10-1-2004

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The Astrophysical Journal, 613:1202–1212, 2004 October 1

THE CORRELATION OF LITHIUM AND BERYLLIUM IN F AND G FIELD AND CLUSTER DWARF STARS

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Received 2004 January 30; accepted 2004 May 15

ABSTRACT

Although Li has been extensively observed in main-sequence field and cluster stars, there are relatively fewer observations of Be. We have obtained Keck HIRES spectra of 36 late F and early G dwarfs in order to study the Li-Be correlation we found previously in the temperature regime of 5900–6650 K. The sample size for this temperature range with detectable and (usually) depleted Li and Be is now 88, including Li and Be abundances in both cluster and field stars. Therefore we can now investigate the influence of other parameters such as age, temperature, and metallicity on the correlation. The Be spectra at 3130 Å were taken over six nights from 1999 November to 2002 January and have a spectral resolution of ~48,000 and a median signal-to-noise ratio (S/N) of 108 pixel^{-1}. We obtained Li spectra of 22 stars with the University of Hawaii 88 inch (2.2 m) telescope and coudé spectrograph with a spectral resolution of ~70,000 and a median S/N of 110 pixel^{-1}. We have redetermined the effective temperatures for all the stars and adopted other parameters from published data or empirical relations. The abundances of both Li and Be in the stars we observed were determined from spectrum synthesis with MOOG 2002. The previously observed Li equivalent widths for some of our Be stars were used with the new temperatures and MOOG 2002 in the "blends" mode. For the 46 field stars from this and earlier studies we find a linear relation between A(Li) and A(Be) with a slope of 0.375 ± 0.036. Over the $T_{\rm eff}$ range 5900–6650 K, we find the modest scatter about the Be-Li relation to be significantly correlated with $T_{\rm eff}$ and perhaps also [Fe/H]. Dividing the sample into two temperature regimes of 6300–6650 K (corresponding to the cool side of the Li-Be dip) and 5900–6300 K (corresponding to the Li "plateau") reveals possible small differences in the slopes for the two groups, 0.404 ± 0.034 and 0.365 ± 0.049, respectively. When we include the cluster stars (Hyades, Pleiades, Praesepe, UMa Group, and Coma), the slope for the full temperature range (88 stars) is essentially the same, at 0.382 ± 0.030, as for the field stars alone. For the hotter temperature group of 35 Li-Be dip stars in the field and in clusters the slope is higher, at 0.433 ± 0.036, while for the cooler star group (54 stars) the slope is 0.337 ± 0.031, different by more than 1 σ. This small difference in the slope is predicted by the theory of rotationally induced mixing. The four stars with [Fe/H] less than −0.4 are all below the best-fit relation, i.e., there is more Be depletion at a given A(Li) or less Be ab initio. The youngest stars, i.e., Pleiades, have less depletion of both Li and Be. This too is predicted by rotationally induced slow mixing. Combining the Be results from both field and cluster stars, we find that there are stars with undepleted Be, i.e., near the meteoritic values of 1.42 dex, at all temperatures from 5500 to 6800 K. Depletions of Be of up to and even exceeding 2 orders of magnitude are common between 6000 and 6700 K.

Subject headings: stars: abundances — stars: evolution

Online material: color figures

1. INTRODUCTION

The most practical way to obtain information about the layers beneath stellar photospheres is through the study of the trio of rare light elements, Li, Be, and B. While Li observations alone can reveal whether the star depletes its surface Li by mixing it down to an interior temperature near 2.5×10^6 K, adding Be observations provides another probe down to 3.5×10^6 K.

There is a large amount of information about the Li abundances in F and G dwarfs in both clusters and in field stars.

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There is relatively less information on Be abundances because (1) it is more difficult to observe the resonance lines of Be II near the atmospheric cutoff near 3000 Å, (2) there is more line blending in that spectral region, which can blur the spectra of relatively slowly rotating stars, and (3) the spectrum synthesis requires knowledge of the UV opacity sources and effects and of the atomic parameters of many transitions.

Progress has been made in the simultaneous study of these two elements since the discovery by Boesgaard & Lavery (1986) that the star 110 Her (F6 V) is depleted in both Li and Be, but has detectable amounts of both elements. Stephens et al. (1997) determined Be abundances in 59 F and G field stars that were Li-deficient and found another 12 stars that were depleted in Be, but have measurable, and depleted, Li. They presented arguments that showed (1) that the pattern of Li and Be depletion could best be explained by rotationally induced turbulent mixing and (2) that other proposed mechanisms (mass loss, microscopic diffusion, meridional circulation, or internal gravity waves) either failed or were far less satisfactory explanations.

Deliyannis et al. (1998) have determined Li and Be abundances in 24 F dwarfs in the temperature range 6000–6700 K. Nine of those stars were depleted in both Li and Be yet had positive detections resulting in abundances of Li and Be, five others were undepleted in both Li and Be, and the remaining 10 had only upper limits on Li. They found a striking correlation between Li and Be abundances. These observations also were well matched by the predictions of models that include rotationally induced mixing and less well matched by the gravity-wave models. As in Stephens et al. (1997) both mass loss and diffusion below the surface convective zone were excluded. Boesgaard et al. (2001) obtained Be observations of an additional 46 solar-type stars at a spectral resolution of 120,000 at Canada-France-Hawaii Telescope and companion Li observations at the University of Hawaii (UH) 2.2 m coudé and Keck I HIRES. This increased sample size from 14 to 27 stars with detectable but depleted Li and Be. They found a linear relation between the logarithmic quantities A(Li) and A(Be) ($A(\text{element}) = \log[N(\text{element})/N(\text{H})] + 12.00$) with a slope of 0.359 ± 0.037. The range in temperature was limited to 5850–6680 K; all stars were main-sequence stars with near-solar metallicity: $[\text{Fe/H}] = -0.40$ to $+0.15$.

In addition, in recent studies we have determined Be abundances in open star clusters that had already been extensively observed for their Li abundances: the Hyades (Boesgaard & King 2002), the Pleiades and α Per (Boesgaard et al. 2003a), Coma and UMa (Boesgaard et al. 2003b), and Praesepe (Boesgaard et al. 2004a). One virtue of using open clusters for this study is that the stars' ages are known; this is a much less certain parameter to obtain for field stars. These studies showed that like Li, Be undergoes depletion during main-sequence evolution in a narrow temperature range; the Li dip, first discovered by Boesgaard & Tripicco (1986), is a Li-Be dip. A correlation was also found between A(Li) and A(Be) in the clusters for stars between 5900 and 6650 K with a slope of 0.43 ± 0.05 (Boesgaard et al. 2004a). There were enough stars to separate the investigation into two temperature subgroups: the more restricted range of 6300–6650 K—corresponding to the cool side of the Li-Be dip—and the Li plateau region of 5900–6300 K. There is a difference in the slopes: on the cool side of the dip it is steeper at 0.48 ± 0.08, while for the Li plateau it is 0.30 ± 0.05. The slope is shallower for the cooler stars as the convection zone deepens and more Li is depleted relative to Be.

In this paper we present new Be observations for 36 stars along with new Li observations for 22 of them. The Li observations preceded the Be ones and were used as a guide to select the stars to be studied for Be. That is, if a star had low Li, depleted but detected, it was thought to be a good candidate to further examine the Li-Be correlation. The other 14 stars have been observed for Li in other Li surveys. The results from this Be study in field F and G dwarfs can be added to those of Deliyannis et al. (1998) and Boesgaard et al. (2001). The field star results can be compared with those in the young clusters cited above. The sample of field and cluster stars in the temperature range from 5900 to 6650 K becomes 88 with the addition of the stars in this paper. The increased statistics allow us to investigate the strongly correlated depletions of Li and Be, and also to study in more detail the influence of parameters such as temperature, age, and metallicity on this correlation.

2. OBSERVATIONS

2.1. *Beryllium Observations*

As described in the introduction, Be remains one of the most difficult elements to measure in stellar atmospheres, and its abundance determination must be done with care. All the Be spectra were taken with the Keck I 10 m telescope and the HIRES spectrometer with a Tektronix 2048×2048 CCD (Vogt et al. 1994). The spectra were in the near-UV wavelengths of the Be II resonance lines at 3130.421 and 3131.065 Å, and have a 3 pixel spectral resolution of ~48,000, or 0.021 Å pixel^{-1}. There were six nights of observation between 1999 November 13 (UT) to 2002 January 05 (UT). Depending on the magnitude of the field stars, the exposure times were 3–30 minutes. The bulk of these observations were obtained in the twilight hours for the bright stars. Typical signal-to-noise ratios (per pixel) in the Be II line region are greater than 100; the median is 108 and the mean is 113. The log of observations can be found in Table 1, with the HD and HR numbers (when available) of our objects, the V and $B - V$ values from the General Catalog of Photometric Data (GCPD), and the nights of observation, exposure times, and signal-to-noise ratios (S/N) just shortward of the Be II blend. The data reduction was carried out using the routines in IRAF as described in Boesgaard & King (2002).

2.2. *Lithium Observations*

The selection of the stars that were observed for Be was motivated in part by prior Li observations. In the early 1990s we made a survey of bright F and G dwarfs that had not been studied for Li. One objective of that survey was to search for stars with depleted but detectable Li. Then Be observations would be made of suitable candidates to determine if they were also depleted in Be. The Li survey was conducted on the UH 2.2 m telescope at the coudé focus with the longest focal-length camera and a Tek 2048^2 CCD. This gave a dispersion of 0.040 Å pixel^{-1} and a spectral resolution of 70,000. These observations are also listed in Table 1 with dates, exposure times, and S/N (per pixel). The median S/N pixel^{-1} is 110. The data reduction procedures for the Li spectra were standard (see Boesgaard et al. 1998) and done with IRAF. Multiple spectra of the same star were co-added before fitting the continuum.

In addition, 13 stars (of the total of 36) had been observed earlier for Li by Lambert et al. (1991), and one was newly observed by Lambert for us: HR 366. For that star two spectra

TABLE 1

Log of the Be and Li Observations of the Field Stars

Star ID				Beryllium Observations			Lithium Observations		
HR	HD	V	$B-V$	Night (UT)	Exposure (minutes)	S/N (pixel^{-1})	Night (UT)	Exposure (minutes)	S/N (pixel^{-1})
33	693	4.89	0.492	2002 Jan 05	5	145	...	...	...
107	2454	6.04	0.432	1999 Nov 13	7	128	1993 Dec 22	120	412
217	4568	6.56	0.490	1999 Nov 13	12	108	1992 Aug 19	11	100
313	6479	6.35	0.385	1999 Nov 13	10	129	1993 Oct 03	25	110
314	6480	7.25	0.486	1999 Nov 14	30	121	1993 Oct 03	45	110
340	6920	5.66	0.589	1999 Nov 15	10	130	...	...	...
366	7439	5.12	0.451	2002 Jan 05	5	157	2002 Jun 30[a]	10	580
368	7476	5.69	0.427	2002 Jan 05	8	154	...	...	...
409	8671	5.96	0.498	1999 Nov 14	10	121	1993 Dec 22	120	448
458	9826	4.09	0.537	2002 Jan 04	3	202	...	...	...
720	15335	5.88	0.581	1999 Nov 15	10	108	...	...	...
869	18256	5.62	0.433	1999 Nov 14	6	98	1993 Oct, 2, 5, 29	175	620
1013	20853	6.39	0.540	2001 Feb 01	10	35	1992 Aug 19	10	105
1101	22484	4.29	0.574	1999 Nov 15	4	71	...	...	...
2798	57517	6.55	0.538	1999 Nov 15	12	94	1993 Oct 31	12	110
2835	58551	6.54	0.461	2002 Jan 05	12	145	...	...	...
2866	59380	5.86	0.480	1999 Nov 15	6	104	1993 Mar 07	7	115
3271	70110	6.18	0.600	1999 Nov 14	10	99	1993 Mar 08	10	32
3395	72945	5.99	0.520	1999 Nov 14	7	114	1993 Mar 07	7	85
3625	78366	5.96	0.582	1999 Nov 15	5	99	1993 Mar 07	7	95
4572	103799	6.62	0.469	2002 Jan 04	10	140	...	...	...
7386	182807	6.19	0.509	1999 Nov 15	10	104	1993 Nov 03	13	75
8013	199260	5.71	0.501	1999 Nov 15	20	63	1992 Aug 18	09	95
8041	199960	6.20	0.630	1999 Nov 13	12	93	...	...	...
8077	200790	5.94	0.538	1999 Nov 15	9	110	1996 Jun 06[b]	17	850
8430	210027	3.77	0.433	1999 Nov 14	3	199	1992, 1993[c]	6	210
8532	212395	6.20	0.490	1999 Nov 14	7	104	1993 Jun 06	15	85
8581	213429	6.14	0.558	1999 Nov 14	12	107	1992 Aug 19	9	140
8931	221356	6.49	0.531	1999 Nov 13	12	105	1992 Aug 19	12	125
8999	222872	6.17	0.496	1999 Nov 14	25	75	1992 Aug 19	9	110
	186226	6.89	0.477	1999 Nov 15	20	94	1993 Oct 2, 31	105	160
	186379	6.86	0.577	1999 Nov 13	12	70	...	...	...
	200877	6.64	0.460	1999 Nov 15	18	126	1993 Oct 02	45	126
	201891	7.37	0.510	1999 Nov 13	25	105	...	...	...
	208906	6.96	0.501	1999 Nov 13	15	108	...	...	...
	219476	7.61	0.532	1999 Nov 13	30	108	...	...	...

[a] McDonald 107 inch (2.7 m) Tull Spectrograph data.
[b] Keck I HIRES data.
[c] 1992 Aug 17, 1993 Oct 04; spectra co-added.

were obtained with the cross-dispersed echelle spectrograph (Tull et al. 1995) at the coudé focus of the 107 inch (2.7 m) telescope at the McDonald Observatory. It has a spectral resolution of 60,000 and a S/N pixel^{-1} of 580.

3. ANALYSIS

3.1. *Stellar Parameters*

Atmospheric parameters for each star are needed to derive abundances from the spectra. Among them, the temperatures are the ones for which we must pay the most attention: an error in the temperature not only brings an error in the derived Li and Be abundances, but also prevents us from being certain whether a star is on the cool side of the Li-Be dip, between 6300 and 6650 K, and in the total temperature range of our correlation, 5900–6650 K.

To make sure our effective temperatures are on a consistent scale (to avoid a possible artificial scatter due to the multiplicity of the sources), we have redetermined all the stellar temperatures, including the stars for which a temperature measurement had already been done by Lambert et al. (1991) or Chen et al. (2001). We used the following temperature calibrations:

$$T_1 = 8290 - 6200(b-y)(1 - 0.108[\mathrm{Fe/H}])$$
$$\text{for } 0.2 < (b-y) < 0.4,$$
$$T_2 = 8065 - 3580(B-V)(1 - 0.196[\mathrm{Fe/H}])$$
$$\text{for } 0.3 < (B-V) < 0.63,$$
$$T_3 = 11320\sqrt{\beta - 2.3311} \text{ for } 2.595 < \beta < 2.715,$$
$$T_4 = 8330 - 7040(b-y)\left(1 - 0.09910^{[\mathrm{Fe/H}]}\right),$$
$$T_5 = 7950 - 4230(B-V)\left(1 - 0.20410^{[\mathrm{Fe/H}]}\right),$$
$$T_6 = 8335 - 6670(b-y).$$

The first three calibrations are from Saxner & Hammarbäck (1985), T_4 and T_5 are from Magain (1987), and the last one is

TABLE 2
Stellar Temperatures Determination

Star ID	$B-V$	$b-y$	β	T_1	T_2	T_3	T_4	T_5	T_6	$T_{\rm eff}$	σ
HR 33	0.492	0.328	2.621	6173	6172	6095	6116	6046	6147	6125	49
HR 107	0.432	0.293	2.651	6428	6449	6403	6388	6342	6381	6398	38
HR 217	0.490	0.329	...	6257	6321	...	6260	6330	...	6292	39
HR 313	0.385	0.254	2.682	6691	6649	6706	6670	6562	6641	6653	51
HR 314	0.486	0.322	2.628	6255	6264	6168	6211	6171	6187	6209	42
HR 340	0.589	0.384	2.599	5855	5870	5859	5792	5772	5774	5820	46
HR 366	0.451	0.296	2.645	6391	6349	6342	6345	...	6361	6358	20
HR 368	0.427	0.292	2.650	6433	6464	6393	6391	6356	6387	6404	38
HR 409	0.498	0.326	2.615	6210	6188	...	6157	6074	6161	6158	52
HR 458	0.537	0.346	2.629	6166	6176	6178	6191	6249	...	6192	33
HR 720	0.581	0.383	2.589	5851	5883	5749	5784	5774	5780	5803	52
HR 869	0.433	0.304	2.648	6387	6488	6372	6362	6422	6307	6390	61
HR 1013	0.540	0.349	2.647	6147	6166	...	6172	6239	...	6181	40
HR 1101	0.574	0.367	2.615	5983	5958	6031	5936	5889	5887	5947	56
HR 2798	0.538	0.342	2.640	6193	6177	6292	6222	6259	...	6228	47
HR 2835	0.461	0.322	2.613	6177	6240	...	6128	6115	6187	6169	50
HR 2866	0.480	0.311	2.641	6341	6313	6302	6313	6249	6260	6296	35
HR 3271	0.600	0.384	2.612	5912	5921	...	5901	5942	...	5919	17
HR 3395	0.520	0.329	2.629	6266	6229	6178	6283	6278	6141	6229	58
HR 3625	0.582	0.377	2.602	5948	5973	5892	5927	5968	...	5941	33
HR 4572	0.469	0.326	2.618	6171	...	6063	6116	6110	6161	6124	43
HR 7386	0.509	0.345	2.613	6070	6118	6010	6009	5993	6034	6039	47
HR 8013	0.501	0.328	2.635	6250	6261	6240	6234	6234	...	6244	12
HR 8041	0.630	0.401	2.619	5833	5858	...	5867	5985	5660	5841	117
HR 8077	0.538	0.347	2.624	6129	6124	6126	6108	6098	...	6117	13
HR 8430	0.433	0.294	2.664	6471	6521	6531	6475	6510	...	6502	27
HR 8532	0.490	0.343	2.618	6101	...	6063	6044	6104	6047	6072	29
HR 8581	0.558	0.361	2.616	6057	6075	6042	6052	6094	...	6064	21
HR 8931	0.531	0.347	2.603	6069	6052	5903	6008	5934	6021	5998	66
HR 8999	0.496	0.310	2.657	6362	6279	...	6349	6251	6267	6301	50
HD 186226	0.477	0.316	2.650	6352	6391	6393	6383	6450	...	6394	35
HD 186379	0.577	0.374	2.594	5833	5777	5804	5770	...	5840	5805	32
HD 200877	0.460	0.314	2.632	6282	6325	6210	6232	6208	6241	6250	46
HD 201891	0.501	0.358	2.590	5816	5860	5760	5831	5831	...	5820	37
HD 208906	0.501	0.343	2.605	5998	6018	5924	5961	5913	6047	5977	53
HD 219476	0.532	0.362	2.598	5881	5907	5848	5834	5796	5920	5864	47

from King (1993). The photometric indexes required for these calibrations are mean values from the GCPD. When a calibration gave a temperature value that did not agree with the other ones, we did not include it in the mean. More precisely, when one T_i was in disagreement with all the other T_j by more than 75 K, it was not used.

Table 2 gives the photometric indices, the six calculated temperatures, and the adopted temperature for each star, which is the mean of the selected values. We also show the scatter about the mean in these temperatures, which gives an idea of the uncertainty (random, but not systematic) for each stellar effective temperature; most are below ± 50 K.

Among the 36 stars for which we took Be spectra, 13 had already been studied for their Li by Lambert et al. (1991), 22 are part of our Li survey, and one was kindly observed for us by Dr. David L. Lambert.

In the case of stars from Lambert et al. (1991) we used the metallicities and $\log g$ values for nine of our stars studied for Li by Chen et al. (2001); for one star we used the data from Lambert et al. (1991). The $\log g$ values of the other stars from our Li survey were taken from the *Hipparcos* survey results as determined by Allende Prieto & Lambert (1999). These values are consistent with each other, although the mean difference for the 13 stars in common is $+0.10 \pm 0.12$ in the sense that the Allende Prieto & Lambert values are slightly higher than those of Chen et al., but within the dispersion.

The metallicities of these stars were derived from the prescription of Edvardsson et al. (1993) from their β and m_1 photometric indexes obtained from the GCPD. Finally, with the $\log g$ and $T_{\rm eff}$ values we could determine the microturbulent velocities from the formula given by Edvardsson et al. (1993). Columns (2)–(5) in Table 3 give the stellar parameters for each star.

We can compare the Li and Be abundance results for the field stars with those for the cluster stars and can demonstrate that the stellar parameters used in the cluster papers are consistent with those for the field stars. Results on Li are rather sensitive to $T_{\rm eff}$. We have calculated $T_{\rm eff}$ for the Hyades stars exactly the same way that we did here with the six calibrations above. The temperature differences (in the sense of those in Boesgaard & King [2002] minus the ones from the six calibrations here) give a mean difference of $+8 \pm 29$ K. So we can conclude that the $T_{\rm eff}$ values are consistent. The Be abundances are more sensitive to $\log g$. In this paper our primary source for $\log g$ is in Allende Prieto & Lambert (1999). We used that source for the Hyades and compared that result with the $\log g$ values in Boesgaard & King (2002). The mean

TABLE 3

STELLAR PARAMETERS AND ABUNDANCES FOR 36 FIELD STARS

Star ID (1)	T_{eff} (K) (2)	log g (3)	ξ (km s^{-1}) (4)	[Fe/H] (5)	A(Li) (6)	Source[a] (7)	A(Be) (8)	σ (9)
HR 33	6125	4.11	1.97	−0.38	2.48	LHE	1.10	0.12
HR 107	6398	4.23	1.92	−0.23	<1.12	<1.2	<−0.50	
HR 217	6292	3.95	1.99	0.03	2.85	syn	1.10	0.12
HR 313	6653	4.26	2.08	−0.14	<1.79	<3.7	0.00	0.26
HR 314	6209	4.37	1.59	−0.18	2.65	syn	1.10	0.12
HR 340	5820	3.88	1.90	−0.21	<1.16	LHE	0.00	0.16
HR 366	6358	4.13	2.15	−0.32	<1.09	syn	<−0.60	
HR 368	6404	3.91	2.30	−0.24	2.65	LHE	1.00	0.12
HR 409	6158	4.00	2.03	−0.27	<1.04	<1.5	<−0.80	
HR 458	6192	4.13	1.85	0.09	2.42	LHE	0.95	0.09
HR 720	5803	3.92	1.71	−0.25	2.41	LHE	1.25	0.16
HR 869	6390	4.09	2.11	−0.09	≤1.85	≤6.1	0.70	0.26
HR 1013	6181	4.00	2.05	0.09	<1.04	<1.4	0.40	0.09
HR 1101	5947	4.03	1.69	−0.13	2.39	LHE	1.25	0.16
HR 2798	6228	4.28	1.72	0.10	2.58	syn	1.25	0.12
HR 2835	6169	4.22	1.82	−0.54	2.48	LHE	0.95	0.16
HR 2866	6296	4.32	1.72	−0.10	2.26	syn	1.05	0.12
HR 3271	5919	4.01	1.82	0.01	2.45	syn	1.20	0.08
HR 3395	6229	4.24	1.77	0.07	3.10	syn	1.30	0.08
HR 3625	5941	4.37	1.37	−0.02	2.35	syn	1.20	0.08
HR 4572	6124	4.02	2.02	−0.45	2.22	LHE	0.80	0.09
HR 7386	6039	4.31	1.53	−0.35	2.43	syn	1.10	0.08
HR 8013	6244	4.40	1.58	−0.03	2.95	syn	1.25	0.21
HR 8041	5841	4.17	1.49	0.11	2.36	LHE	1.40	0.09
HR 8077	6117	4.03	1.95	−0.04	<0.58	<0.6	<−0.20	
HR 8430	6502	4.31	1.90	0.02	3.23	syn	1.10	0.16
HR 8532	6072	4.29	1.58	−0.27	2.22	syn	1.05	0.08
HR 8581	6064	4.30	1.56	0.02	2.52	syn	1.15	0.09
HR 8931	5998	4.40	1.38	−0.30	2.50	syn	1.25	0.12
HR 8999	6301	3.78	2.45	−0.03	<1.08	<1.2	<−0.20	
HD 186226	6394	4.04	2.16	0.10	<1.40	<2.2	<−0.30	
HD 186379	5805	4.11	1.66	−0.55	2.29	LHE	0.95	0.08
HD 200877	6250	4.23	1.80	−0.29	<0.93	<1.0	<−0.30	
HD 201891	5820	4.46	1.20	−1.06	1.98	LHE	0.60	0.16
HD 208906	5977	4.41	1.38	−0.72	2.38	LHE	0.70	0.12
HD 219476	5864	4.01	1.83	−0.68	<0.98	LHE	−0.10	0.16

[a] LHE: Li equivalent width from Lambert et al. (1991) with our T_{eff}; <x.x: upper limit equivalent width in mÅ from the Cayrel (1988) formula; syn: spectrum synthesis from our Li spectra.

difference in log g from the two methods is 0.04 ± 0.05. This shows that the values are consistent for log g also.

3.2. *Beryllium Analysis*

We derived Be abundances from the reduced spectra using the spectrum synthesis method exclusively, as described, for example, in Boesgaard & King (2002). Using the stellar parameters previously determined, we made model atmospheres from the Kurucz (1993) grid. We used the MOOG 2002[2] program (Sneden 1973) to build synthetic spectra in the Be line region for each of the 36 stars with the line list used in our earlier papers (modified from the Kurucz list). The Be abundances found this way are given in Table 3. The corresponding uncertainties are evaluated as in Boesgaard et al. (2003a). As in our previous Be studies, we find that the uncertainties in A(Be) come from errors in T_{eff} (ΔT is typically ±50 K), log g (the uncertainty is near ±0.2), and the line broadening, which smears out the blends. The broadening is due to rotation and becomes important for $v \sin i > 15$ km s^{-1}. In the presence of sharp lines, Be abundances are generally derived with a reasonable error between 0.05 and 0.10 dex. However, a star like HR 313 has such broad lines that the Be abundance uncertainty reaches 0.26 dex.

Examples of the Be synthesis fits are shown in Figures 1 and 2. The Be abundances and 1 σ random errors in A(Be) are given in Table 3.

3.3. *Lithium Analysis*

For the stars in Lambert et al. (1991) we rederived Li abundances from their equivalent widths with MOOG 2002. For this we used the newly determined stellar parameters from the previous section. Our new Li abundances, given in Table 3, are similar to the previous values from Lambert et al., however, we found a mean shift of +0.075 between the two sets of data, with 10 stars of 13 increasing between +0.06 and 0.09 dex.

The Li abundances from our own Li survey were determined both from equivalent widths and spectrum synthesis, using MOOG 2002 and the stellar parameters from the previous section in both cases. (The atomic data in the line list are

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

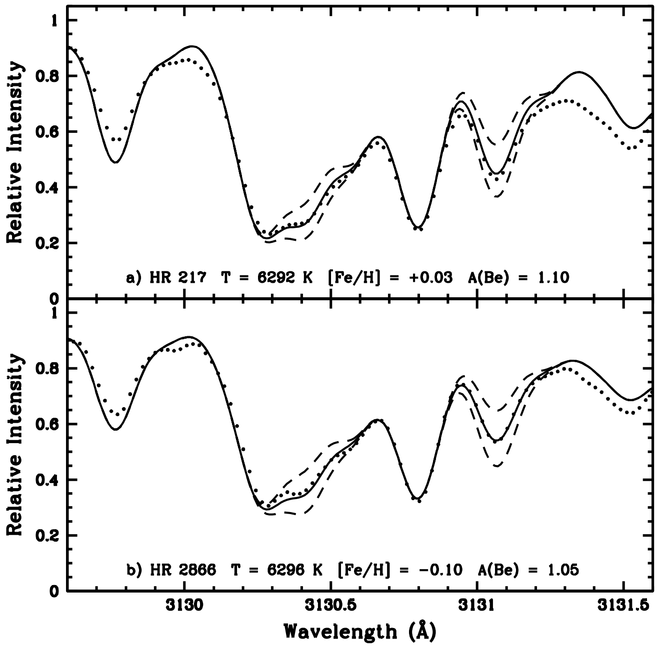

FIG. 1.—Examples of the spectrum synthesis of two stars in the region of the Be II lines. The dots represent the observed spectra, the solid line is the best-fit Be abundance whereas the dashed lines are for Be abundances ±0.30 dex, i.e., a factor of 2 higher and lower. These two stars have similar temperatures and similar Be abundances although the Fe content of HR 217 is 35% higher than that of HR 2866. [*See the electronic edition of the Journal for a color version of this figure.*]

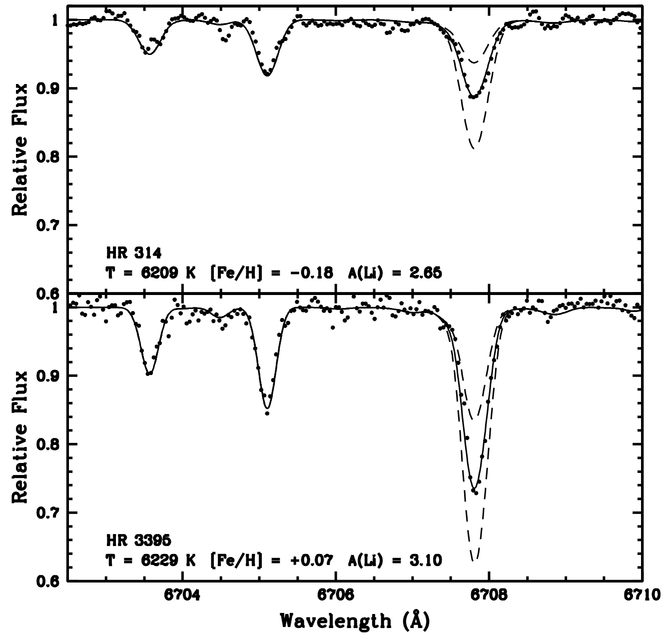

FIG. 3.—Examples of the spectrum synthesis of two stars in the Li I region. The symbols and lines are the same as in Fig. 1. These stars of similar temperatures differ in both their metallicities (by a factor of 1.8) and in their Li abundances. Presumably HR 314 is depleted in Li. [*See the electronic edition of the Journal for a color version of this figure.*]

from Andersen et al. 1984 and include hyperfine structure.) The results of the two methods were generally in excellent agreement with each other. However, we prefer the spectrum synthesis method, as we also fit two neighboring Fe I lines at λ6703 and λ6705; this improves the reliability of the Li abundance determination, especially for the value for the line broadening. When the stellar spectra did not present a significant Li line, we derived upper limit abundances exclusively from upper limit equivalent widths. We used the 3 σ upper limit to the equivalent widths calculated from the Cayrel (1988) formula (see Boesgaard et al. 2001).

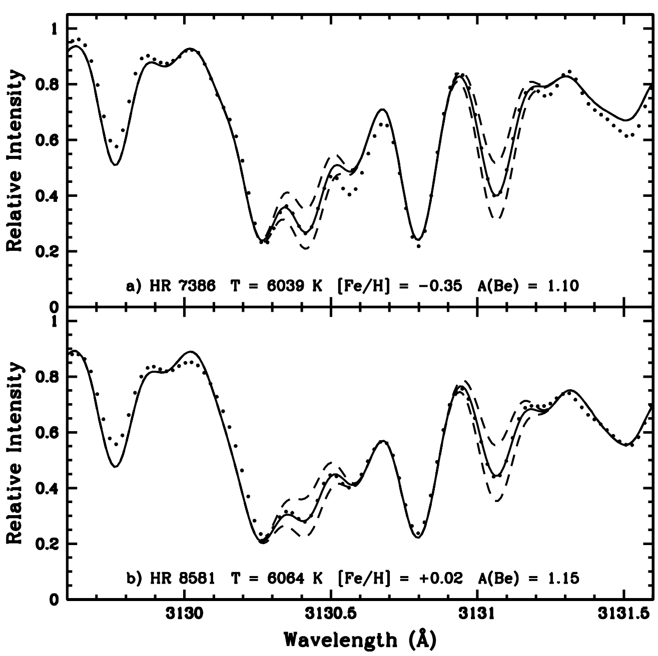

FIG. 2.—Examples of the spectrum synthesis of two stars that are somewhat cooler than those shown in Fig. 1. The symbols and lines are the same as in Fig. 1. These two stars of similar temperature differ in metallicity by a factor of 2.3 yet have similar Be abundances. [*See the electronic edition of the Journal for a color version of this figure.*]

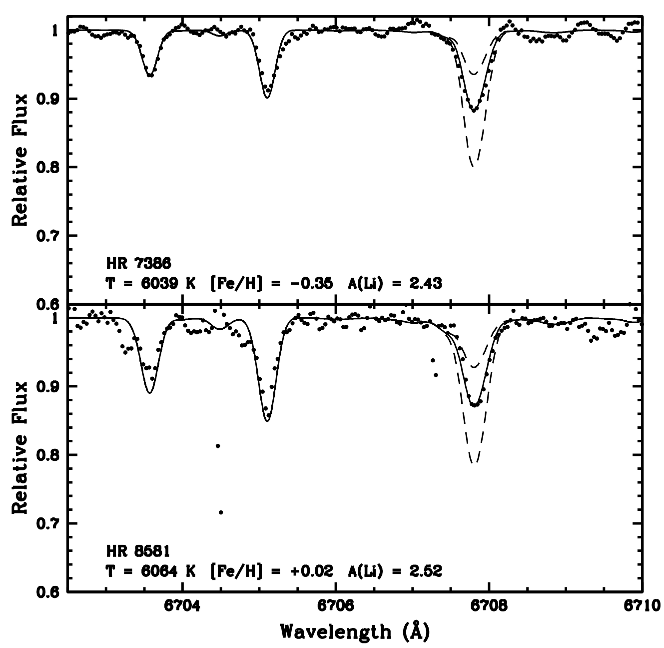

FIG. 4.—Examples of the spectrum synthesis of two stars in the Li region. These are the same two stars whose Be syntheses are shown in Fig. 2. The symbols and lines are the same as in Fig. 1. Although their metallicities differ, they have similar (depleted) Li abundances. [*See the electronic edition of the Journal for a color version of this figure.*]

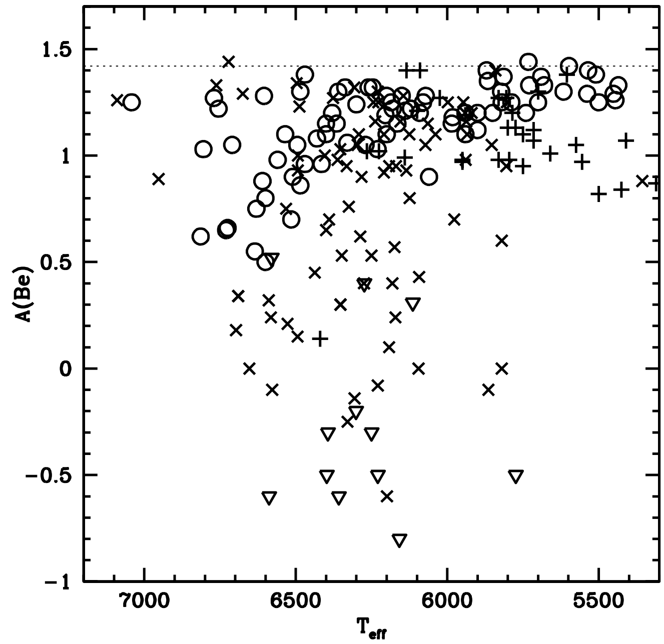

FIG. 5.—Be abundances in F and G dwarfs from several sources as a function of temperature. The crosses are field stars from this paper, Deliyannis et al. (1998), and Boesgaard et al. (2001). The inverted triangles represent upper limits on A(Be) from those papers. The open circles are cluster stars from Hyades (Boesgaard & King 2002, Boesgaard et al. 2004a), the Pleiades and 4α Per (Boesgaard et al. 2003a), Coma and UMa (Boesgaard et al. 2003b), and Praesepe (Boesgaard et al. 2004a). The plus signs are the stars with exoplanets from Santos et al. (2002). See text (§ 4) for discussion.

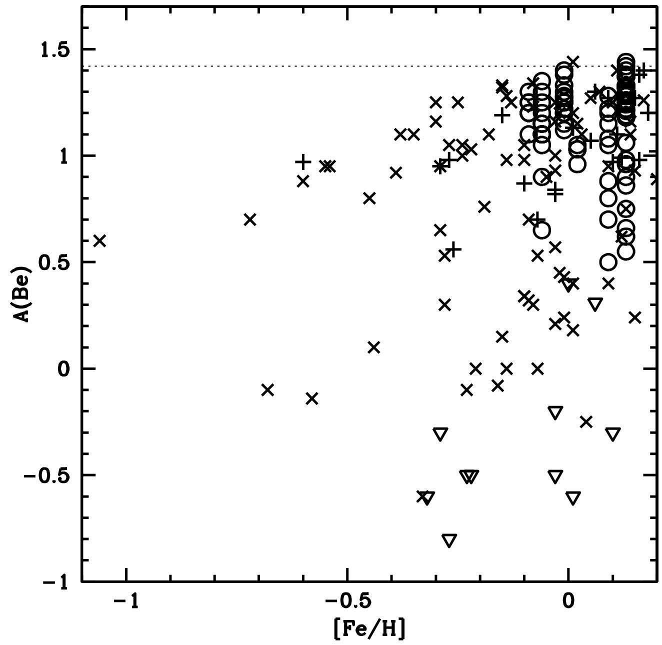

FIG. 6.—Be abundances in F and G dwarfs from several sources as a function of metallicity [Fe/H]. The symbols are the same as in Fig. 4.

Examples of the spectrum synthesis in the Li region are shown in Figures 3 and 4. The values of A(Li) and the type of Li analysis performed are given in Table 3.

4. BERYLLIUM IN F AND G DWARFS

We have assembled the data for A(Be) in field stars from this paper, the "Gecko" paper (Boesgaard et al. 2001), and the "Correlated depletions" paper (Deliyannis et al. 1998) and added the open cluster A(Be) results for Hyades, Coma, UMa, Pleiades, α Per, and Praesepe (Boesgaard et al. 2003a, 2003b, 2004a) and the Be abundances of Santos et al. (2002) for stars that are planet hosts. These values of A(Be) are shown as a function of $T_{\rm eff}$ in Figure 5.

There are stars with Be abundances at or near the meteoritic Be abundance of 1.42 at all temperatures. The cluster stars show Be deficiencies in the Li-Be dip region, but the depletions are no more than an order of magnitude. The field stars can show large Be deficiencies (and upper limits) for stars between 5800 and 6700 K by more than 2 orders of magnitude. Cooler than 5700 K the relatively young cluster stars show little or no Be depletions, but the field stars can be Be-deficient by up to a factor of 4 or a little more. There are effects of both age and mass here. The young cluster stars in the Li-Be dip region show either no Be depletion (e.g., Pleiades stars) or relatively small Be depletions of up to a factor of 10. Some field stars, presumably the young ones, show no Be depletion in the dip region while others are depleted in Be by 100 times. These latter stars may have had high initial rotation and/or are older having had more time to deplete Be. These large Be depletions occur throughout the temperature domain of 5800–6700 K. The lower mass stars, cooler than 5700 K, show only small Be depletions; the young stars show little or no depletion while (presumably older) field stars can be depleted by 0.6 dex.

These same stars are shown with their [Fe/H] values in Figure 6. At solar metallicity (0.0 ± 0.2) the full range of A(Be) of more than two orders of magnitude is seen. This range in A(Be) extends to $[{\rm Fe/H}] = -0.3$. There appears to be an upper envelope in A(Be) as a function of [Fe/H] as shown in Boesgaard et al. (2001) and Boesgaard et al. (2004b).

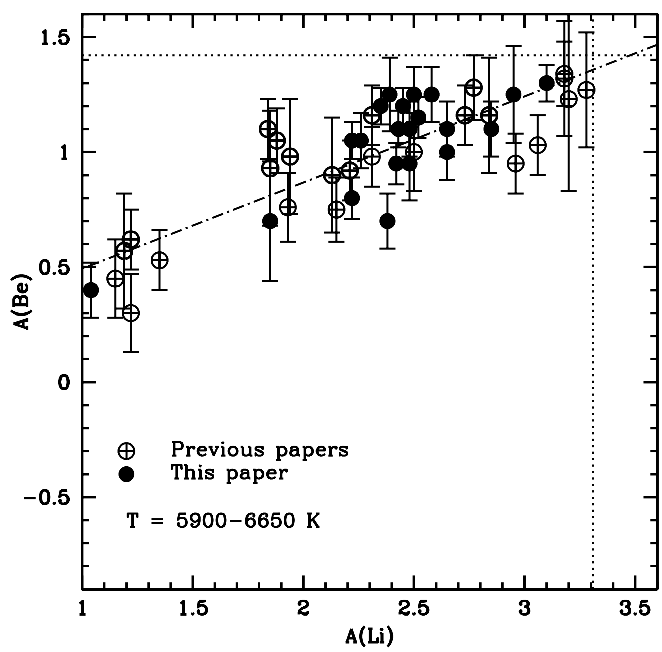

FIG. 7.—Abundances of Li and Be in this and previous papers with temperatures of 5900–6300 K. The dash-dotted line is the least-squares fit to the points. It has a slope of 0.37. The dotted vertical line shows the meteoritic value of $A({\rm Li}) = 3.31$, and the dotted horizontal line shows the meteoritic value $A({\rm Be}) = 1.41$. The error bars on A(Be) are shown.

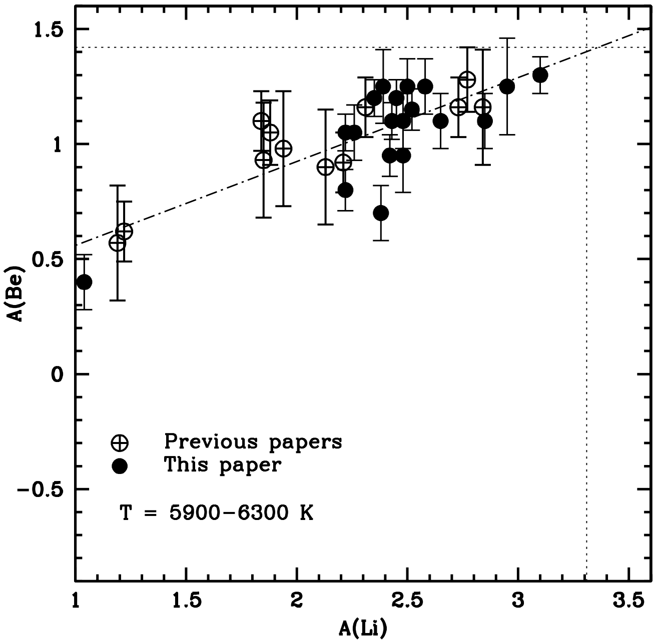

Fig. 8*a*

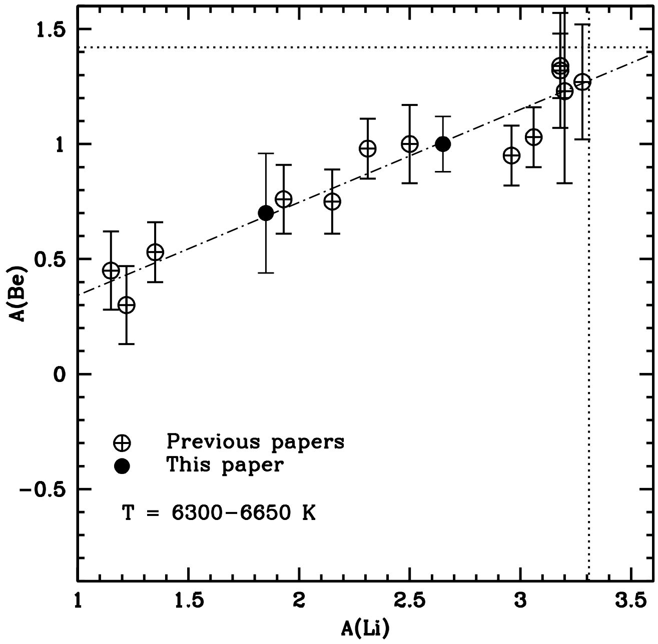

Fig. 8*b*

Fig. 8.—Field star sample divided into two temperature groups: (*a*) 15 stars with 6300–6650 K corresponding to the cool side of the Li-Be dip and (*b*) 31 stars with 5900–6300 K near the Li plateau and cooler. The slope for the hotter (Li-Be dip) stars is 0.40 and for the cooler stars is 0.36. The slopes are similar but there is an offset in the sense that the hotter stars have relatively more Be depletion at a given Li depletion.

Although this upper envelope is not well determined by this sample, the slope between $A(\mathrm{Be})$ and [Fe/H] is $\sim$0.7.

5. Li-Be CORRELATION

5.1. *Field Stars*

The major goal of this study is to examine the correlated depletions of Li and Be in temperature range of 5900–6650 K. These additional stars allow us to investigate the temperature sensitivity of this correlation and whether there is a metallicity dependence. We have examined the age factor in our study of open cluster F and early G dwarfs (Boesgaard et al. 2004a); the youngest cluster, Pleiades at 70 Myr, has the least depletion of both Li and Be.

We have investigated the Li-Be correlation for the entire temperature range of 5900–6650 K, and we also form two subgroups: (1) 6300–6650 K corresponding to the cool side of the Li-Be dip and (2) 5900–6300 K corresponding to the "Li plateau." Both temperature groups were established from the Li-T_{eff} diagram for the Hyades (see Fig. 9 in Boesgaard 2004). We can compare the field stars and the cluster stars. In the cooler temperature group there is very little Be depletion in the young clusters.

Figure 7 shows the results for the field stars from this paper and from previous papers (see Boesgaard et al. 2001 for a tabulation) for the temperature range 5900–6650 K. The dash-dotted line is the least-squares fit to all the data, not weighted by the error bars. This relation is

$$A(\mathrm{Be}) = 0.375(\pm 0.036)A(\mathrm{Li}) + 0.119(\pm 0.087)$$

for 46 field stars where $T = 5900-6650$ K.

This relationship is essentially the same as the one found by Boesgaard et al. (2001) for 26 stars where the slope was 0.359 ± 0.037. For the cluster stars in Boesgaard et al. (2004a) the slope was 0.434 ± 0.050.

In Figures 8*a* and 8*b* we show those stars divided into the two temperature groups. The relation for the cooler stars is

$$A(\mathrm{Be}) = 0.365(\pm 0.049)A(\mathrm{Li}) + 0.194(\pm 0.115)$$

for 31 cooler stars.

Again this is similar to the cooler-star slope of 0.347 ± 0.048 for the 12 stars in the Boesgaard et al. (2001) sample.

The relation for the hotter stars, i.e., those on the cool side of the Li-Be dip is

$$A(\mathrm{Be}) = 0.404(\pm 0.034)A(\mathrm{Li}) - 0.062(\pm 0.084)$$

for 15 Li-Be dip stars.

Although the slopes are similar for the two temperature subgroups, there is an offset of 0.25 dex in the sense that the hotter stars deplete more Be than the cooler ones. This was noted in the earlier field-star paper and is also true in the cluster work. The largest Be depletions occur in the middle of the Li-Be dip. Furthermore, this is predicted by the models of Deliyannis & Pinsonneault (1997) for rotationally induced mixing; see Stephens et al. (1997) for additional discussion.

We tried to examine whether there is an effect due to metallicity on this correlation. Our sample does not cover a large range in [Fe/H], but our four lowest metallicity stars (HR 2835, HR 4572, HD 11592, and HD 208906) all fall below the least-squares fit line in the 5900–6300 K temperature range. These stars have somewhat more Be depletion for their Li abundance than the solar metallicity stars—or they had less Be ab initio. The relation between $A(\mathrm{Be})$ and [Fe/H] shown by Boesgaard et al. (2004b) shows a trend such that the lower metallicity stars have less Be: $A(\mathrm{Be}) = 0.38[\mathrm{Fe/H}] + 1.21$. Observations indicate they would have less Li also, e.g., Boesgaard et al. (2004b).

We can also add the Li and Be abundances from the work of Stephens et al. (1997) for three additional cool stars (HR

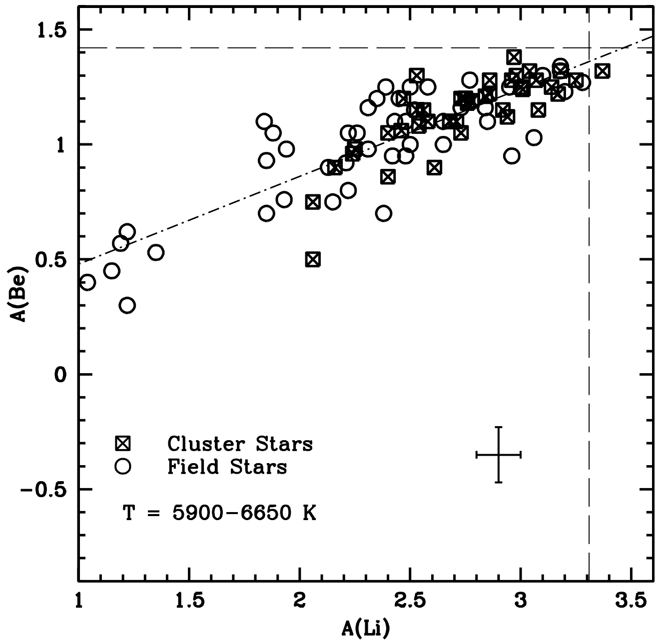

FIG. 9.—Li and Be abundances in 46 field stars and 42 cluster stars in the full temperature range, 5900–6650 K. A typical error bar is shown in the lower right. The error bars on Be in the individual field star points are shown in Fig. 7 and in the cluster star points in Fig. 9 in Boesgaard et al. (2004a); there are so many points that including the error bars here obfuscated the trends. The slope for this larger sample of both cluster and field stars of 0.382 ± 0.030 (*dash-dotted line*) is essentially the same as for the field stars alone: 0.375 ± 0.036.

6775, HR 8514, and HR 8969); these stars fall perfectly in the midst of ours in Figure 8*b*. From Santos et al. (2002) there are two additional hot stars (HR 7973 and HR 8205); one of these fits our relation well, but the other, HR 8205 at 2.35, 0.46, seems either too high in Li or overly depleted in Be.

5.2. *Field and Cluster Stars*

As noted in § 3.1, the stellar parameter scales for the field stars and the cluster stars are consistent with each other, so we can combine the results of these samples. The Li and Be abundances for the total sample of 88 stars (46 field stars and 42 cluster stars) in the full temperature range of 5900–6650 K are shown in Figure 9. The individual error bars have been replaced by a single, typical error bar in order to clarify the trend. The least-squares fit is given by

$$A(\mathrm{Be}) = 0.382(\pm 0.030)A(\mathrm{Li}) + 0.105(\pm 0.078)$$

for 88 cluster and field stars with $T = 5900-6650$ K.

This relation is very close to that given above for the 46 field stars, only with a slope of 0.375 ± 0.036. As shown by Deliyannis et al. (1998), this relation is well matched by rotation models of Deliyannis & Pinsonneault (1997) and Charbonnel et al. (1994).

The temperature sensitivity of this Li-Be correlation can be seen in the differences in Figures 10 and 11 for the full sample of field and cluster stars. Figure 10 shows the results for the 35 Li-Be dip stars in clusters and in the field. The least-squares fit is

$$A(\mathrm{Be}) = 0.433(\pm 0.036)A(\mathrm{Li}) - 0.071(\pm 0.094)$$

for 15 field stars and 20 cluster stars with $T = 6300-6650$ K.

Figure 10 also shows the least-squares fit for the cooler stars as a light dotted line. The Li and Be abundances of the cool-star sample of 54 field stars and cluster stars are shown in Figure 11. That relation is given by

$$A(\mathrm{Be}) = 0.337(\pm 0.031)A(\mathrm{Li}) + 0.248(\pm 0.078)$$

for 31 field stars and 23 cluster stars with $T = 5900-6300$ K.

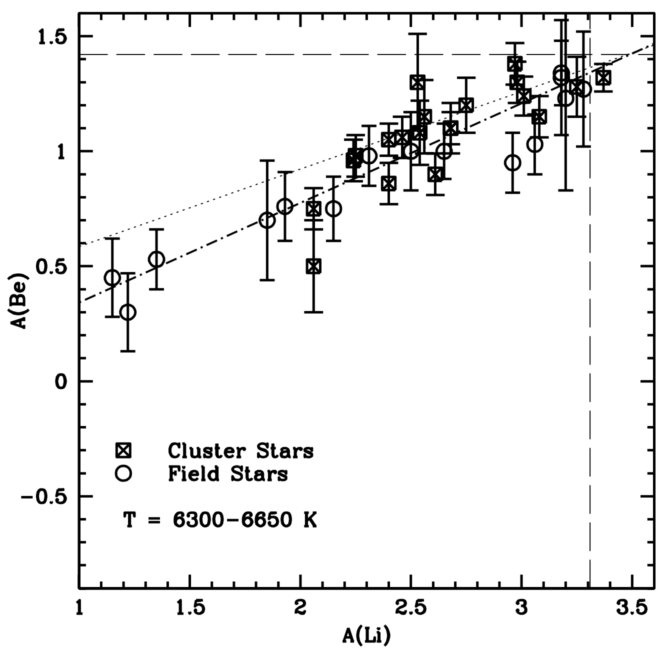

FIG. 10.—Li and Be abundances for 15 field stars and 20 cluster stars on the cool side of the Li-Be dip with temperatures between 6300 and 6650 K. The dash-dotted line is the least-squares fit for these stars. It has a slope of 0.433 ± 0.036. Shown for comparison is a light dotted line, which is the relationship for the cooler sample of field and cluster stars in Fig. 11.

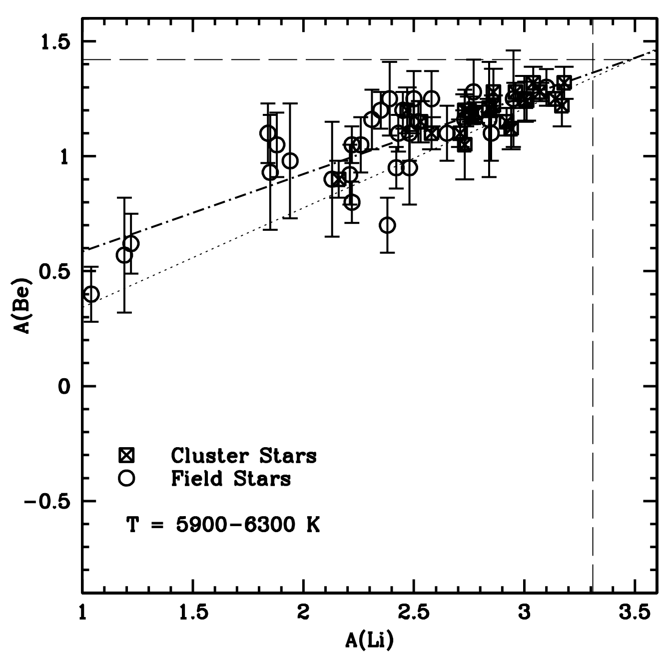

FIG. 11.—Abundances of Li and Be for the cooler sample (5900–6300 K) of 31 field stars and 23 cluster stars. The least-squares fit is shown by the dash-dotted line; its slope is 0.337 ± 0.031. The light dotted line is the fit for the hotter stars in Fig. 10, which has a steeper slope of 0.43.

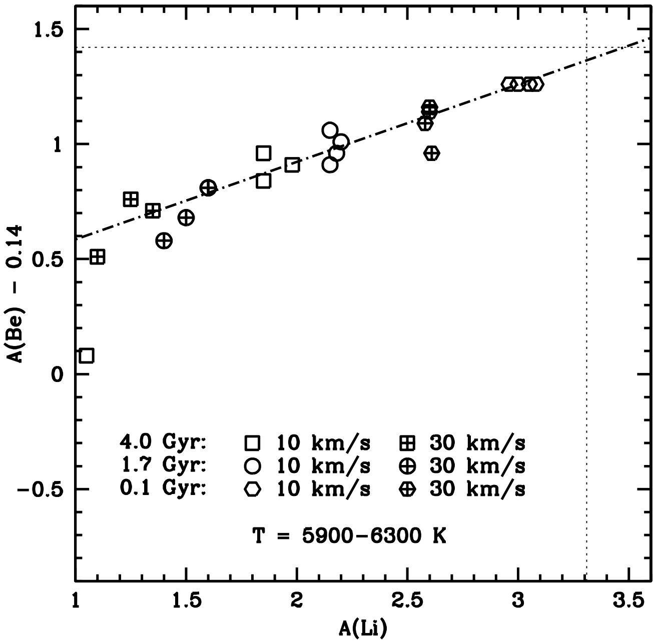

FIG. 12.—Model predictions of Deliyannis & Pinsonneault (1997) for Li and Be depletion due to rotationally induced mixing compared to our observations. The dash-dotted line is the fit for the data in Fig. 11 for the temperature range from 5900 to 6300 K. The predictions for A(Li) and A(Be) from the age of 4 Gyr are given by squares, with open squares for $v_{\rm init} = 10$ km s^{-1} and crossed squares for $v_{\rm init} = 30$ km s^{-1}. Similarly, the predictions for 1.7 Gyr are shown by circles and crossed circles for 10 and 30 km s^{-1}, and for 0.1 Gyr by hexagons and crossed hexagons. The model temperatures for the points are 5950, 6050, 6150, and 6300 K. Note that the y-axis corresponds to an initial A(Be) of 1.28 for these models rather than the meteoritic value of 1.42.

That fit is shown as a dash-dotted line, while the light dotted line shows the fit for the hotter Li-Be dip stars. These two figures show the temperature effect on the Li-Be correlation. In the hotter stars there is more Be depletion at a given Li depletion. As Li is depleted by a factor of 100, Be is depleted by a factor of 7.3 in the hotter stars and by 4.7 in the cooler stars.

Deliyannis et al. (1998) compared the relatively sparse data on Li and Be with the predictions of depletion by diffusion, mass loss, and mixing induced by rotation and by gravity waves. Both diffusion and mass loss could be ruled out. Here we examine anew the predictions for rotationally induced mixing of Deliyannis & Pinsonneault (1997). Figure 12 shows the fit to the observations from Figure 11 (the cooler sample of stars) with their model predictions at temperatures of 5950, 6050, 6150, and 6300 K. They are shown for three ages, 0.1, 1.7, and 4.0 Gyr, and two different initial rotation velocities, 10 and 30 km s^{-1}. The models and the observations fit well when we use, as we do here, an initial value of $A(\rm Be) = 1.28$ for the models. This is a value obtained from the average of the upper 70 field and cluster stars in Figure 5.

The predictions for the youngest stars are in the upper right, with little depletion of Li or Be. For the young stars with the larger $v_{\rm ini}$ of 30 km s^{-1} there is more depletion of both elements. The oldest stars with the highest $v_{\rm ini}$ have the most depletion. The trend of the models matches the observations very well. If the initial value for A(Be) is taken to be the meteoritic value 1.42, then there is an offset between the observations and the predictions. The offset is in the sense of more Li depletion by 0.4 dex, more Be depletion by 0.13 dex, or, more likely, some depletion of both. Similarly, the predictions of Charbonnel et al. (1994) of the effect of rotation on Li and Be depletion for their oldest model stars at 1.7 Gyr also fit the observations well. [With initial $A(\rm Be) = 1.42$ their model predictions are also above our best fit for the observations.] The youngest models have the least depletion, and the more rapid rotators in each age group have greater depletion. In comparing the model predictions with the Li and Be abundances in the Hyades, Boesgaard & King (2002) found that the Be predictions matched the observations very well, but that Li was overdepleted in the models in the temperature range of 5900–6300 K.

For the higher temperature stars (Fig. 10) it is more difficult to make the comparisons with the models because Li and Be both plummet toward the center of the Li-Be dip. Comparison can be made for the models at 0.1 and 1.7 Gyr isochrones at

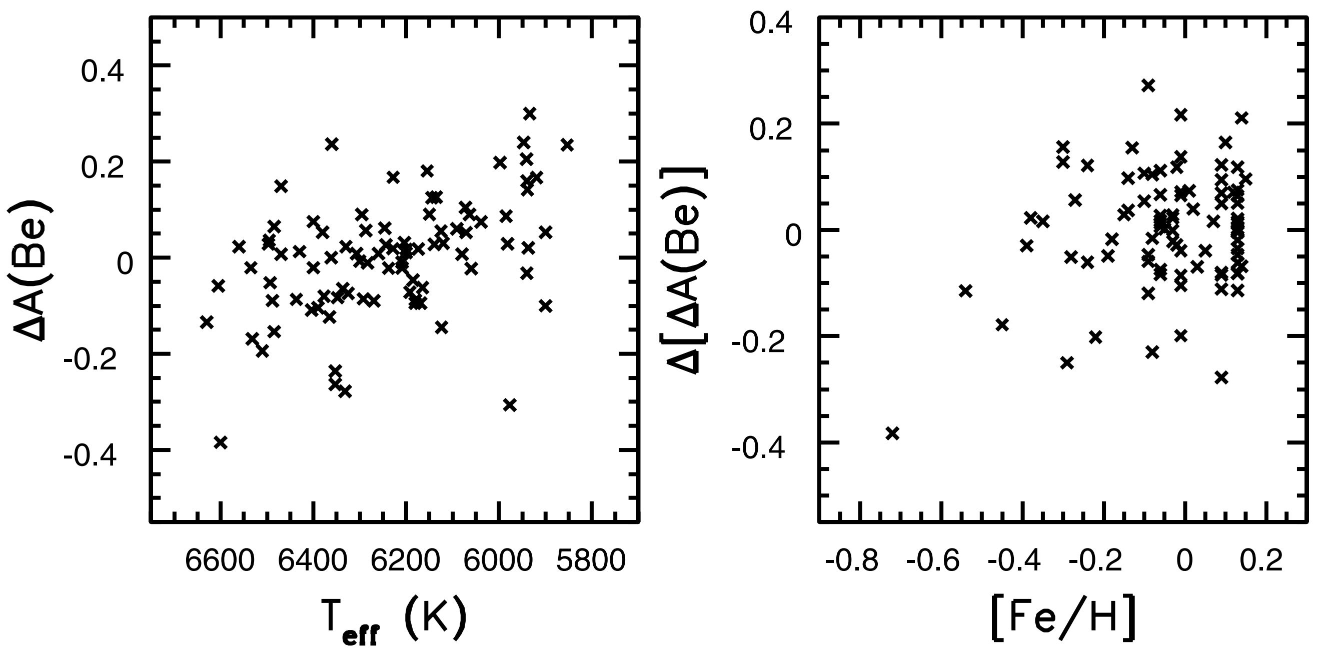

FIG. 13.—*Left*: Residuals of $A(\rm Be) - A(\rm Be)_{fit} = \Delta A(\rm Be)$ as a function of temperature. *Right*: Residuals about a least squares fit to the ΔA(Be)-$T_{\rm eff}$ relation in the left panel are plotted versus [Fe/H].

6400 and 6475 K. Again, the model predictions are good with an initial Be of 1.28.

Moving beyond the formalism of these subgroups, we find that the residuals about the mean Be-Li mean relation in Figure 9 appear to be continuous functions of $T_{\rm eff}$ and metallicity. We took the Be and Li results from this paper and Boesgaard et al. (2001) for stars in the temperature range 5900–6650 K. For each star we took the observed A(Be) and subtracted the value of A(Be) on the observed fit at that A(Li), i.e., the displacement of the observed A(Be) above or below the least-squares, best-fit line, ΔA(Be). The left panel of Figure 13 shows those residuals versus effective temperature. Both the ordinary linear and Spearman rank correlation coefficients indicate a correlation significant at $\geq$99.998% confidence level. Both the linear correlation coefficient and the Spearman coefficient, however, suggest that only a slight majority (50%–60%) of the variance in the residuals is associated with $T_{\rm eff}$ differences. The right panel of Figure 13, which shows the residuals about a least-squares fit to the residual data in the left panel of Figure 13 versus [Fe/H], offers suggestive evidence that metallicity may also contribute to the scatter about the mean Li-Be relation in Figure 9; the ordinary linear and Spearman coefficients indicate correlations significant at the 99.6% and 90.0% confidence levels, respectively. For the full range in $T_{\rm eff}$ of 5900–6650 K there is a temperature dependence and a slight metallicity dependence in the relationship between A(Li) and A(Be).

6. SUMMARY AND CONCLUSIONS

The light element Be has not been as extensively observed as its predecessor on the periodic table, Li, because of the greater difficulty of the observations of Be. We have determined Be and Li abundances in 36 F and early G dwarfs. The major purpose was to investigate the correlation between A(Li) and A(Be) first found by Deliyannis et al. (1998) for a short temperature range of 5900–6650 K. Our sample of cluster and field stars in this temperature range with abundances (not upper limits) of both Li and Be is now 88 stars. Because of the large number of stars, we can investigate the effects of temperature, age, and metallicity on this correlation.

The Be spectra are from Keck I HIRES and have a spectral resolution of $\sim$48,000 and a median S/N of 108 pixel^{-1}. The Li spectra are primarily from the longest camera of the coudé spectrograph of the UH 2.2 m telescope and have a spectral resolution of $\sim$70,000 and a median S/N of 110 pixel^{-1}. Abundances of both Be and Li have been determined by spectrum synthesis, except for the stars for which only upper limits could be found for A(Li).

For the sample of 46 field stars from this and previous papers we find a correlation between the logarithmic quantities A(Li) and A(Be) with a slope of 0.375 ± 0.036. When we include the 42 cluster stars for the total sample of 88, we find a slope of 0.382 ± 0.030, i.e., virtually identical. This general trend is predicted by the models that include stellar rotation and consequent mixing, although the models do not predict as much depletion as is observed.

We have divided the stars into two temperature groups: the hotter sample, $6650 > T_{\rm eff} > 6300$ K, which corresponds to the cool side of the Li-Be dip and the cooler stars, $6300 > T_{\rm eff} > 5900$ K, corresponding to the Li-plateau region. We find a small difference in slope for the two groups with the hotter stars having a steeper slope. For the 35 hotter stars the slope is 0.433 ± 0.036, while the 54 cooler stars have a slope of 0.337 ± 0.031. The models of rotationally induced mixing of Deliyannis & Pinsonneault (1997) and of Charbonnel et al. (1994) predict greater depletion of Li and Be in the Li-Be dip region and more Li depletion relative to Be, thus a steeper slope for the hotter stars than for the cooler stars. The model predictions are a good match to the observations with an initial value of $A(\rm Be) = 1.28$ from the mean stellar value of 70 stars. But if the meteoritic value of $A(\rm Be) = 1.42$ is used, there is an offset in the sense that the stars have larger depletions than the models.

Age is an important effect as the depletions come from slow mixing, and the younger cluster stars have less Li and Be depletion; this can be seen in the papers about Be in open clusters, summarized by Boesgaard et al. (2004a). Metallicity effects either do not exist for [Fe/H] in our range of -0.45 to $+0.11$, or they are hidden by the errors in the abundance determinations. The four stars with $[\rm Fe/H] < -0.50$ all fall below the best-fit line. This could be because of more depletion of Li and Be in these stars or because of lower initial abundances.

We are grateful to Scott Dahm and Elizabeth Barrett for their assistance during observing runs at Keck. We thank David L. Lambert for obtaining the spectrum of HR 366 and G. Pandey for reducing that data. This work was supported by NSF grants AST-0097945 to A. M. B. and AST-0086576 and AST-0239518 to J. R. K.

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