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BERYLLIUM ABUNDANCES IN F AND G DWARFS IN PRAESEPE AND OTHER YOUNG CLUSTERS FROM KECK HIRES OBSERVATIONS

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ABSTRACT

The study of both Be and Li gives useful clues about stellar internal structure. Of particular interest is the study of these light elements in open clusters, which have a known age and metallicity. In this paper we present a study of Be abundances in 10 F-type stars in Praesepe and a comprehensive discussion about Be abundances in other open clusters: Hyades, Pleiades, α Per, Coma, and UMa. We have made observations of the doublet of Be II around 3130 Å in Praesepe stars, using the Keck I telescope and the High Resolution Echelle Spectrometer (HIRES). Beryllium abundances were derived from the spectra using the spectrum synthesis method. We find four stars with definite Be depletion in the temperature range of the Li dip like we found in our previous cluster studies, notably for the Hyades and Coma clusters. Putting all the clusters together, we confirm the existence of a Be dip in a narrow temperature range for F stars. Beryllium depletion in this dip is less pronounced than Li depletion. For the cooler stars there is little or no Be depletion, even though there are large depletions of Li. For stars that have little or no Li depletion, $A(\mathrm{Li}) \geq 3.0$, the ratio Li/Be is 75 $\pm$ 4.6, compared to the meteoritic ratio of 77.6. For stars cooler than $\sim$5900 K there appears to be little or no Be depletion, and the mean A(Be) is 1.30 $\pm$ 0.02. For these cooler stars within a given cluster there is no evidence for intrinsic star-to-star differences in A(Be), with the possible exception of the cool Pleiades stars. In the temperature range of the Li-Be dip, a strong correlation exists between Li and Be, consistent with the theory of rotationally induced mixing. Moreover, the slopes of the Li versus Be correlations are different depending on the temperature range. For the full sample of 42 stars between 5900 and 6650 K the slope is 0.43 $\pm$ 0.05 [where A(Li) is the abscissa]. The slope is 0.48 $\pm$ 0.08 for 6300 K $< T_{\mathrm{eff}} <$ 6650 K and 0.30 $\pm$ 0.05 for 5900 K $< T_{\mathrm{eff}} <$ 6300 K. For the Li plateau stars (the cooler subset), the slope is smaller as the impact of the increasing surface convection zone affects the mixing, thus depleting more Li relative to Be. The different behavior in Be depletion for clusters of different ages is consistent with the idea of slow mixing related to rotation during the main-sequence phase of evolution. The range in metallicity in this sample of clusters is only 0.2 dex, so it is difficult to discern any influence of metallicity on the Li-Be relationship; however, the mean A(Be) in the cooler Hyades stars (with [Fe/H] = +0.13) is 1.35 $\pm$ 0.02, which is higher than that for the Coma stars (with [Fe/H] = $-$0.09) of 1.26 $\pm$ 0.02 by 0.09 dex.

Subject headings: open clusters and associations: individual (Praesepe) — stars: abundances — stars: interiors

1. INTRODUCTION

The understanding of stellar internal structure and mixing mechanisms via light-element depletion is enhanced by abundance determinations of more than one of the trio of Li, Be, and B. The three dominant isotopes of each of these elements are destroyed by nuclear fusion reactions at different depths inside stars corresponding to temperatures near 2.5×10^6 K for Li, 3.5×10^6 K for Be, and 5×10^6 K for B. In previous papers we have added Be abundances to the Li abundances in F and G dwarfs in several young open clusters: Boesgaard & King (2002) derived Be abundances in 34 stars in the Hyades cluster; Boesgaard, Armengaud, & King (2003a) measured Be in 14 dwarfs in the Pleiades and α Per clusters; while Boesgaard, Armengaud, & King (2003b) determined the Be content of 20 stars in the Coma cluster and the UMa moving group.

The major results from those studies are as follows: (1) A Be dip, similar to the Li dip, was discovered in the mid-F stars and in the Hyades and Coma clusters, but not in the younger Pleiades cluster. (2) Be is undepleted in the G stars in all the clusters, whereas Li has undergone major depletion in the G stars, especially in the Hyades and Coma clusters. (3) The Li and Be abundances are correlated in the temperature range 5850–6650 K, which corresponds to the temperature range from the Li plateau to the bottom of the Li dip in the Hyades. More detailed discussions are given in the above three papers.

In this project we have analyzed 10 F dwarfs in the Praesepe cluster and determined Be abundances; these are compared with Li abundances from Boesgaard & Budge (1988) and Soderblom et al. (1993). Praesepe is similar to Hyades in

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TABLE 1
Log of the Observations of the Praesepe Cluster

Star ID: Name	Star ID: BD	V	$B-V$	Night (UT)	Exposure (minutes)	S/N
KW 218.............	+21 1882	9.34	0.405	1999 Nov 14	46	69
KW 222.............	+20 2151	10.10	0.490	2002 Jan 4	45	52
KW 227.............	+19 2066	9.54	0.415	1999 Nov 13	49	77
KW 293.............	+19 2832	9.89	0.480	2002 Jan 5	44	54
KW 332.............	+19 2074	9.50	0.424	1999 Nov 14	47	61
KW 371.............	+20 2176	10.11	0.507	2002 Jan 4	45	48
KW 396.............	+20 2180	9.89	0.470	2002 Jan 5	45	55
KW 416.............	+20 2183	9.60	0.406	2001 Feb 1	50	34
KW 439.............	+19 2082	9.42	0.393	2002 Jan 4	45	71
KW 536.............	+19 2045	9.50	0.451	2002 Jan 4	45	70

both age and composition, but its main-sequence stars are somewhat fainter, and many are rotationally broadened. We assemble the results for all six clusters and examine the trends of Li and Be with age and metallicity.

2. OBSERVATIONS AND ANALYSIS

Ten F dwarf stars belonging to the Praesepe cluster were observed with the Keck I 10 m telescope and the High Resolution Echelle Spectrometer (HIRES) spectrometer with a Tektronix 2048 × 2048 CCD (Vogt et al. 1994). The spectra were taken on five nights between 1999 November 13 and 2002 January 5 UT. Since the Be II resonance lines are at 3130.421 and 3131.065 Å, near the atmospheric UV cutoff, we needed low air mass observations. The spectra were obtained when the stars were close to the meridian; Praesepe is at a declination of +20, virtually overhead at Mauna Kea. The spectral resolution was ∼48,000. Typical exposure times were about 45 minutes, leading to signal-to-noise ratios (S/Ns) per pixel between 48 and 77, the mean and median S/N being 59; the S/N is per pixel, where 1 pixel = 0.021 Å. Quartz flat-field and bias frames were also obtained on each night of observation, along with Th-Ar comparison spectra. Table 1 lists the objects observed with the Klein-Wassink (1927) and the BD numbers, the V and $B-V$ photometric indexes, the nights of observation, the exposure time, and the S/N in the Be region of the spectra. To carry out the data reduction, we used standard routines in IRAF as described in Boesgaard & King (2002).

All the stars in this study had been previously studied for their Li, either in Boesgaard & Budge (1988) or in Soderblom et al. (1993). In the latter case we used the data from the erratum of Soderblom et al. (1993). Figure 1 shows the Li abundances plotted versus effective temperature, pointing out the evidence for a Li dip in the Praesepe cluster. The circles indicate the stars we observed for Be. For the Li and Be abundances we use the notation $A(\text{element}) = \log N(\text{element/H}) + 12.00$, as in Figure 1 for A(Li). The meteoritic values for these two elements are $A(\text{Li}) = 3.31 \pm 0.04$ and $A(\text{Be}) = 1.42 \pm 0.04$ (Grevesse & Sauval 1998).

For observational and theoretical reasons, it is important to know whether the stars that we are studying are binaries or not. The temperature calibration and spectroscopy of binaries are often much less accurate than in the case of a single star. In the case where the initial rapid rotation is braked by tidal locking in a close (short-period) binary, the light-element depletion could be limited. For binaries with short enough periods, this braking occurs during pre–main-sequence evolution, when the mixing caused by braking does not result in light-element depletion because the internal temperatures are not high enough. We have used recent investigations of the radial velocities in Praesepe from Mermilliod & Mayor (1999) and the adaptive optics study of Bouvier et al. (2001) in order to identify as many binaries as we could among all the stars that have been previously studied for their Li. In particular, there are four detected binaries among the 10 stars that we have studied for Be : KW 371, KW 416, KW 439, and KW 536. They are all SB1s, except for KW 371, which is thought to be a binary on the basis of its photometry and position in the color-magnitude diagram. These stars are noted in Table 2.

Figure 2 shows Li abundance against temperature for the stars that have not been identified as binaries in either of these two papers. By eliminating the binaries, we reduce the dispersion in the Li-T_{eff} pattern of the cluster. The hot side of the dip is represented by only one nonbinary member, namely KW 370. One object that does not follow the Li-T_{eff} trend, KW 392 with $T_{\text{eff}} = 6040$ K and $A(\text{Li}) = 1.66$, is nevertheless

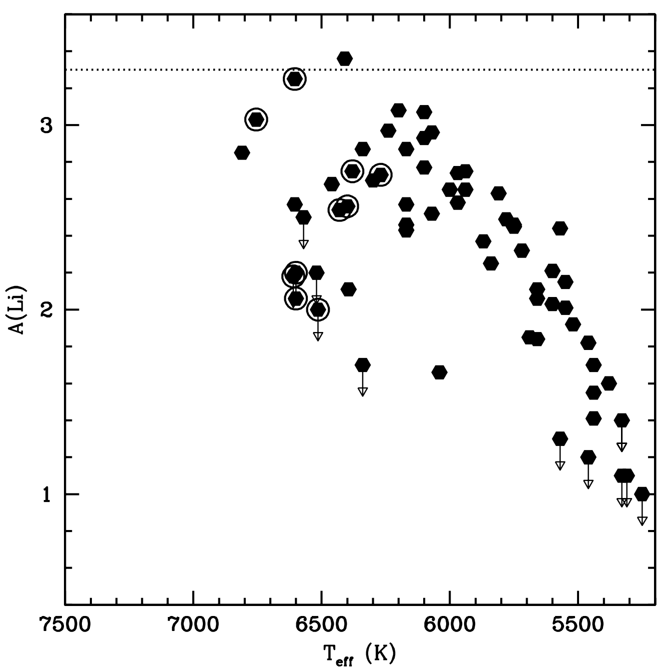

Fig. 1.—Lithium abundances against effective temperature for all the Praesepe stars from Boesgaard & Budge (1988) and Soderblom et al. (1993). The upper limits on Li abundances are indicated. The stars that we observed for Be are represented by circled points. The meteoritic abundance of Li, $A(\text{Li}) = 3.31$, is represented by the horizontal dotted line.

TABLE 2

Stellar Parameters and Abundances for Praesepe Cluster ([Fe/H] = 0.09)

Star ID	T_{eff} (K)	σ	log g	ξ (km s^{-1})	$v \sin i$ (km s^{-1})	A(Li)	Source[a]	A(Be)	σ
KW 218..........	6600	15	4.32	1.96	69	<2.20	S	0.80	0.20
KW 222..........	6380	35	4.36	1.74	14	2.75	S	1.20	0.12
KW 227..........	6600	21	4.33	1.95	21	2.06	B	0.50	0.20
KW 293..........	6400	21	4.35	1.77	43	2.56	S	1.15	0.16
KW 332..........	6610	17	4.33	1.96	48	<2.18	B	0.88	0.25
KW 371[b]........	6270	47	4.36	1.65	32	2.73	S	1.05	0.15
KW 396..........	6430	38	4.35	1.79	22	2.54	S	1.08	0.14
KW 416[b]........	6605	97	4.32	2.13	9.6	3.25	B	1.28	0.13
KW 439[b]........	6755	49	4.32	2.07	15	3.03	S	1.22	0.12
KW 536[b]........	6515	19	4.34	1.76	17	<2.00	S	0.70	0.26

[a] B = Boesgaard & Budge 1988, S = erratum of Soderblom et al. 1993.
[b] Binary star.

a high-probability member of the cluster (Soderblom et al. 1993). Figure 2 also shows the binaries for which Be is studied in this paper.

3. ABUNDANCES

The stellar temperatures have been determined by Soderblom et al. (1993), Boesgaard & Budge (1988), and Boesgaard (1989). Inasmuch as accuracy in the temperature is needed to locate the Be gap, we recomputed T_{eff} using five calibrations given by Saxner & Hammarbäck (1985) and Magain (1987). The photometric indexes $b-y$, $B-V$, and β were taken from the GCPD, whereas the metallicity is taken as constant for the Praesepe stars: [Fe/H] = +0.09 (see below). Saxner & Hammarbäck's calibration using β, $T_{eff} = 11,320(\beta-2.3311)^{1/2}$, sometimes gave results that disagreed with the other four temperatures. In that case (4 stars out of the 10), we did not include this temperature. Using the remaining calibrations, we were able to find the mean and uncertainty for the temperature of each star. In seven cases, the temperatures obtained this way were within ±50 K of the previous ones. In order to be consistent with the other papers, we decided to keep the previous temperatures. We had to change the temperatures of the other three objects, namely KW 416, KW 439, and KW 536. It is noteworthy that all three of them are binaries.

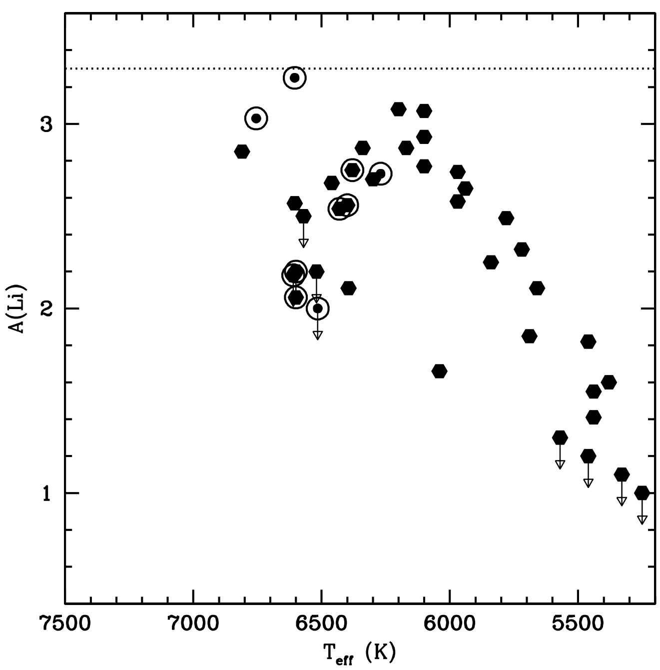

Fig. 2.—Lithium abundances plotted against temperature for the Praesepe stars. The values of T_{eff} and A(Li) are from Boesgaard & Budge (1988) and Soderblom et al. (1993). The circled points correspond to the stars that we observed for Be. The stars that are thought to be binaries have been removed from the data plotted here, except for four that we observed for Be; those four are shown as small filled circles instead of hexagons. The horizontal dotted line is at A(Li) = 3.31, the meteoritic abundance of Li.

Other stellar parameters were determined the same way as in Boesgaard & King (2002); log g was derived using the relation from Gray (1976), and microturbulent velocity is from the formula of Edvardsson et al. (1993). Previous studies of the cluster's metallicity have been done by Boesgaard & Budge (1988), Boesgaard (1989), and Friel & Boesgaard (1992). Their respective mean metallicities for Praesepe were +0.128, +0.092, and +0.038. The mean value of these is 0.086, and we adopted [Fe/H] = +0.09 for all the Praesepe stars. This value is similar to that of the Hyades at +0.13.

The Be abundance derivation from the spectra was done the same way as in Boesgaard & King (2002). A model atmosphere was first interpolated for each star from the Kurucz (1993) grid and the stellar parameters; all elements, except Be, have enhancements of +0.09 dex, like the derived [Fe/H]. Then spectrum synthesis in the Be ii lines region was done with MOOG 2002[2] (Sneden 1973), which contains the UV opacity edges. We used the atomic and molecular line list used in the previous papers and achieved a good match between the observational and synthetic spectra by convolving the synthetic spectra by a Gaussian, to take macroscopic broadening mechanisms into account. It is possible to use other broadening kernels in MOOG, e.g., Lorentz, rotation, and macroturbulence. We found that we derived similar Be abundances with either Gauss or rotation, but the match of the observed and synthetic spectra was better with a Gaussian.

Table 2 gives the effective temperature for each star with the internal agreement from the various colors and calibrations (the uncertainty in the temperature is probably larger, 40–50 K), the stellar parameters log g and ξ, and an approximate estimate of $v \sin i$ that was inferred from the

[2] MOOG is available on-line at http://verdi.as.utexas.edu/moog.html.

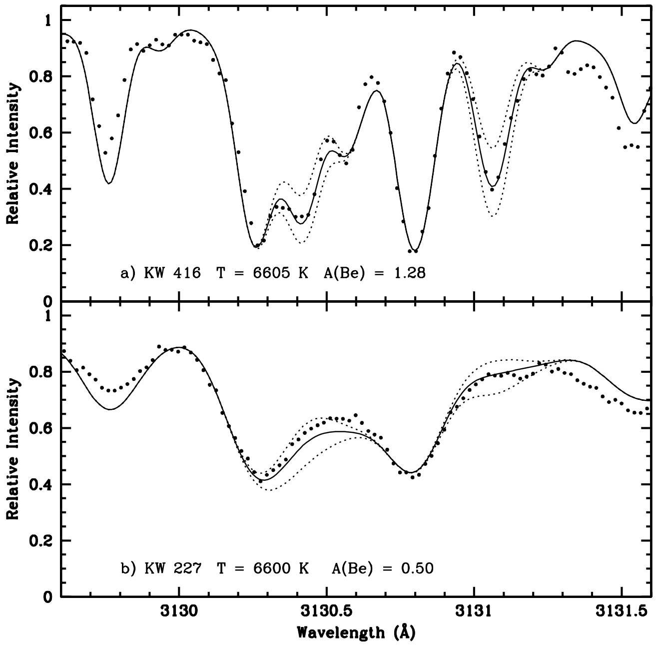

FIG. 3.—Examples of spectrum synthesis for the Praesepe stars. The dots represent the observed spectra and the solid line is the best fit Be abundance, whereas the dotted lines are for Be abundances ±0.30 dex, i.e., a factor of 2 higher and lower. The temperature of KW 416 is uncertain (±100 K), and the sharpness of the lines might indicate that it is cooler than the mean temperature in Table 2.

Gaussian fit of the spectrum, the published Li determination, and the reference for the A(Li) value.

Examples of spectrum synthesis for Praesepe are shown in Figures 3 and 4. Figure 3 shows two stars of apparently similar temperatures but different Be abundances. KW 416, although presumably located in the Be gap temperature range, does not show any significant Be depletion. KW 227, with the same temperature as KW 416, has a different behavior: its rotational broadening limits the accuracy of Be determination, but we are still able to ascertain a significant Be depletion for this star. We point out that the temperature of KW 416 is uncertain by ±100 K. It is a slow rotator (or seen close to pole-on) and an SB1. In Figure 4 we can see examples of two stars in the same temperature range, for which rotational broadening makes the Be abundance determination difficult, but Be is clearly present.

The last columns of Table 2 list the Be abundance and the estimated error for each star. The error estimates were done in the same way as in Boesgaard et al. (2003a, 2003b). An error in $T_{\rm eff}$ of ±80 K leads to an uncertainty in A(Be) of ±0.01 dex, and an error in $\log g$ of +0.10 results in an uncertainty in A(Be) of +0.036 to +0.052, depending on the temperature of the star. The largest errors are due to the difficulty in determining Be abundances when rotational broadening in the spectra is high.

4. RESULTS AND DISCUSSION

4.1. *Praesepe*

The Be abundances that we found are plotted against effective temperature in Figure 5. The error bars for both Be abundance and temperature are shown for the Praesepe stars. The black points represent the Hyades data for comparison. These have all been reanalyzed with MOOG 2002, the latest MOOG version with enhanced new UV opacities. Table 3 presents the new Be abundances that we found for the Hyades, along with their estimated uncertainties. The Be abundances have increased on average by +0.02 dex for the stars cooler than 5900 K and by +0.08 dex for the hotter stars (excluding the rapid rotators where the increase is +0.06 dex, but the abundance determination is more difficult).

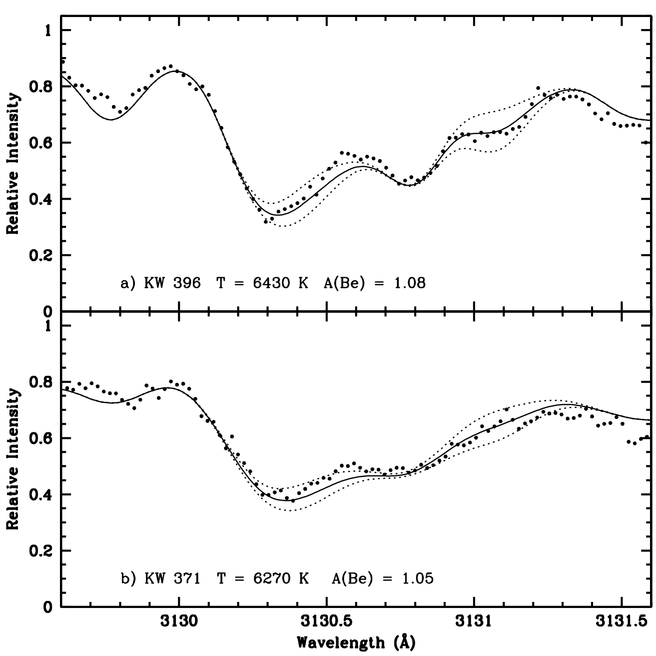

FIG. 4.—Examples of the spectrum synthesis of two Praesepe stars. The symbols and lines are the same as in Fig. 3. These two stars have similar, but somewhat depleted, Be abundances. The rotational broadening adds additional uncertainty to the derived A(Be) values.

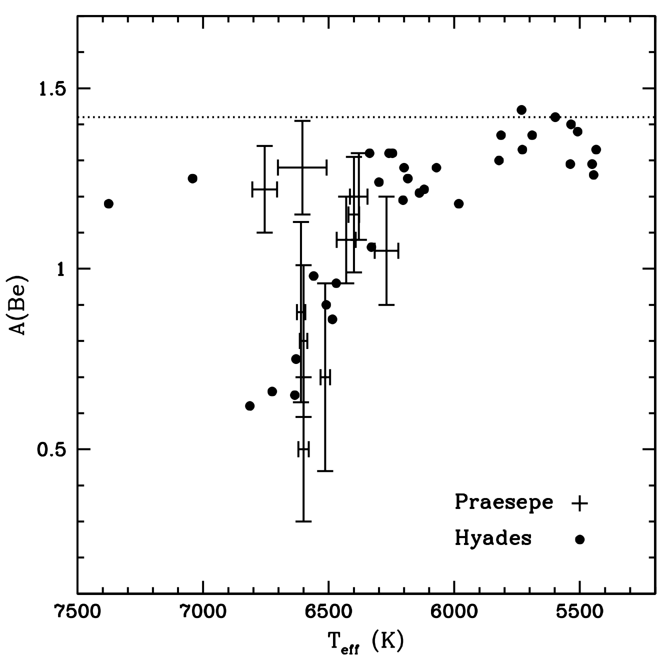

FIG. 5.—Be abundances in the Praesepe stars compared with those in the Hyades, a cluster of similar age and metallicity. The trends are similar with the exception of KW 416 at [6605, 1.28], which is the sharp-lined SB1 with a large temperature uncertainty; its spectrum synthesis is shown in Fig. 3. The other hot star, KW 439 at [6755, 1.22], is also a single-line spectroscopic binary. The horizontal dotted line represents the meteoritic Be abundance.

TABLE 3
New Abundances for Hyades Cluster ([Fe/H] = 0.13)

Star ID	T_{eff} (K)	Source[a]	A(Li)	A(Be)	σ
VB 9	5538	T	<0.79	1.29	0.05
VB 10	5982	T	2.76	1.18	0.03
VB 13	6725	B	<1.78	0.66	0.10
VB 14	7042	B	3.43	1.25	0.07
VB 15	5729	T	2.29	1.33	0.05
VB 17	5598	T	1.99	1.42	0.05
VB 19	6300	B	3.01	1.24	0.085
VB 27	5535	T	1.61	1.40	0.05
VB 31	6071	T	2.96	1.28	0.04
VB 37	6814	B	2.29	0.62	0.08
VB 38	7376	B	3.03	1.18	0.10
VB 48	6246	B	3.04	1.32	0.07
VB 59	6120	B	2.86	1.22	0.045
VB 61	6260	B	3.18	1.32	0.07
VB 62	6185	B	3.14	1.25	0.03
VB 63	5822	T	2.51	1.30	0.05
VB 64	5732	T	2.32	1.44	0.05
VB 65	6200	B	3.07	1.28	0.04
VB 66	6204	T	2.78	1.19	0.045
VB 69	5435	T	1.13	1.33	0.05
VB 77	6330	B	2.46	1.06	0.09
VB 78	6510	B	2.61	0.90	0.09
VB 81	6470	B	2.24	0.96	0.09
VB 86	6485	B	2.40	0.86	0.09
VB 87	5445	T	1.18	1.26	0.05
VB 92	5451	T	1.30	1.29	0.06
VB 97	5814	T	2.64	1.37	0.05
VB 101	6635	B	<1.16	0.55	0.21
VB 106	5690	T	2.42	1.37	0.05
VB 113	6139	T	2.84	1.21	0.04
VB 114	5509	T	1.79	1.38	0.05
VB 121	6337	B	3.27	1.32	0.06
VB 124	6630	B	2.06	0.75	0.09
VB 128	6560	B	2.25	0.98	0.09

[a] B = Boesgaard & Tripicco 1986 and Boesgaard & Budge 1988, T = Thorburn et al. 1993.

There is Be depletion for Praesepe stars in the same temperature range as for the Hyades cluster. The cool side of the Be dip has a similar shape in the two clusters. There are four stars near the core of the Li-Be dip, KW 218, KW 227, KW 332, and KW 536, which have some of the lowest Be abundances in our series of papers, $A(\mathrm{Be}) = 0.50-0.88$ dex. All four are also depleted by factors of 200 or more in Li. These four stars have large errors in A(Be) of ± 0.20 to ± 0.26 dex, primarily due to their large rotational broadening. This could be another clue to the major role that rotation plays in light-element depletion in F stars.

There are two stars in Praesepe with apparently normal Be abundances but with derived temperatures that locate them in the middle of the Hyades Li-Be dip. These objects, KW 416 and KW 439, which have no significant Be depletion, are both SB1 binaries. Both stars have major temperature uncertainties. We cannot exclude the idea that they are actually on the hot side of the dip, or even on the cool side. This is particularly problematic for KW 416, for which the $b-y$ temperature calibrations give T_{eff} around and even below 6500 K, the $B-V$ calibrations give T_{eff} around and even over 6650 K, and the β calibration gives a still higher $T_{eff} = 6730$ K. The synthesis fit in Figure 3 for KW 416 shows that the spectrum of this star contains sharp lines; the Gaussian fit is for 0.10 Å. KW 439 is another sharp-lined star, which was fitted to a Gaussian of 0.16 Å. Evidence has accumulated in favor of rotation/differential rotation as the cause of light-element depletion in the dip; we can therefore hypothesize that these binaries are tidally locked, braking the rotation and inhibiting light-element mixing. This could explain the anomalously high Li and Be content. However, Mermilliod & Mayor (1999) have measured the orbital parameters of both binaries and found periods of 25 days for KW 416 and 457 days for KW 439. These periods are too long to be consistent with tidally locked systems. Even though they are not tidally locked, their slower initial rotation could result in little or no Li and Be depletion.

In Figure 6 we have plotted both Li and Be abundances in our 10 Praesepe stars on the same scale, coincident with their respective meteoritic abundances. This plot is similar to the ones in our earlier papers on Hyades, Coma/UMa, and Pleiades/α Per. The vertical shift from the meteoritic value shows the depletion amount of Li and Be. In the case of Praesepe, two hot stars are virtually undepleted in both Li and Be. The other stars are all depleted in Li. Those with severe Li depletions are also Be-depleted. Those with more mild Li depletions have only small Be depletions, if any. For those eight stars the Li depletions are systematically larger than the Be depletions; this is consistent with the predictions from theories of slow mixing of the surface material down to the respective temperature of nuclear destruction of Li ($\sim 2.5 \times 10^6$ K) and Be ($\sim 3.5 \times 10^6$ K).

4.2. *Praesepe and the Other Young Clusters*

4.2.1. Be-*deficient Stars*

The most Be-deficient star in our sample is KW 227 at $A(\mathrm{Be}) = 0.50 \pm 0.20$. At 6600 K this star is near the bottom of the Li-Be dip. Figure 7 reveals that it is indeed Be-deficient, but with Be present. For comparison with the best-fit Be

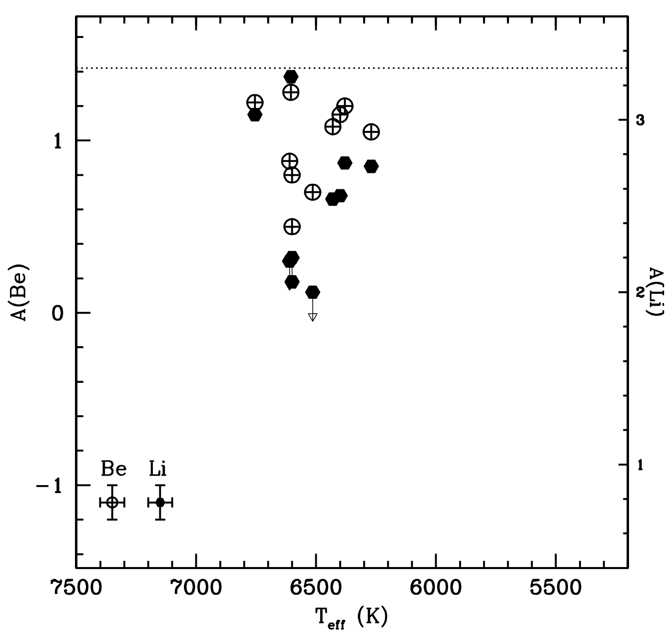

Fig. 6.—Abundances of Li and Be in our Praesepe stars on the same vertical scale, rectified to their respective meteoritic abundances. The circled crosses represent the Be abundances (*left y-axis*) and the filled hexagons represent the Li abundances (*right y-axis*). Sample error bars appear in the lower left of the figure. The Li depletions are consistently larger than the Be depletions, as expected from the respective temperatures of nuclear destruction.

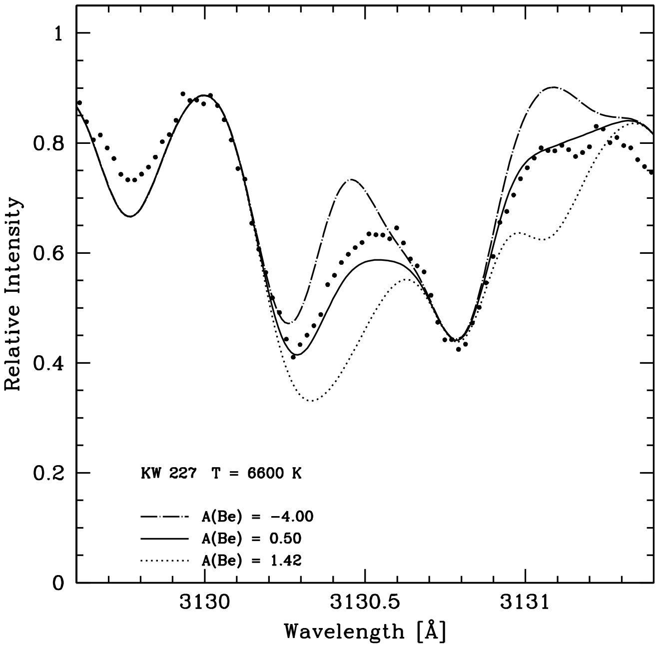

FIG. 7.—Synthesis fit for Be in KW 227 showing that the Be is present, but depleted. The best fit through the data points is the solid line; the dotted line is for the meteoritic Be abundance, and the dot-dashed line is for essentially no Be.

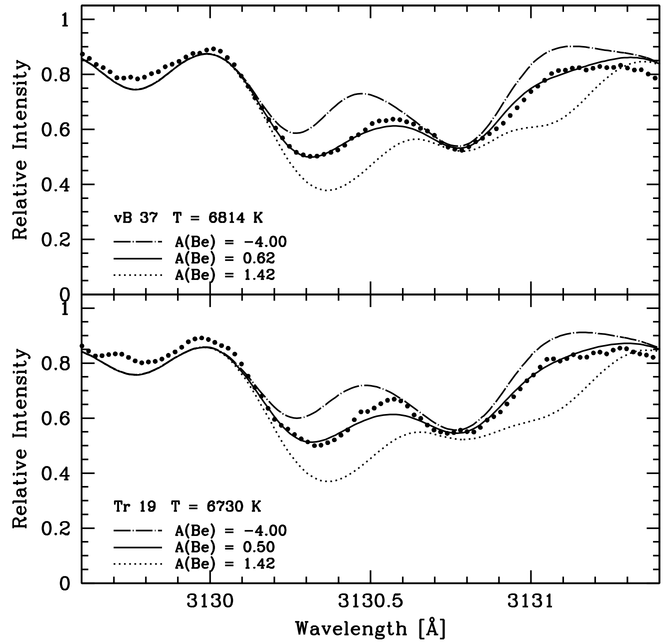

FIG. 8.—Synthesis fits for Be in a Hyades star, VB 37, and a Coma star, Tr 19, both in the Li-Be dip. Both have detectable but depleted Be. The symbols and lines are as in Fig. 7.

abundance, this figure also shows the synthesis with the meteoritic abundance at the temperature and gravity for this star. The best-fit Be abundance is clearly below that. Also shown is what the spectrum is calculated to be with essentially no Be; this clearly does not fit the observed spectrum either. Even though the spectrum is rotationally broadened, the Be deficiency of this star can be determined.

This Praesepe star is very similar to ones we have found in the Hyades and Coma clusters. Figure 8 shows similar fits for VB 37 and Tr 19 in the Hyades and Coma, respectively. (These plots are adapted from Boesgaard & King 2002 and Boesgaard et al. 2003b.) The best fits are shown along with the meteoritic Be synthesis and the "no Be" synthesis.

These stars, from three different clusters, demonstrate the reality of the Be dip and show Be deficiencies that are smaller than the Li deficiencies. While Be is reduced by factors of 6–8, Li can be depleted by more than 100 times.

4.2.2. *Correlation of* Li *and* Be *in the Hotter Stars*

In previous studies we have found a correlation between Li and Be in a narrow temperature range of ~5850 to ~6650 K (Deliyannis et al. 1998; Boesgaard et al. 2001, 2003a, 2003b; Boesgaard & King 2002). For 27 field stars from 5850 to 6680 K, Boesgaard et al. (2001) found a slope of 0.36 ± 0.04 between A(Be) and A(Li) [with A(Li) as the abscissa].

In Figure 9 we plot A(Be) against A(Li) for 42 stars from five young clusters in the temperature range 5900–6650 K. The uncertainties in A(Be) are shown; the typical error bar for A(Li) is ± 0.10 dex. Four of the stars have only upper limits for A(Li), and these were not used to determine the best-fit slope through the points. One star with an upper limit Li abundance is not shown: VB 101 has a very uncertain Be abundance due to its high rotation. The slope of the relation shown is 0.43 ± 0.05. (We recognize the existence of techniques to deal with upper limit data. However, there are only four such stars, which will have minimal impact on the slope. More importantly, however, in this series of papers we are looking at correlations between ongoing Li and Be depletion; that is, we presume that we are looking at stars actively depleting both Li and Be. This is the meaning of the slope in Fig. 9. We cannot use stars with upper limits of Li or Be to trace the ongoing correlation of Li and Be depletion.)

In this temperature range the abundances are well correlated and Li is decreasing faster than Be. In these young clusters, as

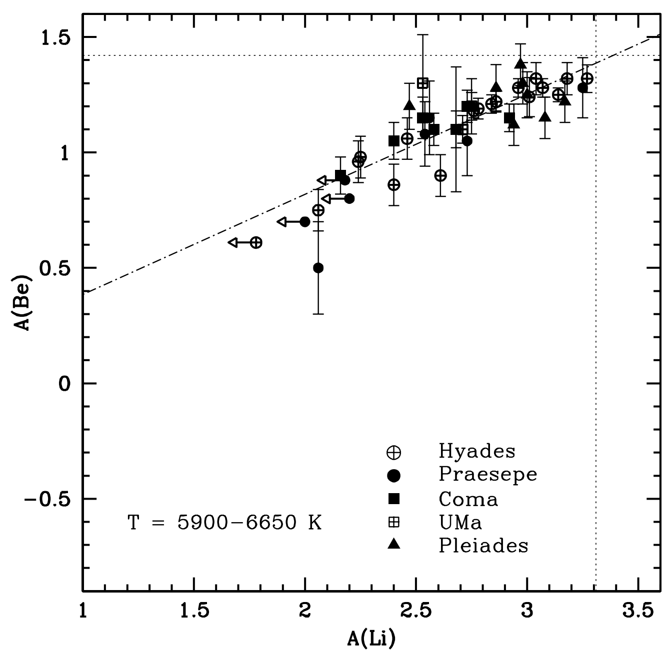

FIG. 9.—Li-Be relation for hot stars from five different clusters. The temperature range selected here is 5900 K < $T_{\rm eff}$ < 6650 K, the temperature at the Li plateau to the center of the Li dip in the Hyades. The upper limits on Li abundances are indicated, but those values were not included in the least-squares fit. The meteoritic abundances are shown by the horizontal (Be) and vertical (Li) dotted lines. The dot-dashed line represents the least-squares fit for all the points with Be and Li detected. The slope for these stars is 0.43.

Li decreases by a factor of 10, Be decreases by only 2.7 times. The stars on the upper right (low depletion of both Li and Be) are preferentially younger and cooler. The hotter stars near the center of the Li-Be dip inhabit the lower left part of the slope. The correlation is given by

$$A(\mathrm{Be}) = (0.434 \pm 0.050)\,A(\mathrm{Li}) - 0.049 \pm 0.139$$
$$(T = 5900\text{–}6650\ \mathrm{K}).$$

We have decided to restrict the sample of stars to those that occupy the cool side of the dip and not include the early G stars. In the Li-T_{eff} diagram for the Hyades, the Li abundances are high on the hot side of the dip, then plummet into the dip and rise again on the cool side of the dip to a plateau near 6300 K; for still cooler stars Li begins to decrease again slowly with decreasing temperature. The physical mechanism(s) causing the Li decrease with decreasing temperature in the G stars may, depending on the cluster age, be more associated with the deepening convection zone than with rotation; it may also be a result of pre–main-sequence Li depletion, which is negligible in the hotter stars. In order to investigate the phenomena causing the slow mixing in the Li-Be dip, we examined stars in the narrower region of 6650 K (near the core of the dip) to 6300 K (the Li plateau). In this region, both Li and Be are *increasing* with *decreasing* temperature. This is shown in Figure 10 for the reduced sample of 20 stars with detected Li and Be. In this case the slope is somewhat higher at 0.48. The relation is

$$A(\mathrm{Be}) = (0.482 \pm 0.082)\,A(\mathrm{Li}) - 0.189 \pm 0.219$$
$$(T = 6300\text{–}6650\ \mathrm{K}).$$

Interestingly, at the meteoritic Li abundance of $A(\mathrm{Li}) = 3.31$, this relation gives $A(\mathrm{Be}) = 1.41$, while the meteoritic $A(\mathrm{Be}) = 1.42$. This is a steeper slope than that for all the stars in the larger temperature range. On the cool side of the Li-Be dip, a factor of 10.0 decline in Li is a factor of 3.0 decline in Be.

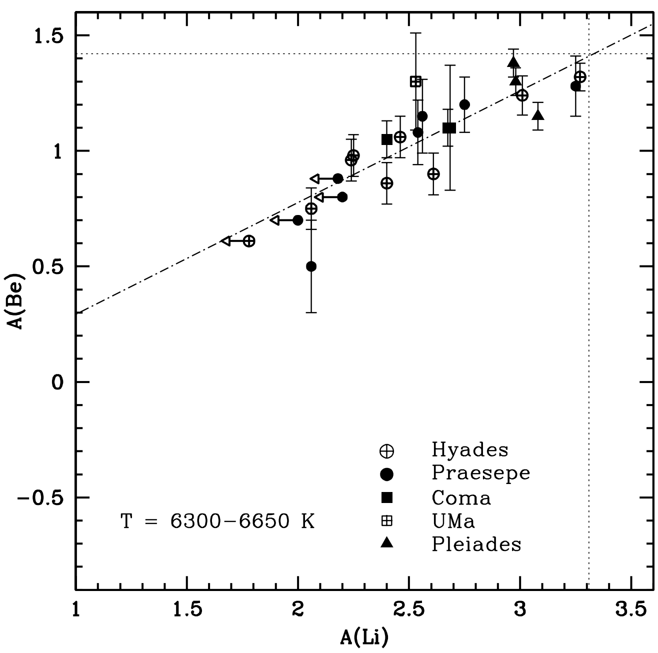

Fig. 10.—Similar to Fig. 9, but only the stars in the temperature range 6300 K < T_{eff} < 6650 K are included; this temperature range corresponds to the temperatures on the cool side of the Hyades Li dip, where Li increases with decreasing temperature. The meteoritic abundances are shown by the horizontal (Be) and vertical (Li) dotted lines. Stars with upper limits on A(Li) are shown, but were not included in the least-squares fit. The slope of this relation is 0.48.

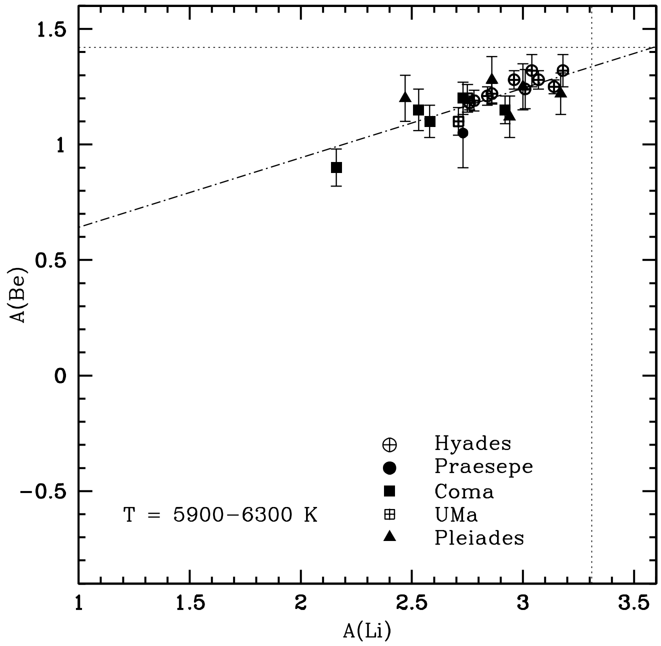

Fig. 11.—Counterpart to Fig. 10; only the cooler stars between 5900 K < T_{eff} < 6300 K are plotted. These stars are near the Li plateau as Li begins its decline with decreasing temperature. The meteoritic abundances are shown by the horizontal (Be) and vertical (Li) dotted lines. The slope is 0.301, shallower than that in Figs. 9 and 10. This is expected because convection begins to play an increasing role in the mixing processes, so Li is subject to more depletion relative to Be.

The cooler sample of the other 23 stars is for temperatures of 6300–5900 K, where Li is *decreasing* with *decreasing* temperature. This Li-Be correlation is shown in Figure 11 and has, as expected, a shallower slope: 0.30. The cooler stars have deeper convection zones, and thus Li is destroyed more readily relative to Be than in the warmer stars in Figure 10. This relation is

$$A(\mathrm{Be}) = (0.301 \pm 0.054)\,A(\mathrm{Li}) + 0.340 \pm 0.153$$
$$(T = 5900\text{–}6300\ \mathrm{K}).$$

This relation breaks down at cooler temperatures because there is little, if any, Be depletion (within the errors) in stars cooler than 5900 K in any of the clusters.

4.2.3. Be *Dispersion in the Cooler Stars*

We have examined whether there is a real dispersion in the Be abundances in a given cluster (unrelated to star-to-star depletion mechanism differences) by examining the observed scatter (standard deviation about the mean) in Be abundance for the cool stars in our sample. Any star-to-star differences in these objects, taken here as stars cooler than $T_{\mathrm{eff}} = 5900$ K, are presumably less dominated by star-to-star depletion differences than for warmer objects in or near the Be gap. Thus, they provide a picture of initial differences unrelated to those responsible for the marked F-star depletions. For 12 stars in this temperature regime in the Hyades, the average error for A(Be) is ± 0.051. The mean A(Be) is 1.348 ± 0.057 (standard deviation). Thus the error in the abundance is comparable to the dispersion in the abundances for the 12 stars. For the seven cool stars in Coma/UMa the average error is ±0.061, while the mean *A*(Be) is 1.257 ± 0.053; again the dispersion and the typical error are similar. For the five cool Pleiades stars we find $\langle A(\mathrm{Be})\rangle = 1.260 \pm 0.109$, and the average error in the abundance determination is slightly less than that at 0.094 dex. If there is a small dispersion in *A*(Be) at a given temperature, it is the size of the error determinations.

Comparing the observed variance with the weighted average of the expected individual variances for each cluster via a χ^2 test, we find the following. The observed scatter in the 12 cool Hyades dwarfs is significant at only the 77% confidence level. The observed scatter in the seven Coma/UMa cool dwarfs is *smaller* than expected at the 94% confidence level. The meager five cool Pleiades dwarfs evince a scatter larger than expected from our uncertainty estimates at the 98.4% confidence level. The level of even this best case of "real" dispersion needed to produce the observed scatter is ±0.08 dex. If real, a modest degree of Pleiades Be scatter is not surprising given the well-known Li scatter in the Pleiades, which itself is small and of only marginal significance in the T_{eff} range considered here (a cool subregion of region D in Fig. 4 of King, Krishnamurthi, & Pinsonneault 2000).

4.2.4. *Effects of Age and Metallicity*

We have now examined six clusters and can divide them into three groups: young with solar metallicity (Pleiades and α Per at ~50 Myr), intermediate with a small metal deficiency (Coma and UMa at ~400 Myr and [Fe/H] ~ −0.08), and intermediate with enhanced metals (Hyades and Praesepe at ~700 Myr and [Fe/H] ~ 0.12).

In the F stars in the youngest clusters, Pleiades and α Per, there is evidence for only a mild Li dip and no Be dip. In the G stars there is some evidence of a real dispersion in Li (Soderblom et al. 1993), but the typical error in the Be abundance (0.09 dex) is only slightly smaller than the standard deviation of the mean Be abundance (0.11 dex). So any dispersion in Be is comparable to the precision of the abundance derivation.

The four intermediate-age clusters show both Li and Be dips (except for Be in UMa, where we did not observe any Li dip stars for Be). The Be dip is less deep than the Li dip since Be is not as depleted as Li. The Be dip seems to be wider than the Li dip; the Be abundance continues to increase on the cool side of the dip to reach the meteoritic value at ~5900 K, whereas the Li abundance is already declining again in stars that are cooler than ~6300 K.

Although there are large Li depletions in the cool stars of the intermediate clusters (and Li dispersions detectable in the younger clusters), there are small or no Be depletions in stars with $T_{\mathrm{eff}} < 5900$ K. For those 24 stars the average value for *A*(Be) is 1.303 ± 0.017 (uncertainty in the mean). As reported in Boesgaard et al. (2003a), we find *A*(Be) = 1.30 (±~0.10) for the Sun from our Keck spectrum of the daytime sky. Although this value is lower than the meteoritic value of *A*(Be) = 1.42, the differences in analysis methods between stars and meteorites and possible systematic effects makes it difficult to know whether the Sun is depleted in Be.

Our clusters span only a small range in metallicity, [Fe/H] = −0.09 to +0.13, thus making the discernment of metallicity-associated evolution of the Be abundance a difficult prospect. We examine this issue by restricting attention, again, to Be abundances for the cool stars in our sample, i.e., stars cooler than $T_{\mathrm{eff}} = 5900$ K, since these presumably suffer minimal depletion. For those 12 stars in this temperature regime in the Hyades, the mean *A*(Be) is 1.348, while uncertainty in the mean is ±0.017. For the seven cool stars in Coma/UMa, the mean *A*(Be) is 1.257, and ±0.022 is the uncertainty in the mean. For the five cool Pleiades stars we find a mean *A*(Be) of 1.260 ± 0.055 (uncertainty in the mean). Comparing the difference of the means with the respective uncertainties, the Hyades-Pleiades difference is not considered significant. The Hyades-Coma/UMa difference is significant at the 3.3 σ level, given the statistical measurement uncertainties. The possibly lower Li abundances near the Li plateau $T_{\mathrm{eff}} \sim 6300$ K in Coma compared to the Hyades do lend some support to the idea of an intercluster difference. A definitive claim of a real Hyades-Pleiades initial cluster Be difference assumes that cluster-to-cluster systematic errors are vanishingly small. Indeed, if these are only a scant couple hundredths of a dex, they lead to a conclusion of statistically insignificant Hyades-Coma/UMa difference when combined with the internal random measurement uncertainties. Given the inability to rigorously exclude nearly vanishingly small insidious cluster-to-cluster differences (metallicity- or age-dependent errors in model atmospheres, the effects of different chromospheric properties, differing photospheric spot/faculae coverage, etc.), which is well beyond the scope of this work, we are hesitant to make such a claim.

4.2.5. *The* Li/Be *Ratio*

We have reexamined the Li/Be ratio in these young clusters using the most practical, although possibly still imperfect, approach on the basis of the extant data. In order to avoid those stars having undergone the greatest Li depletions that would skew the Li/Be ratios (since the Li-Be depletion is not a one-to-one mapping), we restrict attention to only those stars with $A(\mathrm{Li}) \geq 3.0$ in the temperature regime near the Hyades plateau, excluding stars also on the hot side of the Li-Be dip. There are six Hyades stars meeting these criteria, and they yield a Li/Be ratio of 69 ± 6.3 (uncertainty in the mean). Four Pleiades stars meeting the same conditions give Li/Be = 69 ± 11.5, and excluding one suspect member brings Li/Be = 77 ± 12.7.

Comparison with the results for the Sun is not completely straightforward, since the meteoritic ratio of 77.6 is a precision value from meteorites and thus known to be unaffected by stellar depletion. Considering cluster stars with $A(\mathrm{Li}) \geq 3.0$ may produce a lower limit to Li/Be, since it is possible that some objects with real Li depletions of perhaps up to a factor of 2 [depending on the initial cluster *A*(Li) values] are present in the sample. The identical (to within the uncertainties) Pleiades and Hyades ratios would simply seem to argue that this possible bias is not very important. Given the present uncertainties, both cluster's ratios are indistinguishable from the solar system value; the nine assured Hyades and Pleiades members indicate Li/Be = 75 ± 4.6. The only Praesepe stars with $A(\mathrm{Li}) \geq 3.0$ are on the hot side of the dip. The average Li/Be ratio for these two stars is 79. There are no stars with $A(\mathrm{Li}) \geq 3.0$ in our sample of Coma, UMa, and α Per stars.

4.3. *Interpretation*

The correlation of *A*(Be) with *A*(Li) implies that the cause of the depletion is rotationally induced mixing. The rotation models of both Charbonnel et al. (1994) and Deliyannis & Pinsonneault (1997) match this correlation very well, as discussed in Deliyannis et al. (1998), where this relation was first presented. Other depletion mechanisms such as mass loss and diffusion can be ruled out for the stars in our temperature regime (Stephens et al. 1997; Deliyannis et al. 1998). The predictions of rotational mixing are a better match than those of wave-driven mixing, e.g., García López & Spruit (1991), also discussed in the Stephens et al. and Deliyannis et al. papers. Newer gravity-wave models quoted in Randich et al. (2002) do not match our observations for stars hotter than 6000 K because they predict no Be depletion, contrary to our observations of Be depletion. At 6000 K the predicted Be depletion is about 0.2 dex too low for a given Li depletion. For more discussion of light-element destruction, see the trio of papers by Deliyannis, Pinsonneault, & Charbonnel (2000), Pinsonneault, Charbonnel, & Deliyannis (2000), and Charbonnel, Deliyannis, & Pinsonneault (2000).

With our sample of 42 cluster stars with temperatures between 5900 and 6650 K, we find a strong correlation between the Li and Be abundances shown in Figure 9. The slope of the full sample is 0.43 ± 0.05. We can discern a temperature effect as well with a slope for the hotter stars of 0.48 ± 0.08 and for the cooler stars of 0.30 ± 0.05. This temperature effect is consistent with an interplay between slowing rotation and increasing surface convection zone size with decreasing surface temperature and stellar mass. [See Fig. 3 in Boesgaard 1987, which shows the decline of $v \sin i$ and the increase in A(Li) from 6700 to 6000 K in the Hyades.]

The analysis done in Deliyannis et al. (1998) strongly favors mixing caused by rotation to account for the Li-Be correlation. Other evidence that supports rotation as the agent of slow mixing includes the following: (1) The M67 subgiants have evolved from the region of the Li dip; if the dip were due to diffusion, then the Li would be stored below the convection zone and circulated back up to the surface in the subgiants in excess of the observed upper limits (Deliyannis, King, & Boesgaard 1997). The models of Sills & Deliyannis (2000) for M67 strongly support rotationally induced mixing as the cause of the Li dip. (2) Each proposed mixing mechanism produces a distinct effect of Li, Be, and B. In a study of B in very Li- and Be-depleted stars, Boesgaard et al. (1998) found that B was constant in spite of the huge deficiencies in Li and Be. This argues against diffusion and supports slow mixing. In addition, the stars in the Li-Be dip in Hyades, Praesepe, and Coma are all rapid rotators. These stars show significant Li depletion and moderate (but real) Be depletion.

5. SUMMARY AND CONCLUSIONS

We have obtained high-resolution spectra of 10 F stars in the Praesepe cluster to compare the Li and Be abundances. Praesepe is known to have a mid-F star Li dip (see Figs. 1 and 2), and our purpose has been to add Be information in order to understand the internal stellar structure better. We now have Be data for 78 F and G dwarfs in six young open clusters.

The Praesepe cluster is similar in age and metallicity to the Hyades, but with fainter V magnitudes at a given temperature. Our spectra have a resolution of $\sim$48,000, with a median and mean S/N per pixel of 59. We have determined the parameters and the Be abundances in the same manner as in the previous papers (see Figs. 3 and 4). We find that there is a definite Be dip, but, as in the other clusters, it is not as deep as the Li dip. Although the dip stars have broad lines due to rotation, we derive some of the lowest Be abundances for four of the stars: $A(\mathrm{Be}) = 0.50-0.88$. The cool side of the Be dip is similar to that in the Hyades (see Fig. 5). There are two stars with temperatures corresponding to the dip that are undepleted in both Li and Be; these two stars have sharper lines (presumably from slower rotation) than the other stars depleted stars in the Li-Be dip, and their temperatures are uncertain. Where there is depletion, Li is always more depleted than Be (see Fig. 6).

We compare the results for all six clusters. We present evidence (see Figs. 7 and 8) of the reality of the Be dip with synthetic spectra of a Be dip star in each of three clusters: Praesepe, Hyades, and Coma. The younger Pleiades and α Per clusters have no Be dip. In the G stars in all the clusters there is little, if any, Be depletion.

A major result of these cluster studies is the correlation between A(Li) and A(Be) in a specific temperature region. The 42 stars of our 78 that fall within 5900–6650 K show a relation in log-log space that has a slope of 0.43 ± 0.05 [see Fig. 9 with A(Li) as the abscissa and A(Be) as the ordinate]. We can subdivide this temperature range into two: the cool side of the Li dip, $T_{\mathrm{eff}} = 6650$–6300 K, and the Li plateau region where Li begins to decline as the surface convection zone deepens and the surface temperature decreases, $T_{\mathrm{eff}} =$ 6300–5900 K. For the Li dip region the slope between A(Li) and A(Be) is 0.48 ± 0.08; as Li declines by a factor of 10, Be declines by a factor of 3 (see Fig. 10). This result indicates that the phenomenon responsible for the cool side of the Li dip is rotationally induced mixing.

The cooler stars have a somewhat shallower slope of 0.30 ± 0.05 between the logs of the abundances (see Fig. 11). The smaller slope is due to the fact that the increasing dimension of the convection zone aids the mixing due to rotation, but this affects Li relative to Be because Li is destroyed at a cooler temperature corresponding to a smaller depth in the star. For stars still cooler than 5900 K there would be no correlation inasmuch as Be shows little or no depletion in those stars even as Li is significantly depleted. Our coolest stars are near 5500 K; it is difficult to derive Be abundances in stars below 5400 K because of the weakening of the Be II lines and the strengthening of some of the blending features.

In a given cluster we find no conclusive evidence for an intrinsic star-to-star dispersion in A(Be) in the cool stars. A possible exception is a small dispersion in A(Be) in the Pleiades, which seems to have a dispersion in Li in the cooler stars. For the 24 stars in all the clusters that are cooler than 5900 K, we derive a mean A(Be) of 1.30 ± 0.02. There is little evidence that the parameter of metallicity contributes to differences in Li or Be between clusters, although there may be a real differences between the more metal-rich Hyades and the more metal-poor Coma cluster. The effect of the parameter age is evident in the Li-Be dip region such that the younger Pleiades shows little Li dip and no Be dip compared to the intermediate-age clusters.

We have determined Li/Be ratios for stars that have little or no Li depletion, $A(\mathrm{Li}) \geq 3.0$, and are cooler than 6300 K; for nine Hyades and Pleiades stars we find a value of 75 ± 4.6, which compares well with the meteoritic ratio of 77.6.

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