 1, which marks the location of their strong Li I λ6707.8 features.

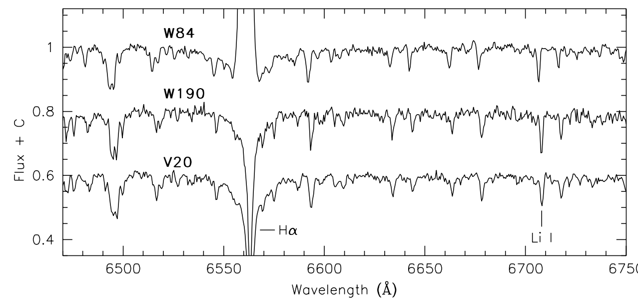

FIG. 1.—Lick Observatory spectra of NGC 2264 objects W84, W190, and V20. Locations of the Hα line (in emission in W84) and the (unresolved) strong Li I λ6707.8 doublet are marked.

The first column of the top portion of Table 1 lists the objects according to their Walker (1956) or Vasilevskis, Sanders, & Balz (1965) designations. The cluster membership probability is given in the second column, and is taken directly from Vasilevskis et al. (1965). These values suggest membership for all the objects in our small sample. The HJD of observation is given in the third column. Radial velocities were derived from the spectra using a cross-correlation analysis as described by King (1993). The heliocentric values and the uncertainties are given in the fourth column; nightly zero-point uncertainties of 2 km $\mathrm{s^{-1}}$ are assumed. Liu, Janes, & Bania (1989) determined radial velocities for seven early-type stars in NGC 2264. They find a median and mean radial velocity for the cluster of $+24.8$ and $+23.7 \pm 8.4$ km $\mathrm{s^{-1}}$, respectively. The estimates from our velocities, $+23.1$ and $+25.5 \pm 4.5$ (mean uncertainty) km $\mathrm{s^{-1}}$, are in good agreement, but show ample scatter (~ 12 km $\mathrm{s^{-1}}$), probably reflecting the presence of spectroscopic binaries in our small sample.

TABLE 1

NGC 2264 RADIAL VELOCITIES AND LITHIUM ABUNDANCES

STAR (1)	P (%) (2)	HJD (2,440,000+) (3)	RV (km $\mathrm{s^{-1}}$) (4)	W(Li) (mÅ) (5)	SPECTRAL TYPE (6)	$(B-V)_0$ (7)	$(V-I)_0$ (8)	T_{eff} (K) (9)	ϵ(Li) LTE (10)	ϵ(Li) NLTE (11)
V20	94	6,759.054	34.6 ± 2.1	177	F5	0.486	0.616	6219	3.56	3.33
W84	98	6,513.705	12.3 ± 2.1	206	G0	0.517	0.558	6279	3.82	3.50
W108	95	6,512.764	16.6 ± 2.3	160	F7	0.519	0.619	6142	3.38	3.21
W121	92	6,758.999	26.6 ± 3.6	...	F8				...	...
W125	96	6,513.753	19.5 ± 2.1	200	F9	0.529	0.612	6135	3.65	3.37
W154	97	6,775.039	48.7 ± 3.3	183	G2	0.617	0.711	5758	3.17	3.02
W190	95	6,514.722	14.5 ± 2.1	219	G0	0.564	0.646	5992	3.60[a]	3.35
		6,759.027	30.9 ± 2.1	205						
W134A	96			367[b]	G5[c]	0.873[d]	0.976[d]	4968	3.52	3.20
W134B	96			367[b]				4808	3.29	3.08
IO Mon	65			485[e]	K3	1.016	1.206	4444	3.24	3.14
LR Mon......	97			625[e]	K3	0.995	1.269	4421	3.56	3.49
SS Mon	...			751[e]	K3	1.29[f]	...	4035	3.30	3.21

[a] Li abundances derived from average equivalent width.
[b] Flux dilution–corrected Li equivalent widths, as described in the text.
[c] Composite spectral type.
[d] Composite colors.
[e] Veiling-corrected equivalent widths from Magazzù et al. 1992.
[f] $B-V$ from Rydgren & Vrba 1981.

Our spectrum of W84 confirms the strong Hα emission already noted by Sagar & Joshi (1983); we measure an equivalent width of 8.6 Å. W108 shows two Hα emission peaks (~ 1.4 Å in strength) with a central absorption and a blueshifted absorption feature. Sagar & Joshi also note Hα emission for this star. W121 appears, on the basis of our spectrum, to be a double- or triple-lined system. In addition, relatively weak Hα emission (~ 0.6 Å) with a central absorption is present. W154 has a radial velocity that differs substantially from the cluster value. Because its membership probability is high (97%), it may be a good spectroscopic binary candidate; while our spectrum appears somewhat "grassy," there is no evidence for double lines. Our two spectra of W190 yield very different radial velocities. We identify this star, too, as an SB1. Sagar & Joshi note that the star is variable. The radial velocities of V20 and W84 differ significantly from the systemic cluster value; these stars are SB1 candidates, too.

3. LITHIUM ABUNDANCE DERIVATION

3.1. Li *Equivalent Widths*

The measured equivalent widths of the unresolved ^{7}Li 6707.8 Å doublet are listed in Table 1. The estimated uncertainties in these values are 20–30 mÅ. For W84 and W108, the raw equivalent widths (176 and 152 mÅ) have been corrected for veiling as prescribed by Strom et al. (1989); these line-strength corrections are modest (17% and 5%). We also include in Table 1 the double-lined short-period binary W134 observed by PS94; the membership probability is that of the composite system as given by Vasilevskis et al. (1965). The raw Li I equivalent widths for W134A and W134B were taken from PS94 and corrected for flux dilution following them but using our $T_{\rm eff}$ estimates; the flux-corrected line strengths differ by only a few percent from their values. Veiling corrections based on (variable) Hα were ignored, since the effect is $\lesssim 4\%$ based on their quoted Balmer strengths. The three NGC 2264 stars studied by MRP are also included in Table 1, where we list the veiling-corrected equivalent widths used by them. We note that the CCD photometry study of Sung, Bessell, & Lee (1997) indicates that IO Mon is a close (0\".8) binary. The effect of this on the MRP Li line-strength measures is unclear.

3.2. *Effective Temperatures*

There is uncertainty in the values (and perhaps meaning) of $T_{\rm eff}$ for PMS stars like those considered here. MRP favored the use of de Jager & Nieuwenhuijzen's (1987, hereafter dJN87) spectral type–$T_{\rm eff}$ calibration for luminosity class IV. For the spectral types considered here, these $T_{\rm eff}$ values are some 300–500 K cooler than estimates based on the Cohen & Kuhi (1979, hereafter CK79) luminosity class V calibration, which is in very reasonable (typically within 100 K) agreement with the dJN87 class V relation. Martín et al. (1994, hereafter MRMP) use the dJN87 calibrations without any a priori assumptions about luminosity class; their $T_{\rm eff}$ estimates appear to be some ~ 300 K warmer than those of MRP.

Padgett (1996) has used spectroscopic metallic line ratio determinations to derive spectroscopic $T_{\rm eff}$ estimates for numerous PMS stars that are typically some 400 K hotter than the spectral type–based estimates of MRMP. Cunha et al. (1995) derive spectroscopic $T_{\rm eff}$ estimates from the fine analysis of Fe I lines for three Orion stars in common with King (1993), who estimated temperatures from the Cohen & Kuhi (1979) spectral type calibration and various luminosity class V color-$T_{\rm eff}$ relations; the differences between the Cunha et al. (1995) and King (1993) $T_{\rm eff}$ estimates are only 10, 50, and 60 K.

Improved understanding of the large (500–700 K) differences in extant PMS-star $T_{\rm eff}$ estimates would be useful for securely employing PMS Li abundances to infer implications for Galactic Li enrichment. At present, we proceed as follows: The work of MRMP and the spectroscopic $T_{\rm eff}$ determinations of Padgett and Cunha et al. favor the hotter scales, like those used by King (1993). Because the limited coverage, resolution, and S/N of our spectroscopy prevents us from determining spectroscopic $T_{\rm eff}$ values from fine analysis or line ratios, we are left with temperature estimates derived from main-sequence spectral type–$T_{\rm eff}$ and color-$T_{\rm eff}$ relations. Padgett notes that her spectroscopic $T_{\rm eff}$ values often indicate errors in PMS spectral types, and we suggest later that some may be present for our NGC 2264 stars. Because we wish to avoid any such errors' propagating to our $T_{\rm eff}$ estimates, and because precision photometry is available for our stars, we have decided to rely on photometric $T_{\rm eff}$ determinations. We shall, however, consider the effect of different choices of $T_{\rm eff}$ determination on our conclusions.

The preferred temperatures we use are determined from the $B-V$ and $V-I$ (Cousins) photometry[1] of Sung et al. (1997), using the calibrations of Bessell (1979). This is the same procedure used by RAPPS to derive temperatures in their Li study of the 30 Myr cluster IC 2602. We made corrections for reddening using the value $E(B-V)=0.071$ determined by Sung et al. (1997) and assuming $E(V-I)/E(B-V)=1.31$, deduced from Dean, Warren, & Cousins (1978). The dereddened photometry is given in the seventh and eighth columns of Table 1. The ninth column gives the mean $T_{\rm eff}$ derived from the Bessell calibrations. Comparison of the individual temperatures indicates that the relative $T_{\rm eff}$ values are good to within ± 140 K.

For later comparison, untabulated $T_{\rm eff}$ estimates were made from the spectral types (from Young 1978 and CK79) given in the sixth column of Table 1 and the relations of CK79 and dJN87. We note that the scatter (250–300 K) in the differences between the spectral type–based and mean photometry-based $T_{\rm eff}$ values is twice that in the differences between the $(B-V)$-based and $(V-I)$-based $T_{\rm eff}$ values. This increase in scatter is consistent with Padgett's (1996) conclusion of frequent errors in PMS spectral type–based temperatures and may provide ad hoc support for relying on photometric estimates.

3.3. *Li Abundances*

LTE Li abundances, listed in the tenth column of Table 1, were derived from the equivalent widths and temperatures in Table 1 using the abundance grid in Table 2 of Soderblom et al. (1993b). These curve-of-growth calcu-

[1] Individual $T_{\rm eff}$ estimates were made for W134A and W134B by deriving a temperature from the composite photometry and then preserving the 160 K difference between the two components estimated by PS94 via line ratios. For IO Mon, the photometry of the two components has significant uncertainty. Moreover, the bluer component gauged from $B-V$ is redder as gauged from $V-I$. We have thus assigned a $T_{\rm eff}$ value based on the mean $B-V$ and $V-I$ indexes. For SS Mon, $B-V$ was taken from the photoelectric photometry of Rydgren & Vrba (1981).

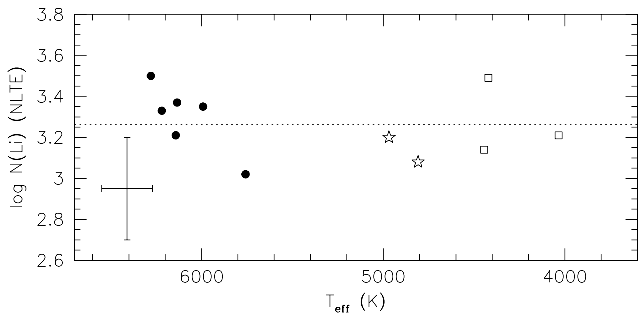

FIG. 2.—Final NGC 2264 NLTE Li abundances vs. photometric $T_{\rm eff}$ estimates. Circles represent new F and G star Lick data presented here. Stars represent cluster short-period binary components W134A and W134B of PS94. Squares represent cluster K stars of MRP. The mean abundance of all 11 stars is given by the dotted line. The error bar is based on the uncertainties estimated in §§ 3.2 and 3.3.

lations were carried out using two Li I components; however, inclusion of additional hyperfine components affects the abundances of our stars negligibly. The calculations also assume a microturbulent velocity of 1 km s^{-1}, but Soderblom et al. note that there are no significant differences for a value of 2 km s^{-1}. The calculations also ignore the presence of the nearby Fe I λ6707.4 feature, whose contribution is included in our (low resolution) line-strength measurements (and probably those of PS94 and MRP). The effect on the derived abundances is small, however; assuming the Fe I line-strength parameterization from § 2.2 of Soderblom et al. (1993b), the final NLTE Li abundances of our NGC 2264 objects would be overestimated by only $\sim$0.04 dex.

NLTE abundances were determined using the corrections calculated from the FORTRAN code of Carlsson et al. (1994) and assuming[2] solar metallicity and $\log g = 3.8$. The same abundance grids and NLTE corrections were employed by RAPPS; thus our NGC 2264 abundances and their IC 2602 abundances should be on a very similar scale, facilitating a fair comparison. The final NLTE results based on our preferred photometric $T_{\rm eff}$ values are listed in the eleventh column of Table 1. The NLTE Li abundances are plotted versus our photometric $T_{\rm eff}$ values in Figure 2. Given the uncertainties in the equivalent widths and relative $T_{\rm eff}$ values, we expect internal uncertainties of ± 0.25 dex in the Li abundances. We also determined abundances for all stars in the same fashion, but employing the spectral type–based $T_{\rm eff}$ values from the calibrations of dJN87 and CK79.

4. DISCUSSION

4.1. *NGC 2264* Li *Abundance and Galactic Enrichment*

The mean NLTE Li abundance derived from our six hotter NGC 2264 stars is $\log N({\rm Li}) = 3.30 \pm 0.07$ (mean internal error) with a scatter of $\sim$0.17 dex, which (as can be judged from Fig. 2) is considerably less than that expected from the equivalent width and $T_{\rm eff}$ uncertainties (0.25 dex). The mean Li abundance derived using $T_{\rm eff}$ values derived from the luminosity class IV spectral type calibration of dJN87 is 3.13. The scatter of 0.26 dex is considerably larger; again, this appears consistent with the suggestion of Padgett (1996) that spectral type errors may lead to errant relative PMS $T_{\rm eff}$ estimates. The mean Li abundance derived using $T_{\rm eff}$ values derived from the luminosity class V spectral type calibrations of dJN87 and CK79 is 3.22. Thus, the Li abundance of 3.30 derived from photometric $T_{\rm eff}$ values appears to be a maximal abundance compared with those derived from spectral type–based $T_{\rm eff}$ values. Our mean NGC 2264 Li abundance is identical to the meteoritic value and thus provides no supporting evidence for global Galactic Li enrichment in the past 4.6 Gyr. Of course, such a conclusion assumes that the meteoritic value was characteristic of a "cosmic" Li abundance at this time.

Our mean NGC 2264 abundance appears to be $\sim$0.2 dex larger than demonstrated by the hotter 30 Myr–old IC 2602 stars in the RAPPS study. Since the $T_{\rm eff}$ estimates and abundances have been derived in a nearly identical manner, there is no evidence that scale differences are the cause of the offset. RAPPS note that the warmer IC 2602 stars appear to be slightly more Li abundant than those of Pleiades (their Figs. 7 and 9), whose abundances are also derived with the same photometric $T_{\rm eff}$ calibrations, abundance grids, and NLTE corrections as for NGC 2264 and IC 2602.

There are at least three possible explanations for these differences. First, previous Li enrichment may have been modestly nonuniform. Second, there may have been very recent Galactic Li enrichment such that the initial Li abundances of the Pleiades ($\sim$100 Myr), IC 2602 ($\sim$30 Myr), and NGC 2264 (few Myr) are increasing functions of younger age, implying that Li enrichment is not global and/or that the meteoritic (initial solar) value is anomalously high. Third, this pattern may reflect increasing Li depletion with age. If so, however, this depletion cannot be fully understood in terms of extant standard or rotational stellar models. Standard stellar model calculations (PKD90; D'Antona & Mazzitelli 1994, hereafter DAM94) are unable to accommodate the implied 0.2–0.3 dex Li depletion in the 1.3–1.4 $M_\odot$ IC 2602 and Pleiades stars shown in Figure 9 of RAPPS. Thus, if the cluster offsets are the result of depletion, it would appear to be caused by a mechanism operating over and above ordinary PMS burning.

We note that a few of the rotational stellar models of PDK90 nearly provide the needed depletion in these more massive stars. However, as noted by RAPPS, both standard and rotational stellar models predict far too much Li depletion for slightly lower mass stars, near 1 $M_\odot$ (see their Fig. 11). Indeed, the standard models, lacking any additional depletion from rotationally induced mixing, predict that the 1 $M_\odot$ stars in IC 2602 have already been depleted by $\gtrsim$0.5 dex—suggesting a very curious "initial" (or prior) cluster Li morphology that has 1.4 $M_\odot$ stars with $\log N({\rm Li}) \sim 3.1$ and cooler stars of 1.0 $M_\odot$ with $\log N({\rm Li}) \sim 3.6$. While such an "initial" abundance distribution might be readily dismissed as absurd and the stellar models instead indicted as deficient, we find in § 4.3 that temperature estimates based on spectral types result in such an odd Li-$T_{\rm eff}$ morphology for our NGC 2264 stars. The photometric $T_{\rm eff}$ estimates remain our preferred values, however, for reasons also summarized there.

Comparison of the PMS temperatures derived from line ratios by Padgett (1996) with those derived from photometric indexes as done here and in King (1993) indicates

[2] For the three cool MRP stars we adopted $T_{\rm eff} = 4500$ K in calculating the NLTE correction.

that the former typically are a couple hundred kelvins hotter; indeed, Padgett's $T_{\rm eff}$ for W134 is some 500 K hotter than our adopted value. Until these differences are understood and spectroscopic $T_{\rm eff}$ estimates are available for our NGC 2264 stars, the possibility of an NGC 2264 Li abundance that is a couple tenths of a dex larger than the meteoritic value remains open.

4.2. Li *in the Short-Period Binary W134*

The Li abundances of the components of the short-period binary W134 derived on the preferred photometric $T_{\rm eff}$ scale appear unremarkable compared with our other NGC 2264 stars. This same behavior is also seen in short-period binaries in the young (~ 100 Myr) Pleiades cluster and is in stark contrast to the "enhanced" abundances with respect to similar single stars seen in older clusters such as the Hyades. As noted by Ryan & Deliyannis (1995), this result is consistent with the combined predictions of tidal theory and rotational stellar models.

While analysis of PS94's W134 data in a fashion consistent with our own data indicates an Li abundance much lower than that inferred by PS94 and consistent with our other NGC 2264 stars, different conclusions are reached if $T_{\rm eff}$ values derived from spectral types (or the line ratio–based $T_{\rm eff}$ value of PS94) are used. This is a simple reflection of the fact that the large $B-V$ and $V-I$ imply a much lower $T_{\rm eff}$ than the G5 spectral type, or ~ 5400 K temperature, estimate of PS94. When consistently employing $T_{\rm eff}$ values from the dJN87 luminosity class V and/or the CK79 calibrations and/or PS94's $T_{\rm eff}$ value, the abundance of the W134 components is a few tenths of a dex larger than the mean abundance of our other stars. Such behavior, which is counter to that seen in the young Pleiades cluster, would have important implications. Specifically, it might suggest (1) that massive[3] single stars have already undergone significant Li depletion at a very young age ($\lesssim 10^7$ yr), which would be in conflict with the predictions of extant standard and rotational stellar models; (2) that the initial NGC 2264 Li abundance is a few tenths of a dex above meteoritic; and (3) that the maximal abundances measured in hot stars of other clusters such as the Pleiades or the Hyades may not reflect the initial cluster abundance as closely as currently believed.

Consistent spectroscopic $T_{\rm eff}$ estimates (from fine analyses or line ratios) and Li abundance determinations for a larger number of NGC 2264 stars having higher quality data are needed in order to explore these intriguing unsettled possibilities. Such estimates would avoid any effects of unknown differential reddening on the photometry.

4.3. Li *Abundance Scatter and Trends with* $T_{\rm eff}$

Our mean Li abundance of the three MRP NGC 2264 K stars is virtually identical to the mean abundance of the other cluster stars. The mean abundance of all the NGC 2264 stars considered here is $\log N({\rm Li}) = 3.27 \pm 0.05$ with a $1\ \sigma$ scatter of 0.16 dex. As noted above, this abundance is essentially identical to the meteoritic value and modestly higher (~ 0.2 dex) than the hotter stars in the 30 Myr–old cluster IC 2602 (RAPPS). Our analysis using photometric $T_{\rm eff}$ values in a manner consistent with the other cluster stars results in lower K star Li abundances than derived by MRP—a reduction of a factor of 2 above meteoritic in the mean, to agreement with our hotter NGC 2264 stars. The scatter in the MRP K star abundances is also reduced. This is mostly a consequence of the significantly lower $T_{\rm eff}$ value for SS Mon. In contrast to the identical spectral types, the $B-V$ values strongly suggest that SS Mon is much cooler than IO Mon or LR Mon; again, this seems to justify the concern of Padgett (1996) about using spectral types as reliable relative $T_{\rm eff}$ indicators.

As is evident from Figure 2, the small Li abundance scatter is well within the expected observational and parameter uncertainties and gives no indication of differential Li depletion that would conflict with the predictions of standard stellar models (e.g., DAM94) and those incorporating rotationally driven mixing (e.g., PKD90). The masses of the K stars (estimated as above) are 1.0, 1.0–1.1, and 0.5 $M_\odot$ for LR Mon, IO Mon, and SS Mon. The mass estimate of SS Mon must be regarded with caution given the large sensitivity of the models to the input physics at cool $T_{\rm eff}$, as well as the close spacing of the theoretical mass tracks in $T_{\rm eff}$ at the luminosity of SS Mon. Nevertheless, our $T_{\rm eff}$ for SS Mon suggests a significantly lower mass relative to the other two K stars; as an example, the new models of Krishnamurthi et al. (1997) indicate 0.6 $M_\odot$ for SS Mon. The nonrotating stellar models of PKD90 and DAM94 and the rotational models of PKD90 all predict little relative surface Li depletion for ages of a few Myr, which is consistent with age estimates of NGC 2264. Comparison of our K star Li abundances with those of IC 2602 stars of similar mass (Fig. 9 of RAPPS) clearly suggests a much younger age for NGC 2264. The various stellar models all suggest an age of $\lesssim 4$ Myr for the NGC 2264 K stars. At larger ages, unobserved significant Li depletion in the K stars with respect to the hotter stars is predicted. For example, the 10 Myr PKD90 and DAM94 models predict large unobserved differential Li depletions of 0.5–1.0 dex for the NGC 2264 K stars relative to our hotter F and G stars.

An aside of interest for the discussion below is that, at very young ages of only a few Myr, the PKD90 and DAM94 models predict that Li depletion is actually larger in the 1 $M_\odot$ models than in the 0.5 $M_\odot$ models—though the small theoretical difference is observationally indistinguishable from our data. This behavior, which can be seen in Figure 3 of PKD90, is counter to that predicted in models of greater age and that observed in open clusters at least as young as IC 2602 (30 Myr), which demonstrate increasing Li depletion with declining mass. This is a consequence of the details of the stellar structure. While the convection zones are larger in extent (as measured by the mass in the convective region relative to the total mass of the model) in the less massive models, at very young ages the temperatures at the base of the convection zone are smaller in the less massive models. This leads to less Li depletion in the less massive models.

A different view of the Li-$T_{\rm eff}$ morphology arises when abundances are derived using $T_{\rm eff}$ values determined from the spectral types. For example, when employing temperatures from the dJN87 and CK79 luminosity class V relations for all stars, the resulting Li abundances of IO Mon, LR Mon, SS Mon, W134A, and W134B are all 0.3–

[3] Using our $T_{\rm eff}$ values and the NGC 2264 distance determined by Sung et al. (1997) to place our six NGC 2264 stars in the theoretical H-R diagram shown in their Fig. 9 yields masses of $M \gtrsim 1.4\ M_\odot$.

0.8 dex larger than the mean abundance of our six hotter (more massive) NGC 2264 stars. One is then left with the cooler NGC 2264 stars exhibiting significantly larger Li abundances than the hotter stars by several tenths of a dex. Such a trend is not seen in any of the standard or rotational models presented by PKD90 or DAM94.

This unexpected trend, the results of Padgett (1996), and the very red color of SS Mon compared with the other two K stars of identical spectral type seem to form a consistent picture in which spectral types do not yield reliable relative PMS $T_{\rm eff}$ estimates. Nevertheless, one might still wonder whether a pattern of increasing Li abundance with decreasing $T_{\rm eff}$ could possibly be real. Indeed, as noted in § 4.1, applying the Li depletion predictions of standard PMS burning models to IC 2602 or the Pleiades data yields initial cluster abundance morphologies that also have increasing Li abundance with declining $T_{\rm eff}$ (mass).

While detailed model calculations are needed to explore such a curious possibility, one could speculate about the role of, e.g., circumstellar disks on PMS Li abundances (Strom et al. 1989). In particular, is it possible that disk locking has occurred in NGC 2264 cluster stars of a wide range of masses and has lead to rotationally induced mixing not considered in standard stellar models (and, to an extent, not incorporated in extant young rotational models)? If so, can models having very young ages accommodate mixing that leads to significantly reduced Li destruction in cooler cluster stars (IO Mon, LR Mon, and SS Mon) compared with hotter cluster stars (the six new stars considered here), as a result of cooler interior temperatures in the former? Such a scenario is of interest, as it would also indicate that the cooler stars (in this very young cluster, at least) provide more reliable estimates of the initial cluster abundance—and these are at least a factor of 2 higher than the meteoritic value. Such a speculative scenario seems unlikely, since current stellar models indicate that, even if additional mixing can be accomplished (by whatever means) early in the PMS, the higher mass ($\gtrsim 1.3$–$1.4\ M_{\odot}$) models simply do not achieve high enough convective-region base temperatures to deplete significant Li during the PMS and early main sequence. Such depletion would apparently require mixing below the convection zone base, and a mechanism to accomplish this is not clear.

As pointed out to the author by G. Herbig, there is evidence implicating the spectral type–based $T_{\rm eff}$ values as the source of the curious Li-$T_{\rm eff}$ (mass) morphology. Seven of our stars also have spectral types from unpublished work summarized in Vogel & Kuhi (1981, hereafter VK81) that are systematically later than those in Table 1 by about four subtypes. Such a systematic offset in spectral type translates to a much larger $T_{\rm eff}$ offset for the NGC 2264 K stars than for the F and G stars. Moreover, even a constant $T_{\rm eff}$ shift leads to increasingly larger Li abundance shifts for the K stars than for the F and G stars. Recomputing Li abundances using the VK81 spectral types leads to a mean abundance in IO Mon and LR Mon that is the same as that (~ 3.1) in the five hotter, more massive stars having VK81 classifications. Unfortunately, no VK81 data are available for W134 or SS Mon; nevertheless, we find that even *systematic* differences in PMS spectral types can result in pronounced *differential* trends in the Li-$T_{\rm eff}$ (mass) morphology. This underscores the need for higher quality data of more NGC 2264 stars, so that reliable relative spectroscopic $T_{\rm eff}$ estimates can be derived.

5. SUMMARY AND CONCLUSIONS

We have used moderate-resolution, moderate-S/N spectroscopy to determine radial velocities and Li abundances for several NGC 2264 F- and G-type stars. We find a heliocentric velocity of $+24$ km s^{-1}, which shows significant scatter (~ 12 km s^{-1}) but is in excellent agreement with that derived by Liu et al. (1989) from seven early-type cluster stars. W121 was identified as a multiple-lined system, and V20, W84, and W190 are probably spectroscopic binaries, which likely contribute to the velocity scatter in our small sample.

We combine our abundance data with a consistent reanalysis of that in the literature for the NGC 2264 short-period binary W134 and the three K-type cluster stars IO Mon, LR Mon, and SS Mon. Spectroscopic $T_{\rm eff}$ estimates from fine analyses and line ratios of PMS stars seem to favor a temperature scale at least as hot as that of luminosity class V spectral type–$T_{\rm eff}$ and color-$T_{\rm eff}$ relations. Given (1) previous concerns about the relative accuracy of PMS temperatures derived from spectral types (Padgett 1996), (2) the apparent agreement of the Cunha et al. (1995) spectroscopic $T_{\rm eff}$ values of Orion PMS stars with photometric calibrations for dwarfs, and (3) increased internal $T_{\rm eff}$ and Li abundance scatter when employing spectral type–based temperatures, we favor NGC 2264 $T_{\rm eff}$ estimates from the $B-V$ and $V-I$ calibrations of Bessell (1979). This same scale is employed by RAPPS in their study of the 30 Myr–old cluster IC 2602, and by Soderblom et al. (1993b) in their study of the 100 Myr–old Pleiades cluster. We derive NGC 2264 abundances from the same grids used in these two studies. The resulting abundances for all three clusters, which also have been consistently corrected for NLTE effects, can be compared without undue concern about scale differences.

The mean Li abundance of all 11 NGC 2264 stars is log N(Li) $= 3.27 \pm 0.05$, with a scatter of only 0.16 dex. The dispersion is within the expected uncertainties and does not indicate any evidence for differential Li depletion. The mean abundance is indistinguishable from the meteoritic value of Anders & Grevesse (1989) and provides no evidence of global Li enrichment with the assumption that the meteoritic estimate is representative of a "cosmic" abundance some 4.6 Gyr ago.

Our mean cluster abundance is 0.2–0.3 dex larger than that found in the hotter stars of IC 2602 and the Pleiades. This could indicate previous modestly nonuniform enrichment, or very recent Galactic Li enrichment that is not a global process in the solar neighborhood. Alternatively, it may indicate the increasing effect of Li depletion at the young ages of these clusters. If so, this depletion cannot be satisfactorily understood in terms of extent standard stellar models or those incorporating rotationally induced mixing (DAM94; PKD90). While some of the rotational models seem to be close to providing enough Li depletion in the 1.3–1.4 $M_{\odot}$ IC 2602 and Pleiades stars, even the standard stellar models predict significant ($\gtrsim 0.5$ dex) depletion in the 1 $M_{\odot}$ stars. As noted by RAPPS, this magnitude of differential Li depletion with mass is apparently not observed, suggesting shortcomings in the stellar models.

Another possibility, though perhaps unpalatable, is that the initial or very early PMS Li-$T_{\rm eff}$ (mass) morphology of IC 2602 and the Pleiades demonstrated increasing Li with declining $T_{\rm eff}$. We did not immediately dismiss such a possibility, given the results for NGC 2264 Li abundances derived using the spectral type–based temperatures. When employing such $T_{\rm eff}$ values, the five coolest NGC 2264 stars all have Li abundances 0.3–0.8 dex greater than the six hotter NGC 2264 stars. This is qualitatively (if not quantitatively) similar to the behavior found for IC 2602 and the Pleiades if one estimates initial abundances by mapping the results of stellar model depletion factors onto the observed current abundances. We wondered if such a near-initial distribution could be caused by the effects of rotational mixing, perhaps induced by circumstellar disks, acting such that cooler stars deplete less Li than hotter stars because of lower convective temperatures. This scenario might also suggest that the initial NGC 2264 Li abundance is over a factor of 2 greater than the meteoritic value, and that even the Li abundances in the hotter stars of young clusters have been significantly depleted. However, such an explanation seems unsatisfactory, since the higher mass models never have high enough convective-region temperatures to burn significant Li during the PMS or early main sequence. Our suspicion is that (1) the odd Li-$T_{\rm eff}$ morphology in NGC 2264 is a result of less reliable relative $T_{\rm eff}$ estimates derived from spectral types, and (2) the odd initial morphology for IC 2602 and the Pleiades inferred from mapping model depletion factors onto their observed current abundances is caused by remaining shortcomings in stellar models, as suggested by RAPPS. Direct evidence for the former contention is found when comparing independent spectral classifications of our NGC 2264 stars, and examining the effects of their differences on the derived Li abundances; in particular, when the VK81 spectral types are employed for $T_{\rm eff}$ estimates, the K stars appear to have Li abundances indistinguishable from the F and G stars. These intriguing issues could be further clarified by accurate self-consistent spectroscopic $T_{\rm eff}$ estimates for a larger number of NGC 2264 stars.

Deriving the Li abundance of the components of the short-period binary W134AB in a consistent fashion brings the large abundance of PS94 below the meteoritic value and into agreement with our other NGC 2264 stars. The equality of Li abundances in short-period and other cluster stars is also seen in young clusters, like the Pleiades (Ryan & Deliyannis 1995), and is predicted by the combination of tidal theory and rotational stellar models.

Similarly, our derived abundances of the NGC 2264 K stars IO Mon, LR Mon, and SS Mon bring the MRP data into agreement with our other cluster stars. The scatter in our K star abundances is reduced, which is principally a result of the large $B-V$ value for SS Mon, which indicates that this star is significantly cooler than the other two K stars, despite their identical published spectral types. The Li-$T_{\rm eff}$ (mass) morphology in NGC 2264 is thus flat, and demonstrates the relative youth of this cluster compared with 30 Myr–old IC 2602. Comparison with the DAM94 and PKD90 models indicates that this flatness implies an age of $\lesssim 4$ Myr, above which significant (observationally distinguishable) differential depletion should be observed. If the model deficiencies perceived above are real, however, then this upper bound may be too low.

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REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Bessell, M. S. 1979, PASP, 91, 589
Boesgaard, A. M., & Tripicco, M. J. 1986, ApJ, 302, L49
Carlsson, M., Rutten, R. J., Bruls, J. H. M. J., & Shchukina, N. G. 1994, A&A, 288, 860
Charbonnel, C., Vauclair, S., & Zahn, J.-P. 1992, A&A, 255, 191
Cohen, L. S., & Kuhi, L. V. 1979, ApJS, 41, 743 (CK79)
Cunha, K., Smith, V. V., & Lambert, D. L. 1995, ApJ, 452, 634
D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467 (DAM94)
Dean, J. F., Warren, P. R., & Cousins, A. W. J. 1978, MNRAS, 183, 569
de Jager, C., & Nieuwenhuijzen, H. 1987, A&A, 177, 217 (dJN87)
Deliyannis, C. P., King, J. R., & Boesgaard, A. M. 1997, in Wide-Field Spectroscopy, ed. E. Kontizas, M. Kontizas, D. H. Morgan, & G. Vettolani (Dordrecht: Kluwer), 201
Duncan, D. K., & Jones, B. F. 1983, ApJ, 271, 663
King, J. R. 1993, AJ, 105, 1087
Krishnamurthi, A., Pinsonneault, M. H., Barnes, S., & Sofia, S. 1997, ApJ, 480, 303
Liu, T., Janes, K. A., & Bania, T. M. 1989, AJ, 98, 626
Magazzù, A., Rebolo, R., & Pavlenko, Ya. V. 1992, ApJ, 392, 159 (MRP)
Makidon, R. B., Strom, S. E., Tingley, B., Adams, M. T., Hillenbrand, L., Hartmann, L., Calvet, N., & Jones, B. F. 1997, BAAS, 191, No. 5.06
Martín, E. L., Rebolo, R., Casares, J., & Charles, P. A. 1992, Nature, 358, 129
Martín, E. L., Rebolo, R., Magazzù, A., & Pavlenko, Ya. V. 1994, A&A, 282, 503 (MRMP)
Muller, E. A., Peytremann, E., & de la Reza, R. 1975, Sol. Phys., 41, 53
Padgett, D. L. 1996, ApJ, 471, 847
Padgett, D. L., & Stapelfeldt, K. R. 1994, AJ, 107, 720 (PS94)
Pinsonneault, M. H., Kawaler, S. D., & Demarque, P. 1990, ApJS, 74, 501 (PKD90)
Randich, S., Aharpour, N., Pallavicini, R., Prosser, C. F., & Stauffer, J. R. 1997, A&A, 323, 86 (RAPPS)
Ryan, S. G., & Deliyannis, C. P. 1995, ApJ, 453, 819
Rydgren, A. E., & Vrba, F. J. 1981, AJ, 86, 1069
Sagar, R. & Joshi, U. C. 1983, MNRAS, 205, 747
Soderblom, D. R., Fedele, S. B., Jones, B. F., Stauffer, J. R., & Prosser, C. F. 1993a, AJ, 106, 1080
Soderblom, D. R., Jones, B. F., Balachandran, S., Stauffer, J. R., Duncan, D. K., Fedele, S. B., & Hudon, J. D. 1993b, AJ, 106, 1059
Stephens, A., Boesgaard, A. M., King, J. R., & Deliyannis, C. P. 1997, ApJ, 491, 339
Strom, K. M., Wilkin, F. P., Strom, S. E., & Seaman, R. L. 1989, AJ, 98, 1444
Sung, H., Bessell, M. S., & Lee, S.-W. 1997, AJ, 114, 2644
Vasilevskis, S., Sanders, W. L., & Balz, A. G. A., Jr. 1965, AJ, 70, 797
Vogel, S. N., & Kuhi, L. V. 1981, ApJ, 245, 980
Walker, M. F. 1956, ApJS, 2, 365
Young, A. 1978, PASP, 90, 144
Zahn, J.-P., & Bouchet, L. 1989, A&A, 223, 112