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BERYLLIUM ABUNDANCES IN F AND G DWARFS IN THE PLEIADES AND α PERSEI CLUSTERS FROM KECK HIGH-RESOLUTION ECHELLE SPECTROMETER OBSERVATIONS

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ABSTRACT

While there are many observations of Li in open clusters, there are very few of the companion light element Be. As we have seen in the study of Be in the Hyades by Boesgaard & King, the two elements together provide important and unique information on the extent and nature of interior mixing in solar-like stars. We have obtained high-resolution (45,000) spectra of the Be II resonance lines in the 14 Pleiades and four α Per dwarfs of spectral types F and G with the Keck I telescope and High-Resolution Echelle Spectrometer. The signal-to-noise ratio in the Be spectral region is typically 40 pixel⁻¹. These two clusters have similar ages and have solar metallicity. Abundances of Be were determined by spectrum synthesis using the newest version of MOOG. For the F dwarfs where there is only a weak Li dip, there is no indication of a Be dip as was found in the Hyades in association with its deep Li dip. Thus, the observed light element depletion in the F dwarfs in the Hyades and in field stars is occurring during main-sequence evolution, and Be depletion does not become evident until ages of more than 100 Myr. The Pleiades G dwarfs are apparently undepleted in Be and the mean value for $\log N(\text{Be}/\text{H}) + 12.00$ in stars cooler than 6000 K is 1.26 ± 0.10 , compared to the Hyades mean of 1.31 ± 0.07 . The star-to-star dispersion in Be in the Pleiades is comparable to the quoted errors. The four α Per stars have lower Be abundances than the Pleiades with a mean of 1.02 dex. The differences in these two clusters in their Li and Be abundances relative to the Hyades is thought to be due to their younger age and possibly their lower metallicity.

Subject headings: open clusters and associations: individual (α Persei, Pleiades) — stars: abundances

1. INTRODUCTION

The only practical way to obtain observational information about the interiors of solar-type stars is to observe their surface abundances of lithium and beryllium. The atomic and nuclear properties of Li and Be make them unique as probes to inspect internal stellar structure. Both Li and Be are readily destroyed in stellar interiors and are only present in the surface layers of stars. The more fragile element, Li, undergoes fusion with protons at temperatures of $\sim 2.5 \times 10^6$ K, while Be burns at $\sim 3.5 \times 10^6$ K. If the atoms of these elements are circulated down to these respective temperatures, the surface content will be diminished over time. But Be atoms must be mixed down to greater depths in the star than Li atoms to be destroyed. Knowledge of the abundances of *both* of these elements provides important information on the type of mixing processes that take place in the invisible layers below the stellar surface.

It is particularly useful to study the light element abundances in different open clusters, because the connections to stellar parameters of age, evolutionary stage, and metal con-

tent can be examined. The stars in clusters form virtually coevally and have known ages and composition. There is an extensive database for Li in open clusters (and even in globular clusters now). By adding Be observations, we can provide more constraints on the models and examine the history of element depletion and the influence of age composition. Furthermore, the study of Be in star clusters of the Galactic disk help to discern the evolution and mixing in the disk component of our Galaxy.

Deliyannis (2000) shows a schematic plot of $A(\text{Li}) = \log[N(\text{Li})/N(\text{H})] + 12.00$ as a function of effective temperature (T_{eff}) for a subset of open clusters. Some show a Li dip in the F dwarfs around 6300–6850 K first discovered by Boesgaard & Tripicco (1986) for the Hyades and subsequently found in other clusters. All show a gradual decline in $A(\text{Li})$ with decreasing temperature in the G dwarfs. The older clusters show increasingly larger Li depletions with increasing age and decreasing temperatures. A comparison of Li in four clusters—Pleiades, M34, Hyades, and M67—is shown in Jones, Fischer, & Soderblom (1999). The standard stellar models cannot account for the observed trends in either the F dwarfs or the G dwarfs in the clusters the age of the Hyades (700 Myr) and older.

Be has been observed less extensively than Li, primarily because the Be resonance lines are located in a crowded

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spectral region near atmospheric cutoff at 3000 Å: the resonance lines of Be II are at 3130.421 and 3131.065 Å, and there is considerable atmospheric extinction there. Boesgaard et al. (2001) derived Li and Be abundances for 49 F and G field dwarfs, which, when coupled with the stars in the discovery paper of Deliyannis et al. (1998), showed a remarkable correlation between $A(\text{Li})$ and $A(\text{Be})$ in the temperature region of 5900–6650 K. As Li declines by a factor of 10, Be declines by a factor of 2.2.

Boesgaard & Budge (1989) observed Be in the Hyades F dwarfs to look for the Be counterpart to the Li dip. While there was not a dramatic Be dip, they could not rule out a possible dip of a factor of 2–4. García López, Rebolo, & Pérez de Taoro (1995) observed Be in four Hyades G dwarfs and found that Be was not depleted, even though there were large depletions in Li of more than 2 orders of magnitude. They also determined (high) upper limits for Be in three UMa group dwarfs. Part of the problem in deriving Be abundances in cool stars is that as the temperature decreases the number of Be II atoms also decreases, as Be is present as Be I. García López et al. (1995) demonstrate that a blending line, probably Mn I, dominates the $\lambda 3131$ feature at temperatures cooler than 5200 K.

Be abundances of 34 F and G dwarfs in the Hyades were recently determined by Boesgaard & King (2002) from observations with Keck I+High-Resolution Echelle Spectrometer (HIRES) at a resolution of 45,000 and signal-to-noise ratios (S/N) of, typically, 90. The main conclusions were as follows: (1) The Li dip in the Hyades F stars is present in Be, as well (shown in their Figs. 6 and 8). This indicates that material is circulated down into the interior of the stars, where it is hot enough to destroy both Be and Li. (2) The Be dip is not as deep as the Li dip. $A(\text{Be})$ is reduced by 0.8 dex, while $A(\text{Li})$ is reduced by at least 2.0 dex at the center of the dip at $T_{\text{eff}} \sim 6680$ K. (3) There is no Be depletion in the G stars, in spite of huge depletions of Li by factors of 100 and more. This indicates that whatever mixing takes place in the interiors of G dwarfs, it does not take material down to the 3.5×10^6 K needed to destroy Be. (4) The abundances of Li and Be are correlated for the mid to late F stars, like the field stars, in the temperature range 5900–6680 K. It is perhaps surprising that the Hyades stars show nearly the same slope of the correlation of Li and Be that the field stars do, because they are so much younger than the typical field star. Many of these results can be explained well by slow mixing caused by stellar rotation.

The Hyades has an age of 700 Myr (Mermilliod 1981) and a metallicity, $[\text{Fe}/\text{H}]$, of +0.13 (Boesgaard 1989; Boesgaard & Friel 1990; Cayrel, Cayrel de Strobel, & Campbell 1985). In this work, we determine Be abundances in two less metal-rich, younger clusters: the Pleiades and α Per clusters. The values for $[\text{Fe}/\text{H}]$ for these two clusters are solar: -0.01 ± 0.03 for the Pleiades and $+0.02 \pm 0.03$ for α Per (Boesgaard, Budge, & Ramsey 1988; Boesgaard 1989; Boesgaard & Friel 1990). The estimated ages are 75 Myr and 50 Myr, respectively (Mermilliod 1981). Note also the work of Pinsonneault, Terndrup, & Yuan (2000), who give 100 and 60 Myr. New ages have been found from the Li depletion boundary method. Stauffer, Schultz, & Kirkpatrick (1998) find the Pleiades to be 125 Myr. Basri & Martin (1999) find the age of α Per to be 65–90 Myr, and Stauffer et al. (1999) find α Per to be 90 ± 10 Myr.

The Pleiades have been studied extensively for Li (Boesgaard, Budge, & Ramsey 1988; Soderblom et al. 1993;

Pilachowski, Booth, & Hobbs 1987). Abundances of Li have been derived for α Per by Boesgaard et al. (1988), Balachandran, Lambert, & Stauffer (1988, 1996), and Randich et al. (1998). It was found that there was a small Li dip for F stars, indicating that the majority of the Li depletion in F stars seems to happen primarily during the main-sequence phase. Studies of other clusters confirmed this. Both clusters show a drop in $A(\text{Li})$ with decreasing temperature in the G dwarfs that can be accounted for by standard stellar evolution models, according to Jones et al. (1999; see their Fig. 4).

2. OBSERVATIONS AND DATA ANALYSIS

We used the Keck I 10 m telescope and the HIRES spectrometer (Vogt et al. 1994) with a Tektronix 2048 \times 2048 CCD to observe 14 Pleiades and four α Per stars, which were chosen to cover a range in T_{eff} . We obtained the Pleiades spectra over six nights: 1999 November 13–15 (UT), 2001 February 01 (UT), and 2002 January 4–5 (UT). The four α Per spectra were obtained on 2002 January 4–5 (UT). Low air mass observations were needed to get good S/N because of the proximity of the atmospheric cutoff near 3000 Å. However, the 2001 February 1 spectra of three of the stars had to be obtained at zenith angles exceeding 15° because the top shutter of the Keck I dome could not be removed. For each night, we obtained 11 bias frames, 15 quartz flat-field frames, and at least two Th-Ar spectra at the beginning and end of the night.

The exposure times for the Pleiades stars ranged from 30 to 75 minutes. For the stars with an exposure time of 75 minutes (HII 152, 250, 761, and 1215), two successive observations were made. HII 2506 was observed on two different nights. The spectra from multiple exposures were coadded. The final S/N values for the Pleiades range from 32 to 59, with a mean and a median of 41. For α Per, the exposures times were 45–50 minutes, and the S/N ratios have a mean of 44. Table 1 lists the objects, with the HII designations for the Pleiades from Hertzsprung (1947) and the He designation for α Per from Heckmann, Dieckvoss, & Kox (1956; with HD and BD numbers where available), the V magnitude, $B-V$, the nights of observation, exposure times, and S/N pixel⁻¹ in the Be II region of the spectra.

The observed stars had all been studied previously for their Li. Figure 1 gives the Li abundances for all the Pleiades stars (references above) plotted against effective temperature, T_{eff} . The circled points correspond to the stars we have observed for Be. The same type of plot for α Per is given in Figure 2 (references above).

The IRAF² standard routines were used to carry out data reduction. We trimmed the frames, subtracted the overscan and bias, fixed bad pixels or columns using the FIXPIX task, and then divided by a flat-field frame made with a combination of quartz lamp frames acquired each night. We removed the scattered light (task APSCATTER) and the cosmic ray impacts (especially for long exposures) with the COSMICRAYS task. Then we extracted the apertures using APALL and made the wavelength identification, with the help of two Th-Ar reference spectra taken at the beginning and the end of the nights and the ECID task. We normalized the spectra with an approximate continuum (a

² IRAF is distributed by the National Optical Astronomical Observatory, which is operated by AURA, Inc., under contract to the NSF.

TABLE 1
LOG OF THE OBSERVATIONS OF THE PLEIADES AND α PERSEI

NUMBER	STAR IDENTIFICATION		V	$B-V$	NIGHT (UT)	EXPOSURE (minutes)	SIGNAL-TO-NOISE RATIO
	HD	BD					
Pleiades							
HII 152 .....	...	...	10.60	0.647	2002 Jan 5	70	41
HII 233	23195	+23°499	9.55	0.493	1999 Nov 14	50	36
HII 250 .....	...	...	10.70	0.637	2002 Jan 5	75	40
HII 530	23326	+23°509	8.99	0.349	1999 Nov 13	40	33
HII 739	23386	+24°055	9.56	0.586	1999 Nov 14	50	44
HII 761 .....	...	...	10.55	0.652	2002 Jan 5	75	42
HII 948	23464	+22°549	8.67	0.586	2001 Feb 1	30	48
HII 1200 .....	...	+22°553	9.97	0.507	1999 Nov 15	50	41
HII 1215 .....	...	+23°527	10.60	0.599	2002 Jan 4	75	46
HII 1726	23713	+23°548	9.25	0.505	1999 Nov 15	50	59
HII 1794	282972	+23°550	10.20	0.589	1999 Nov 14	50	32
HII 1856	282971	+23°552	10.20	0.514	1999 Nov 15	50	42
HII 2506 .....	...	+22°574	10.20	0.552	2001 Feb 1	60	...
HII 2506 .....	...	...	...	...	2002 Jan 4	45	39 ^a
HII 3179	24194	+23°573	10.07	0.529	2001 Feb 1	50	32
α Persei							
He 135.....	...	+49°868	9.69	0.488	2002 Jan 4	45	40
He 490.....	...	+48°892	9.68	0.446	2002 Jan 4	45	47
He 848.....	...	...	10.00	0.60	2002 Jan 5	50	41
He 1225.....	22326	+47°862	8.88	0.492	2002 Jan 4	45	48

^a Signal-to-noise ratio of combined spectra.

more accurate division is done later, during the synthetic spectrum analysis). There is a more complete discussion of the data reduction in Boesgaard & King (2002).

Examples of spectra in the Be region for a range in temperature are given in Figure 3. The position of both of the Be π lines are indicated in each spectrum. The Be π line at λ 3130 is quite blended, but the longward line at λ 3131 is reasonably clean, even in those stars with $v \sin i$ of 12 km s^{-1} .

We used stellar temperatures from Boesgaard et al. (1988), Soderblom et al. (1993), and Balachandran et al. (1988), which are all on similar scales. To find $\log g$, we used the main-sequence relation from Gray (1976), $\log g = 4.17 + 0.38 \times (B-V)$, so the relative $\log g$ values are as good as the relative photometry. As noted in § 1, both clusters have solar metallicity; for the Pleiades, $[\text{Fe}/\text{H}] = -0.01 \pm 0.03$, and for α Per, $[\text{Fe}/\text{H}] = +0.02 \pm 0.03$. For

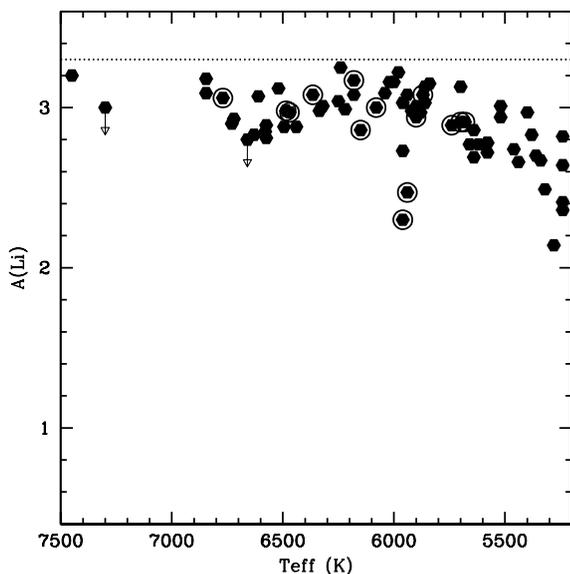


FIG. 1.—Li abundances vs. temperature for Pleiades stars. *Circled hexagons*: Stars that we have observed for Be. The values of $A(\text{Li})$ and T_{eff} are from Boesgaard et al. (1988), Pilachowski et al. (1987), and Soderblom et al. (1993). The cluster membership of the stars at [5870, 3.08] (HII 739) and at [5960, 2.30] (HII 948) has been questioned by King et al. (2000).

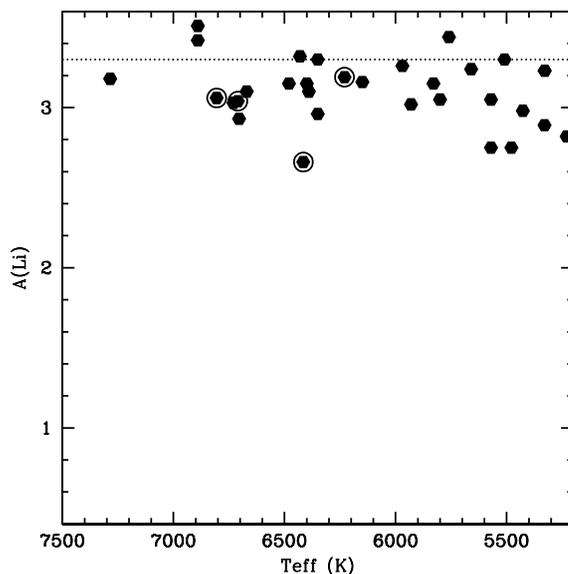


FIG. 2.—Li abundance vs. temperature for α Per stars. *Circled hexagons*: Stars that we have observed for Be. The values of $A(\text{Li})$ and T_{eff} are from Boesgaard et al. (1988), Balachandran et al. (1988, 1996), and Randich et al. (1998). The star at [6415, 2.66] (He 1225) was not included in the Balachandran et al. (1996) list of bona fide members.

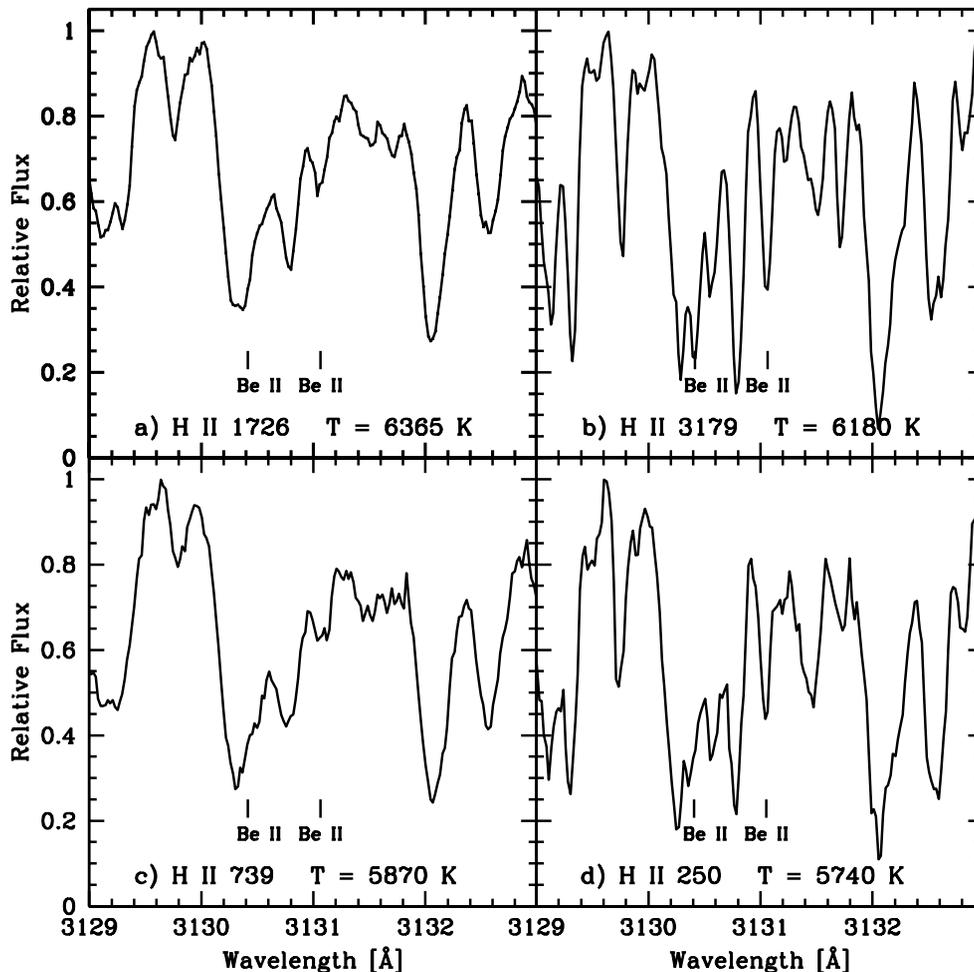


FIG. 3.—Examples of spectra in the Be region of Pleiades stars showing a range in T_{eff} . Values of $v \sin i$ are 12 km s^{-1} for the stars in (a) and (c) and are $\leq 7 \text{ km s}^{-1}$ for the stars in (b) and (d). These spectra are shown normalized to 1.0 with a pseudocontinuum fit that is adjusted during the synthesis procedure.

the microturbulent velocity, we use $\xi = 1.25 + 8 \times 10^{-4}(T_{\text{eff}} - 6000) - 1.3(\log g - 4.5)$ from Edvardsson et al. (1993). The $v \sin i$ values or upper limits are from Soderblom et al. (1993) for the Pleiades and Kraft (1967) for α Per. Our α Per stars seem to have high $v \sin i$ values, which makes the determination of their Be abundances less accurate. The stellar parameters are given in Table 2, along with the Li abundances from the source listed in column (3). With these parameters, we interpolated in the Kurucz (1993) grid of model atmospheres to make a model appropriate for the stellar parameters for each star.

3. ABUNDANCES

Because the spectral region around the Be lines is crowded, the best method to determine Be abundances is spectrum synthesis, which we did with the newest version of MOOG, MOOG2002 (Snedden 1973). Compared to prior versions, this version includes Kurucz's UV opacity edges. Although the Be lines are in the UV part of the spectrum, the use of these new opacities did not result in a significant change in the spectrum synthesis for most stars.

The model atmosphere and an atomic and molecular line list (that used by Boesgaard & King 2002) were input into the synthesis program, along with three trial Be abundance values. (See García López et al. 1995; King, Deliyannis, &

Boesgaard 1997; Boesgaard & King 2002 for a discussion of the line list.) MOOG2002 then produced a synthetic spectrum in the specified wavelength interval. This can be adjusted to match the rotationally broadened observed spectrum by smoothing it with a Gaussian. The observed spectrum usually has to be multiplied by a constant (e.g., 0.92), so that its continuum matches the synthetic continuum. The fit is done on areas where Be does not play any role. We then vary the Be abundances in the model spectrum to get the real abundance in Be of the star. In all the synthesis fits, we favored the $\lambda 3131$ line when the two lines gave different results. These complete steps were done independently for each star by two of us.

Just after sunrise on 1993 October 7 UT, we took a 20 minute exposure of the daytime sky in the Be II region with Keck I+HIRES: this spectrum has S/N of 138 pixel^{-1} . We have done a spectrum synthesis on this spectrum with the Kurucz solar model and MOOG2002 and derive a new solar Be value, $A(\text{Be})_{\odot} = 1.30$ dex. The standard solar value was derived by Chmielewski, Müller, & Brault (1975) and comes from high-resolution center-to-limb spectra and includes non-LTE (NLTE) effects. They found $A(\text{Be}) = 1.15 \pm 0.20$, in agreement with determinations based on LTE. It should be noted that according to Kiselman & Carlsson (1995), competing effects of NLTE apparently cancel each other.

TABLE 2
STELLAR PARAMETERS AND ABUNDANCES FOR PLEIADES AND α PERSEI STARS

Number (1)	T_{eff} (K) (2)	Source ^a (3)	$\log g$ (4)	ξ (km s ⁻¹) (5)	$v \sin i$ (km s ⁻¹) (6)	$A(\text{Li})$ (7)	$A(\text{Be})$ (8)	σ (9)
Pleiades ([Fe/H] = -0.01)								
HII 152	5700	S	4.42	1.11	<7	2.91	1.25	0.09
HII 233	6485	BBR	4.36	1.82	13	2.98	1.30	0.09
HII 250	5740	S	4.41	1.16	<7	2.89	1.20	0.09
HII 530	6770	BBR	4.30	2.13	12	3.06	1.27	0.13
HII 739	5870	BBR	4.39	1.29	<12	3.08	1.40	0.10
HII 761	5680	S	4.42	1.10	11	2.91	1.33	0.10
HII 948	5960	BBR	4.39	1.36	<12	2.30	1.35	0.09
HII 1200	6470	BBR	4.36	1.81	<20	2.97	1.38	0.09
HII 1215	5900	S	4.40	1.30	<7	2.94	1.12	0.09
HII 1726	6365	BBR	4.36	1.72	12	3.08	1.15	0.08
HII 1794	5940	S	4.39	1.35	12	2.47	1.20	0.10
HII 1856	6150	BBR	4.37	1.54	16	2.86	1.28	0.10
HII 2506	6080	S	4.38	1.47	13	3.00	1.25	0.10
HII 3179	6180	S	4.37	1.56	<7	3.17	1.22	0.09
α Persei ([Fe/H] = 0.02)								
He 135.....	6710	BBR	4.36	2.00	<20	3.04	1.05	0.10
He 490.....	6805	BBR	4.34	2.10	<20	3.06	1.03	0.11
He 848.....	6230	BLS	4.40	1.30	...	3.19	1.03	0.17
He 1225.....	6415	BBR	4.36	1.76	<20	2.66	0.96	0.13

^a BBR = Boesgaard, Budge, & Ramsay 1988. S = Soderblom et al. 1993. BLS = Balachandran, Lambert, & Stauffer 1988 and 1996.

Examples of the spectrum synthesis fits are shown in Figures 4–7. Figure 4 shows two Pleiades stars with the same temperature but Be abundances that differ by 0.23 dex. Figure 5 shows two Pleiades stars that are rotationally broadened. They have similar Be abundances but differ in

temperature by over 300 K. Figure 6 has two Pleiades stars with sharp lines with similar Be abundances and different temperatures. An α Per star is shown in Figure 7, along with a Pleiades star of similar temperature.

The Be abundances we obtained are in Table 2 as $A(\text{Be}) = \log N(\text{Be}/\text{H}) + 12.00$. In order to evaluate the

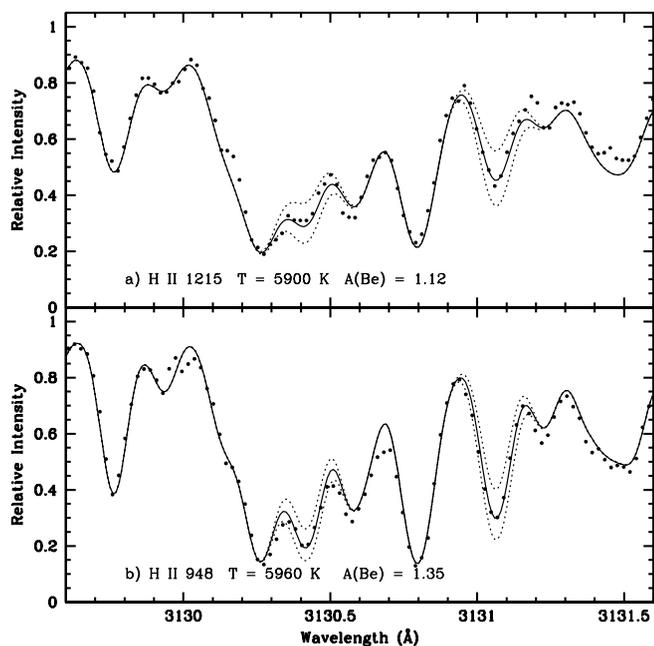


FIG. 4.—Examples of the spectrum syntheses in the Be region. Dots: Observed spectra. Solid line: Best fit. Dotted lines: Correspond to a factor of 2 more Be and a factor of 2 less Be. These stars have the same temperature but differ in $A(\text{Be})$ by 0.23 dex.

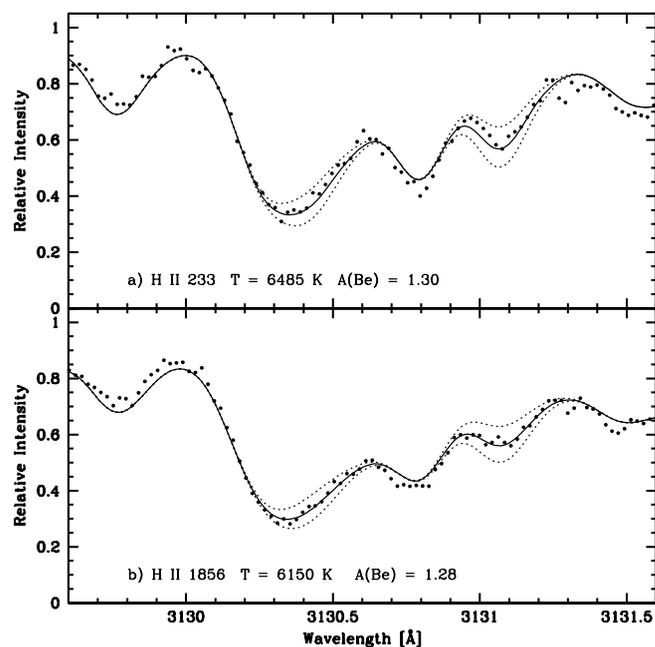


FIG. 5.—Examples of the spectrum syntheses. Symbols are the same as in Fig. 4. These stars have higher rotation (13 and 16 km s⁻¹) than those in Fig. 4. They have similar Be abundances but different temperatures.

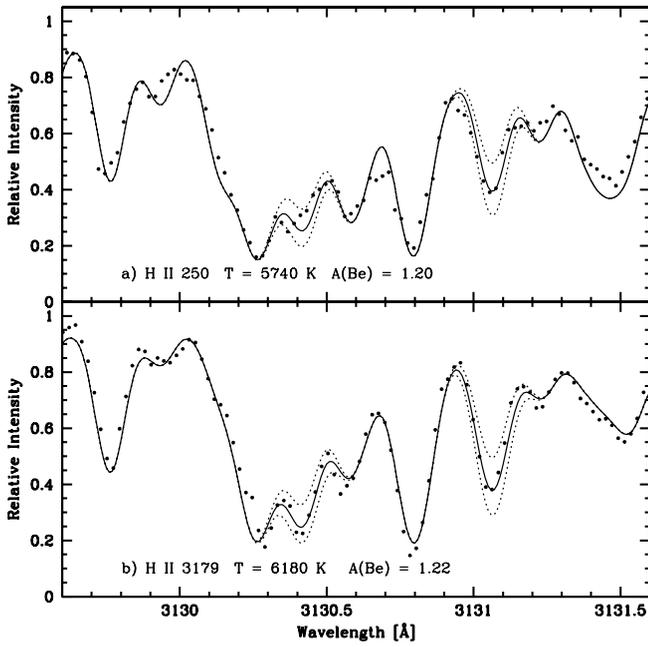


FIG. 6.—Examples of the spectrum syntheses. Symbols are the same as in Fig. 4. These stars have low $v \sin i$ values, different T_{eff} , and similar $A(\text{Be})$.

uncertainties in the Be abundances, we followed a procedure similar to the one we used for the Hyades (Boesgaard & King 2002). We ran syntheses for several stars in which we varied the individual atmospheric parameters one by one by an amount slightly in excess of the 1σ error in each of those parameters. The judgment of the best-fit synthesis is sometimes subjective, so we also used MOOG in the blends mode, using the line list in Table 4 in Boesgaard et al. (1999), covering 3131.015 to 3131.115 Å around the Be II

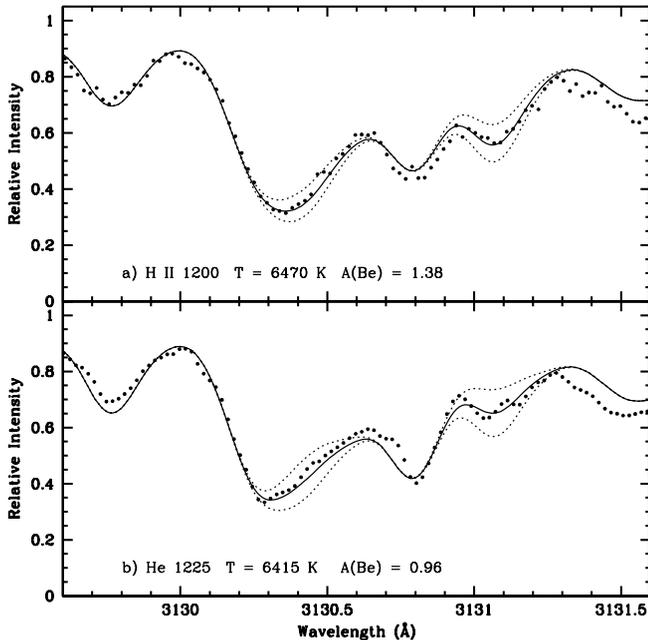


FIG. 7.—Examples of the spectrum syntheses. Symbols are the same as in Fig. 4. (a) Pleiades star. (b) α Per star of the same temperature. They differ in $A(\text{Be})$ by 0.42 dex.

line at 3131.065 Å. We determined what the equivalent width for the Be II line would be to give the same abundance found from the synthesis and used that to find the effects on the Be abundance of changes in the model parameters. For this, we used 16 Kurucz grid-point models, 12 with $\log g = 4.5$ at four temperatures (5750, 600, 6250, and 6500 K) with three values each for $[\text{Fe}/\text{H}]$ (-0.1 , 0.0 , $+0.1$) and four with $\log g = 4.0$ at the four temperatures and $[\text{Fe}/\text{H}] = 0.0$.

According to the agreement in the temperatures found from several colors and calibrations (Boesgaard et al. 1988), the mean error in T_{eff} is ± 53 K. When we increase the model temperature by 80 K, there is little effect on the Be abundance; for the hotter stars, it is 0.01 dex. For the stars at 6000–6250 K, it is 0.00. For the cooler stars, it is 0.01 dex. According to Gray (1976), the probable error in the fit to the relation we use to find $\log g$ is 0.075 dex. When we increase the model atmosphere's $\log g$ by 0.1 dex, the value for $A(\text{Be})$ increases by 0.04 dex for the hotter stars and 0.05 dex for the cooler stars. The derived metallicity is $[\text{Fe}/\text{H}] = -0.01 \pm 0.03$ for the Pleiades. Increasing $[\text{Fe}/\text{H}]$ by 0.05 increases the derived Be abundance by 0.02 dex at all temperatures. A change in the microturbulence of 0.25 km s^{-1} produces a change in the Be abundance of 0.02–0.03 dex.

However, in the case of the Pleiades, there exists the possibility that the color indices could be affected by chromospheric activity. The sensitivity of color-based Pleiades T_{eff} values to chromospheric activity has been considered by King, Krishnamurthi, & Pinsonneault (2000). The difference in the $(B-V)$ - and $(V-I)$ -based T_{eff} values *does* show a relation with chromospheric activity measure (residual flux in the Ca II H and K and $H\alpha$ lines). The star-to-star scatter in the T_{eff} differences is 110 K. The scatter in the T_{eff} differences for six stars in common with the present paper is ± 90 K. This is somewhat smaller, which is not surprising given that most of the objects in King et al. (2000) are cooler (thus having larger residual chromospheric fluxes) than the stars in the present study. If we adopt a conservative estimate of the error in T_{eff} of ± 100 K, this would yield ± 0.04 in $A(\text{Be})$ at 6500 K, ± 0.02 at 6200 K, and 0.00 at 5750 K. However, this is almost certainly an overestimate in the temperature error, because the other indices ($H\beta$, $b-y$) used by Boesgaard et al. (1988) produced good agreement with the $B-V$ temperatures.

We have found from Gray's empirical relation between $\log g$ and $B-V$. In the unlikely assumption that this T_{eff} uncertainty is due exclusively to activity-induced color errors, it is estimated that the uncertainty in $(B-V)$ index corresponding to a T_{eff} uncertainty of 100 K is less than 0.03 mag given the slope of typical main-sequence color- T_{eff} uncertainty relations. Given the slope of the adopted $\log g$ - $(B-V)$ calibration (which is small since $\log g$ is a slowly varying function of color over the T_{eff} range considered in this paper), this translates to an uncertainty in $\log g$ of 0.012 dex. This is very small in comparison with Gray's stated uncertainty in the overall calibration of ± 0.075 dex. Our $\log g$ uncertainty above was taken to be ± 0.1 dex, which gives an uncertainty in $A(\text{Be})$ of ± 0.04 – 0.06 dex depending on the temperature of the star.

Another possible source of uncertainty is the O abundance in the Pleiades, as there are blending lines of OH in the Be region. We had actually made observations of the O I triplet in some Pleiades stars with high-resolution, high S/N

Palomar 5 m coude CCD spectra. For four stars cooler than 6400 K, the $[O/H]$ is $+0.02 \pm 0.04$. The synthesis assumes $[O/H] = [Fe/H] = -0.01$. We ran syntheses with $[O/H] = +0.1$ and found that the fit was not as good as with -0.01 , and the two Be lines agreed less well with each other. Enhanced O is not expected for stars with solar Fe/H in any case. With the blends mode in MOOG, there was no change in $A(Be)$ with the increased O abundance. The molecules that blend with the Be Π $\lambda 3131$ line are CH and CN, not OH. This source of error is negligible.

Uncertainties in the continuous opacity are a source of systematic uncertainty but are unimportant for the relative star-to-star abundances over a narrow T_{eff} range. Thus, the salient issue is the assumed random uncertainty in macroscopic broadening (whether rotation, macroturbulence, etc.). We believe this effect is considered most directly in the fashion we have done by altering the assumed broadening until the line profiles are well matched. The uncertainty determined in this fashion varies from star to star (being a function of macroscopic broadening itself) and ranges from 0.00 to 0.15 dex.

The final abundance errors listed in Table 2 include the effects from the random and systematic uncertainties in temperature, $\log g$, $[Fe/H]$, and microturbulent velocity, the data quality as determined by the S/N ratio, and the uncertainty resulting from the rotational broadening of the stellar spectrum lines. The final error bars range from 0.08 to 0.17.

4. DISCUSSION

The observed Be abundances with their error bars are given as a function of T_{eff} in Figure 8. There appears to be no Be dip for the F stars. Since there is only a small Li dip, this result is not unexpected. The Pleiades G stars appear to show a spread in $A(Be)$, but the spread is comparable to the errors. The seven stars with $T_{\text{eff}} < 6000$ K show a star-to-star dispersion of 0.10 dex compared to the mean error of 0.11 dex. These results can be seen more clearly in Figure 9,

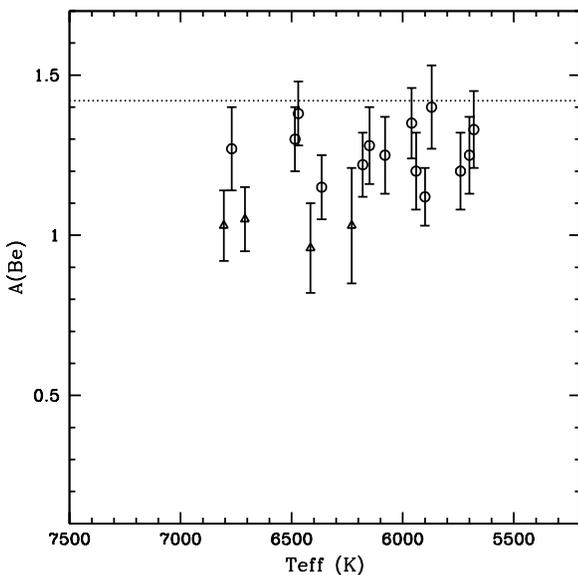


FIG. 8.—Be abundance is plotted as a function of temperature. *Circles*: Pleiades stars. *Triangles*: α Per stars. *Horizontal dotted line*: Meteoritic Be abundance, $A(Be) = 1.42$ dex. All four α Per stars have lower Be than the Pleiades, individually and in the mean.

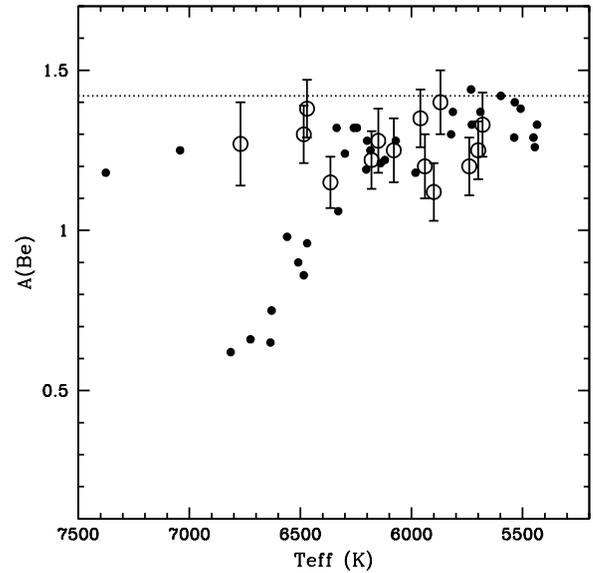


FIG. 9.—Be abundances as a function of T_{eff} . *Large open circles*: Pleiades results. *Dots*: Hyades results of Boesgaard & King (2002; revised). The Pleiades does not show the Be dip in the F dwarfs that the Hyades shows. The cooler stars in the two clusters have similar Be abundances and a similar spread in $A(Be)$.

which shows the Be abundances in the Pleiades compared to those of the Hyades. The Hyades Be dip in the F stars clearly is not present in the Pleiades. In the late F and G dwarfs of both clusters—below 6300 K—the Be abundances are similar in both the distribution of $A(Be)$ with temperature and in its dispersion. Below $T_{\text{eff}} = 6000$ K, the mean Be abundance, $\langle A(Be) \rangle$, for the Hyades is 1.31 ± 0.07 , and for the Pleiades is 1.26 ± 0.10 . We note that the Li depletion in G-type Pleiades becomes obvious below $T_{\text{eff}} \sim 5500$ K, whereas our stars all have $T_{\text{eff}} > 5680$ K.

In Figure 8, we also see that the Pleiades F dwarfs seem to have more Be than the α Per F dwarfs. The mean α Per Be abundance is lower than the Pleiades value by 0.24 dex. While this is significant at the 2.7σ level given the uncertainty in the means, the difference is based on only four α Per stars (one of which may not be a member—see below). Moreover, the α Per stars have higher $v \sin i$ values, and it is difficult to rigorously exclude the possibility that this might introduce small systematic differences in the synthesis-based abundances. Abundances for additional α Per members would be welcome in exploring a real difference in these young clusters' initial Be abundances or whether they may have depleted more Be during spin-down from higher initial rotation rates.

In Figure 10, we plot $A(Be)$ and $A(Li)$ against T_{eff} on the same scale, normalized to their respective meteoritic abundances: 1.42 dex for Be and 3.30 for Li (Anders & Grevesse 1989). Both the Pleiades and α Per have both Be and Li near the initial values from the meteorites. Two stars in the Pleiades appear to be depleted in Li, HII 948 and 1794 (see Fig. 1). They both have normal Be. Both the membership and the Li abundances in these two stars should be checked. HII 1794 was considered to be a member by King et al. (2000), but HII 739 and HII 948 are questionable as members. As can be seen in Table 1, HII 1794 has $V = 10.20$ and $B-V = 0.589$. Both HII 739 and HII 948 have the same $B-V$ (0.586) but are much brighter at $V = 9.56$ and 8.67,

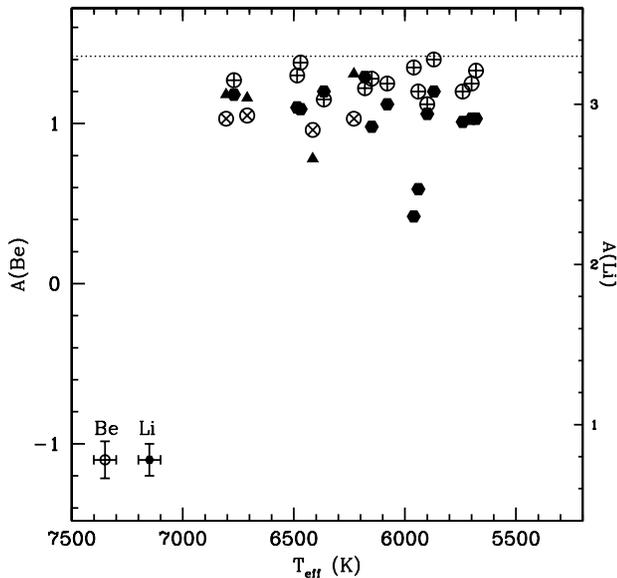


FIG. 10.—Abundances of Be (*left y-axis*) and Li (*right y-axis*) vs. temperature plotted on the same scale and normalized to the meteoritic abundances, 1.42 dex for Be and 3.30 dex for Li. *Circles with plus signs*: Pleiades Be. *Hexagons*: Pleiades Li. *Circles with crosses*: α Per Be. *Filled triangles*: α Per Li. Typical error bars are shown in the lower left.

respectively, and appear to be outliers in the color-magnitude diagram. The α Per star He 1225, which is somewhat depleted in both Li and Be, was not included as a member by Balachandran et al. (1996).

For the Hyades, Boesgaard & King (2002) found Li/Be of 75 ± 30 compared to the meteoritic ratio of 77.6. Both Li and Be abundances are plotted in Figure 10. There are four Pleiades stars with $A(\text{Li}) \geq 3.0$ —these are presumably undepleted in Li. From these four stars, $\text{Li}/\text{Be} = 63 \pm 10$. This may represent the initial ratio for the Pleiades cluster material, the same ratio as the Hyades within the errors.

In the field stars (Boesgaard et al. 2001) as well as in the Hyades cluster (Boesgaard & King 2002), a sharp correlation was found between Be and Li abundances for stars within the temperature range 5850–6680 K. For the field stars, the relationship is

$$A(\text{Be}) = 0.359(\pm 0.037)A(\text{Li}) + 0.146(\pm 0.097).$$

This correlated depletion of both elements is consistent with the theory of rotational mixing Deliyannis & Pinsonneault (1997) for that temperature range from the bottom of the Li dip to the Li plateau in the Hyades. Figure 11 shows the $A(\text{Li})$ versus $A(\text{Be})$ plot for Pleiades stars with the Hyades stars superposed and the least-squares fit from the field stars. Although the Pleiades data are in the upper right corner since there is only a mild Li dip for this cluster, our observations are consistent with that previous correlation. In the absence of significant Be depletion and the possibility of real scatter in the Be abundances, we would not expect perfect agreement with the Li-Be pattern found for the older stars that have undergone real depletion.

The most successful explanations for the various observations of Li and Be depletion patterns in cluster and field stars are slow mixing during the main sequence caused by rotation and internal waves. Observations of both Li and Be have virtually eliminated mass loss and microscopic

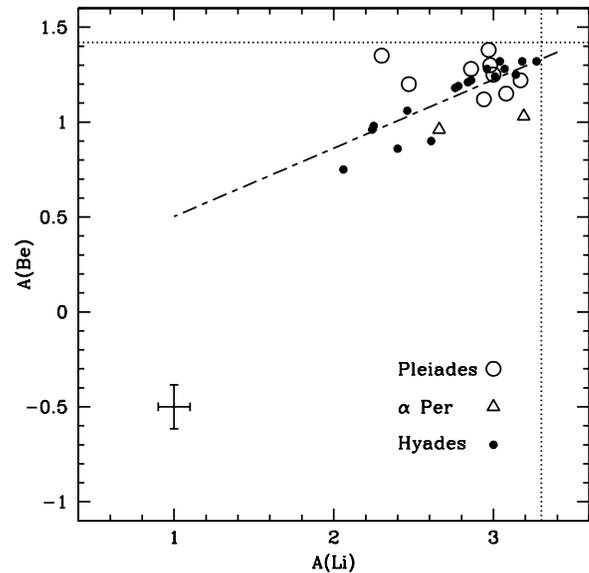


FIG. 11.—Li-Be relation for hot Pleiades (*open circles*) and α Per (*open triangles*) stars. The Hyades (*small dots*) are from Boesgaard & King (2002; revised). The stars plotted here all have temperatures between 5900 and 6650 K. *Vertical and horizontal dotted lines*: Meteoritic abundances. *Dot-dashed line*: Corresponds to the fit for the field stars from Boesgaard et al. (2001). A typical error bar is shown in the lower left. These data cluster in the upper left with no Li or Be depletion. The two stars that seem to have some Li depletion in Fig. 1 have normal Be. One, HII 948 at [2.30, 1.35], is questionable as a Pleiades member.

diffusion as dominant mechanisms (Stephens et al. 1997; Deliyannis et al. 1998; Boesgaard et al. 2001). Be is not expected to be depleted during pre-main-sequence evolution in solar metallicity stars, according to the calculations of Forestini (1994), and, for stars more massive than $0.9 M_{\odot}$, no Be depletion occurs on the main sequence. Some Be depletion is expected on the main sequence from rotationally induced turbulent mixing (Deliyannis & Pinsonneault 1997; Charbonnel et al. 1994) and internal gravity waves (García López & Spruit 1991; Montalbán & Schatzman 1996, 2000). Although our stars seem to have little, if any, Be depletion, we can compare our abundances with predictions.

At 100 Myr, the models of Montalbán & Schatzman (2000) show no depletion of Be at solar metallicity (calculated for stars with temperatures of 4400–6200 K) and virtually no Li depletion for stars hotter than 5600 K. There is modest Be depletion predicted at 100 Myr for models that include stellar rotation. In Figures 12 and 13, we show the Deliyannis & Pinsonneault (1997) model predictions for Be and Li depletion caused by rotationally induced mixing at 100 Myr with our Be and Li abundances for the Pleiades and α Per. The model predictions for initial stellar rotation of 10 and 30 km s^{-1} are shown (*solid lines*). Given the error bar in the observations shown in the lower right corner of each figure, the predictions and observations are in reasonable agreement. Perhaps higher initial rotation velocities should be considered in the models. But note that while the Be abundances would be well matched by including higher initial rotations, the Li abundances would not be. This same inconsistency between the Li and Be results and the model predictions was also found by Boesgaard & King (2002) for the Hyades.

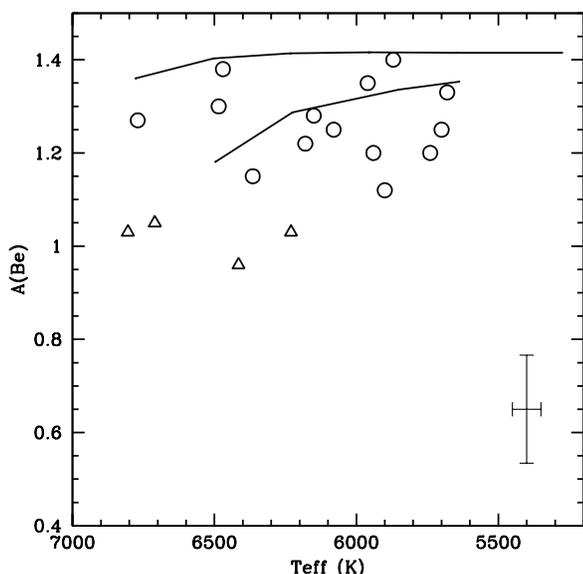


FIG. 12.—Be abundances as a function of temperature along with the predictions of Deliyannis & Pinsonneault (1997) of the effect of rotationally induced mixing on the Be abundance for an age of 100 Myr. *Upper curve:* Initial rotational velocity of 10 km s^{-1} . *Lower curve:* Initial rotation velocity of 30 km s^{-1} . A typical error bar is shown in the lower right.

5. SUMMARY AND CONCLUSIONS

We have obtained high-resolution near-UV spectra of 18 F and G dwarfs in the Pleiades and α Per clusters with Keck I and HIRES spectrometer in order to derive Be abundances. The spectral resolution is 45,000 and the median S/N ratio is ~ 40 . We have determined stellar parameters and made Kurucz model atmospheres for each star. Abundances of Be have been determined through spectrum synthesis with the latest version of MOOG with enhanced UV opacities. The uncertainties in $A(\text{Be})$ range from 0.09 to 0.18 dex.

We can compare our results for these two young clusters with those of the older, more metal-rich Hyades studied for Be by Boesgaard & King (2002). Stars in both Hyades and Pleiades cooler than 6000 K show similar values for $A(\text{Be})$, 1.31 ± 0.07 and 1.26 ± 0.10 dex, respectively: their values are not far from the meteoritic abundance of 1.42 dex. Although the Hyades show a Be dip in the mid-F dwarfs, there is no such dip apparent in the Pleiades. The Hyades Li dip is very dramatic, but the Pleiades has only a minor Li dip, so the absence of a Pleiades Be dip is not surprising. This indicates that the depletion of both Li and Be is occurring *during the main-sequence phase of evolution* and that the effects of the depletion are only marginally evident for Li by the age of the Pleiades stars, near 100 Myr.

In the G dwarfs in both Hyades and Pleiades, there are no Li-like large depletions in Be, but, in both clusters, there could be a small dispersion in $A(\text{Be})$ at a given temperature that is comparable to the quoted errors. If real, this dispersion could result from small amounts of Be depletion from the effects of rotation where the stars that are more rapidly rotating have lower Be, as predicted by the Deliyannis & Pinsonneault (1997) models and as seen in Figure 12 for the Pleiades. This might come from the variation in initial stellar rotation at a given temperature in the cluster. However, this explanation does not account for the Li- T_{eff} pattern in

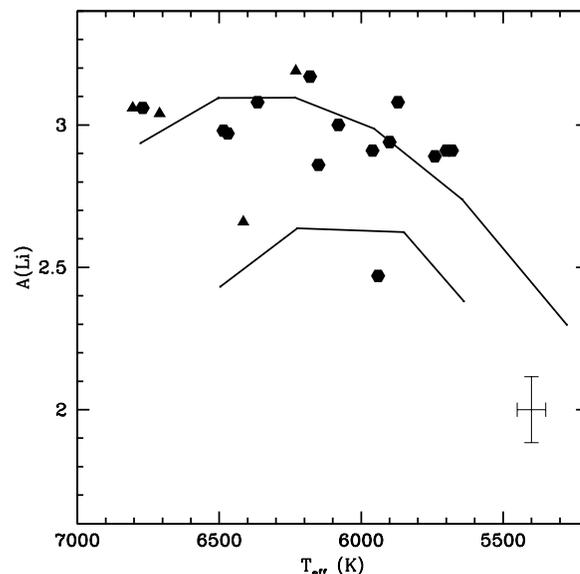


FIG. 13.—Li abundances as a function of temperature along with the predictions of Deliyannis & Pinsonneault (1997) of the effect of rotationally induced mixing on the Li abundance for an age of 100 Myr. *Upper curve:* Initial rotational velocity of 10 km s^{-1} . *Lower curve:* Initial rotation velocity of 30 km s^{-1} . A typical error bar is shown in the lower right.

Figure 13. Four of our stars seem to have retained their initial Li and Be, and the ratio for these of Li/Be is 63.

The later G and K dwarfs in the Pleiades show a remarkable spread in Li abundance, the cause(s) of which remains unknown. Effects such as magnetic fields, opacity variations, and even the possibility that some of the spread is merely illusory have been proposed (e.g., King et al. 2000 and references therein). Whether this spread in Li is related to a possible spread in Be in our early G dwarfs is unknown; unfortunately, the impact of the above effects on Be abundances has not been studied (perhaps heretofore due to the lack of motivating observational data). Such efforts, along with the observational delineation of the existence and magnitude of Be spread in late G Pleiades dwarfs, may provide important clues to address unanswered questions concerning intracluster light element abundance spreads.

The α Per cluster is younger than the Pleiades, but the four F dwarfs we observed in α Per have lower Be than their Pleiades counterparts. Figure 12 suggests that they may have had higher initial rotation velocities than the Pleiades stars and, thus, depleted more Be, but Figure 13 shows that this would make the Li results inconsistent with the predictions. Our observations of Be in these two young clusters do not confirm or refute the rotationally induced mixing model of Deliyannis & Pinsonneault (1997).

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