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BERYLLIUM ABUNDANCES IN F AND G DWARFS IN THE COMA CLUSTER AND THE URSA MAJOR MOVING GROUP FROM KECK HIRES OBSERVATIONS

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ABSTRACT

The study of both light elements Li and Be in open clusters of known properties can reveal the internal structure and the mechanisms of mixing in main-sequence stars as a function of age and composition. In previous work, we have investigated the older Hyades cluster and the younger Pleiades and α Per clusters. The Coma Berenices cluster and the UMa moving group are intermediate in age between the Hyades and Pleiades and provide a good linchpin for the influence of stellar age on light-element abundances; there are dips in the mid-F stars in both Li and Be in the Hyades but no Be dip and only a minor Li dip in the Pleiades. We have made observations of the resonance doublet of Be II near 3130 Å in 13 Coma and six UMa stars with the Keck I telescope and the High Resolution Echelle Spectrometer. The Be abundances were determined by spectrum synthesis. In the F dwarfs in Coma, there are both Li and Be deficiencies, indicating that the depletions occur during the main-sequence phase of evolution but do not become evident until an age of 200–300 Myr. For both UMa and Coma stars, the Li depletion is greater than the Be depletion at all temperatures, but there is little, if any, Be depletion in stars with $T_{\rm eff} < 6000$ K. In the four clusters studied for Be, the mean Be abundance for stars with temperatures less than 6000 K is $\log N({\rm Be/H}) + 12.00 = 1.27$, independent of age or metal content. For the hotter stars (5850–6680 K), the Li and Be abundances are correlated, indicating that the depletion probably occurs simultaneously; this matches the results for the field stars and the Hyades and the predictions of Li and Be depletion by rotationally induced mixing.

Subject headings: open clusters and associations: individual (Coma, Ursa Major Group) — stars: abundances — stars: rotation

1. INTRODUCTION

We have embarked on a study of Be in F and G dwarfs in open clusters in order to use the two elements Li and Be together to examine stellar structure and mixing mechanisms in stars as a function of age and metallicity. When these elements are circulated down into the interior of the stars, they will be destroyed by reactions with warm protons at 2.5×10^6 K for Li and 3.5×10^6 K for Be.

Boesgaard & King (2002) determined Be abundances in 34 Hyades F and G dwarfs from high-resolution, high signal-to-noise ratio (S/N) spectra from the Keck I telescope with the High Resolution Echelle Spectrometer (HIRES). The main discoveries in that work are the following: (1) There is a "Be dip" like the "Li dip" in the mid-F dwarfs, but the Be dip is not as deep as the dramatic chasm seen in Li. Relative to the meteoritic abundances of 3.31 dex for Li and 1.42 dex for Be [on the logarithmic scale, where $\log N({\rm H}) = 12.00$] (Grevesse & Sauval 1998), Li is depleted by more than 2 orders of magnitude in the center of the dip, while Be is depleted by a factor of 7. (2) For stars on the cool side of the dip (5900–6680 K), the Li and Be abundances are correlated and follow the general relationship found for the field stars by Deliyannis et al. (1998) and Boesgaard et al. (2001); if Li is depleted by a factor of 10, Be is depleted by a factor of 2.2. (3) There is no Be depletion in the G dwarfs, even though there are enormous deficiencies in Li of more than 2 orders of magnitude, as was first found by García López, Rebolo, & Pérez de Taoro (1995) in the Hyades. Both Li and Be are destroyed in the mid-F dwarfs, while only Li is destroyed in the G dwarfs. This implies that surface material in the F stars is circulated to temperatures of 3.5×10^6 K or more, but the mixing is shallower in the G stars (reaching at least 2.5×10^6 K), in spite of the fact that G dwarfs have deeper surface convection zones than F dwarfs. A similar result was found for field stars by Stephens et al. (1997), who studied Be in 59 Li-deficient stars of spectral type F and G. Stars cooler than 6000 K showed no Be deficiencies, while Li was depleted by factors of 10–400, and stars in the F star Li dip were also depleted in Be.

We have just completed a study of Be in the younger clusters, Pleiades (14 stars) and α Per (four stars) (Boesgaard, Armengaud, & King 2003). While the age of the Hyades is 700 Myr, the Pleiades age is 75 Myr, and the age of α Per is 50 Myr (Mermilliod 1981). Somewhat older ages of near 100 Myr have been suggested for the two younger clusters (e.g., Stauffer 2000). Another difference with respect to the Hyades is in the cluster metallicity: For the Hyades,

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[Fe/H] = $+0.13 \pm 0.03$ (Boesgaard 1989; Boesgaard & Friel 1990; Cayrel, Cayrel de Strobel, & Campbell 1985), but the Pleiades is -0.01 ± 0.03, and α Per is $+0.02 \pm 0.03$ (Boesgaard, Budge, & Ramsey 1988b; Boesgaard 1989; Boesgaard & Friel 1990). For the F dwarfs, in which there is only a mild Li dip, there was no measurable Be dip. This is not unexpected, given the smaller Be dip in the Hyades relative to its dramatic Li dip. It also indicates that the depletion of both Li and Be in F dwarfs is occurring during the main-sequence phase of evolution, rather than the pre–main-sequence (PMS) phase. Like the Hyades G dwarfs, there is no Be depletion in the Pleiades G dwarfs, but there does seem to be a dispersion in both Li and Be in the Pleiades. For stars cooler than 6000 K, the mean value for $A(\mathrm{Be}) = \log N(\mathrm{Be/H}) + 12.00$ is 1.26 ± 0.10, compared to 1.31 ± 0.07 for the Hyades, i.e., the cool stars all have similar Be abundances.

In this paper we report on the Be results from two open clusters that are older than the Pleiades but younger than the Hyades: Coma Berenices (Mel 111) and the Ursa Major moving group (hereafter Coma and UMa). The canonical age for UMa is 300 Myr (e.g., Soderblom & Mayor 1993) and 500 Myr for Coma (e.g., Janes & Adler 1982). The metallicity for each is slightly less than solar: [Fe/H] = -0.09 ± 0.03 for UMa (Boesgaard 1989; Boesgaard & Friel 1990) and -0.06 ± 0.03 for Coma (Boesgaard 1989; Friel & Boesgaard 1992).

2. OBSERVATIONS AND ANALYSIS

We have observed 12 stars in Coma, and apparently one nonmember, and six bona fide members of UMa in the region of the Be II resonance lines with the Keck I telescope and HIRES (Vogt et al. 1993) with the UV cross disperser. The detector was a Tektronix 2048 × 2048 CCD with 15 μm pixels that has a quantum efficiency of only 8% in the ultraviolet region near 3100 Å. The Be II resonance lines are at 3130.421 and 3131.065 Å. In that order, the measured dispersion is 0.021 Å pixel^{-1}, and the measured FWHM of the comparison lines is 3.12 pixels = 0.0668 Å, resulting in a spectral resolution of 47,000. The observations were made on 2001 February 1 and 2002 January 4 and 5 (UT). Along with the stellar spectra, we obtained typically 15 quartz flat fields, 11 bias frames, and two Th-Ar comparison spectra each night for the data reduction procedures.

For both clusters, Li abundances have been determined. The results for Coma can be found in Boesgaard (1987), Jeffries (1999), and Ford et al. (2001), and the results for UMa are in Boesgaard, Budge, & Burck (1988a) and Soderblom et al. (1993). The Li abundances, as $A(\mathrm{Li}) = \log N(\mathrm{Li/H}) + 12.00$, are plotted against effective temperature, T_{eff}, in Figures 1 and 2 for Coma and UMa, respectively. The stars that we observed for Be are circled. (Only "probable" members of UMa are plotted.) The presence of the Li dip near 6600 K (6450–6850 K in the Hyades) is apparent in each cluster. We could observe one of the dip stars in Coma because its low $v \sin i$ (<12 km s^{-1}) meant that we could determine the Be abundance in that crowded spectral region near the Be II lines.

The stars we observed in Coma are listed in Table 1 along with the V magnitude, $B-V$, the date of the observation, the exposure time, and the S/N of the reduced spectrum. (The Tr number designations are from Trumpler 1938.) The same information on the stars we observed in UMa is given in Table 2. The exposure times for the Coma stars were 20–55 minutes, yielding a S/N of 25–100 with a median of 58. The UMa stars are brighter, and the exposure times were 8–12 minutes and a S/N of 60–250 with a median of 80.

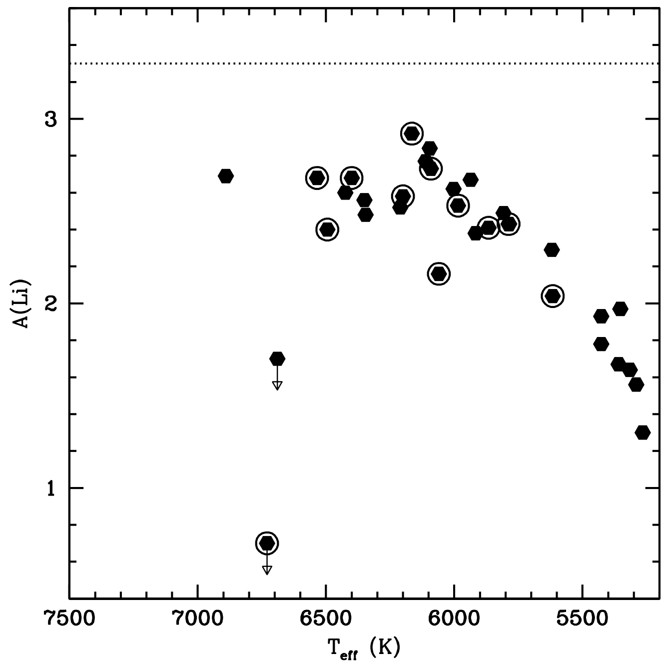

FIG. 1.—Lithium abundances plotted against temperature for the Coma stars. The circled points correspond to the stars we observed for Be. The horizontal dotted line is at $A(\mathrm{Li}) = 3.31$, the meteoritic abundance of Li. The values of T_{eff} and $A(\mathrm{Li})$ are from Boesgaard (1987), Jeffries (1999), and Ford et al. (2001). The membership of Bou 49 [6113, 1.81] (not plotted here) is in question.

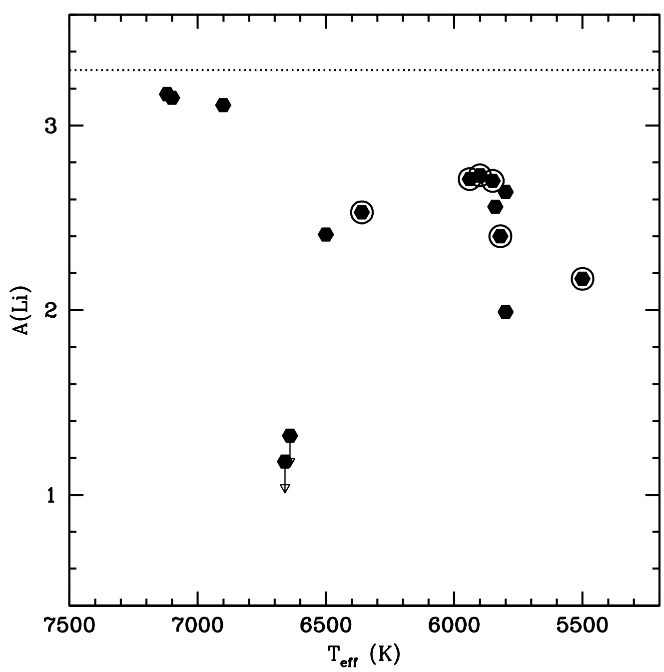

FIG. 2.—Lithium abundances plotted against temperature for the UMa stars. The circled points correspond to the stars we observed for Be. The horizontal dotted line is at $A(\mathrm{Li}) = 3.31$, the meteoritic abundance of Li. The values of T_{eff} and $A(\mathrm{Li})$ are from Boesgaard et al. (1988a) and Soderblom et al. (1993).

TABLE 1
Log of the Observations of the Coma Berenices Cluster

Name	HD	BD	V	$B-V$	Night (UT)	Exposure (minutes)	S/N
Tr 19	106103	+28 2087	8.09	0.35	2001 Feb 1	35	. . .
Tr 19	. . .	. . .	. . .	. . .	2002 Jan 4	20	110[a]
Tr 53	107067	+23 2447	8.70	0.47	2002 Jan 4	30	80
Tr 58	107132	+25 2486	8.81	0.45	2002 Jan 5	30	67
Tr 65	107214	+25 2488	9.02	0.58	2001 Feb 1	35	24
Tr 76	107399	+26 2330	9.09	0.56	2001 Feb 1	40	48
Bou 49	107512	+32 2236	9.10	0.55	2002 Jan 4	35	74
Tr 101	107887	+27 2122	8.35	0.40	2001 Feb 1	23	52
Tr 114	108154	+24 2457	8.56	0.43	2001 Feb 1	55	51
Tr 118	108226	+27 2129	8.34	0.42	2001 Feb 1	30	59
Tr 141	. . .	+29 2290	9.72	0.68	2002 Jan 5	45	52
Bou 50	. . .	+36 2278	9.55	0.59	2002 Jan 5	45	58
	111878	+26 2402	8.81	0.51	2002 Jan 4	25	67
	114400	+34 2398	9.60	0.57	2002 Jan 5	40	57

[a] S/N of combined spectra.

The data reduction was done with standard routines in IRAF.[3] A detailed discussion of the procedures that were used for these data are described in Boesgaard & King (2002) and Boesgaard et al. (2003). The final 1 day spectra cover the range from 3005 to 3285 Å.

Examples of the reduced spectra are shown in Figure 3. The star in panel (*a*) is Tr 19, which is very depleted in Li, $A(\mathrm{Li}) \leq 0.70$, or a depletion relative to the meteoritic value of more than 400 times. This star is also depleted in Be but has a detectable amount of Be, unlike Li, which is undetected at a very low level.

3. ABUNDANCES

We have adopted values for T_{eff} from the literature for our Coma stars from Boesgaard (1987: eight of the 13 stars), Jeffries (1999: two stars), and Ford et al. (2001: three stars). For the five stars in common between Boesgaard and Jeffries, $\Delta T(\mathrm{Boes} - \mathrm{Jeff}) = -14 \pm 17$ K, indicating that the temperature scales are in agreement; Jeffries (1999) and Ford et al. (2001) use the same temperature scale. For the UMa stars, we adopt T_{eff} from Boesgaard et al. (1988a) for three stars and from Soderblom et al. (1993) for the other three stars. The nine stars in common (members and nonmembers both) have $\Delta T(\mathrm{Boes} - \mathrm{Sod}) = -29 \pm 45$ K, a reasonable agreement.

For the Coma stars, we adopted the Gray (1976) relation for $\log g$, $\log g = 0.38\ (B-V) + 4.17$, which we deem best for stars in a cluster. The relative $\log g$ values are as good as the relative $B-V$ photometry. The probable error in the calibration fit is given by Gray as ± 0.075 dex. Since the UMa stars are in a moving group instead of a cluster, the photometry may not be as consistent. Therefore, we used the *Hipparcos* data for $\log g$, as calibrated and presented by Allende Prieto & Lambert (1999) for the four stars in their compilation. The agreement with the Gray relation for these four stars is within ± 0.03 dex. For the other two Coma stars (HR 1321 and HR 3391), we used the Gray relation. There is little star-to-star difference in $\log g$ for these main-sequence stars of the same age and metallicity; from the hottest star to the coolest, $\log g$ goes from 4.30 to 4.48 dex.

As mentioned in § 1, both clusters have small metal deficiencies. For Coma, Boesgaard (1989) found -0.065 ± 0.023, and Boesgaard & Friel (1990) found -0.052 ± 0.047. We adopt -0.06 for Coma. The metallicity for UMa has been determined to be -0.085 ± 0.087 (Boesgaard et al. 1988a), -0.095 ± 0.046 (Boesgaard 1989), and -0.085 ± 0.21 (Boesgaard & Friel 1990). We adopt $[\mathrm{Fe/H}] = -0.09$ for UMa. As in the previous cluster Be papers, we use the formula from Edvardsson et al. (1993) for the microturbulence, ξ.

The stellar parameters for each star are listed in Table 3 and 4, along with the Li abundance from the literature in

[3] IRAF is distributed by the National Optical Astronomical Observatory, which is operated by AURA, Inc., under contract to the National Science Foundation.

TABLE 2
Log of the Observations of the UMa Cluster

Name	HR	HD	V	$B-V$	Night (UT)	Exposure (minutes)	S/N
χ Cet B	531B	11131	6.72	0.61	2002 Jan 5	12	83
v891 Tau	1321	26913	6.96	0.70	2002 Jan 5	12	62
v774 Tau	1322	26923	6.33	0.59	2002 Jan 5	12	67
χ^1 Ori	2047A	39587	4.41	0.59	2002 Jan 5	8	245
π^1 UMa	3391	72905	5.64	0.62	2002 Jan 5	12	62
	4867	111456	5.84	0.46	2002 Jan 5	10	87

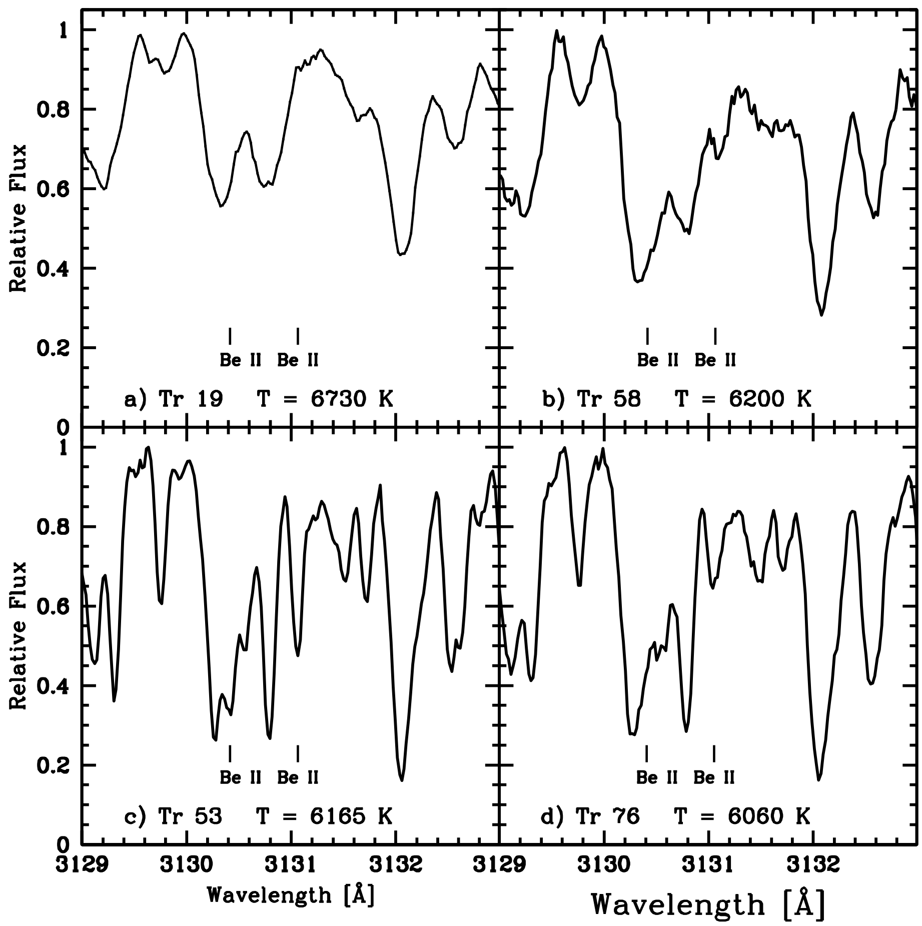

FIG. 3.—Examples of the Be II region of the spectrum of four Coma stars. These spectra are shown normalized to 1.0 with a psuedocontinuum fit; this is adjusted during the synthesis fitting. The spectra in panels (*a*) and (*b*) are more rotationally broadened than those in (*c*) and (*d*). (*a*) The Li is very depleted in Tr 19, and its Be lines are clearly weakened.

the references cited for the temperature. The tables also list the $v \sin i$ values where known; these are from Kraft (1965) and Ford et al. (2001) for Coma and from the Bright Star Catalog for UMa. Armed with the stellar parameters for each star, we used the Kurucz (1993) grid of model atmospheres to make the appropriate model for each star.

Spectrum synthesis is the best method to determine the Be abundance, because the region is crowded with other atomic and molecular spectral features that make it difficult to isolate the Be II lines. We used the latest version of the program MOOG (Sneden 1973), MOOG2002, which includes the UV opacity edges of Kurucz (1993). As input, we employed

TABLE 3

STELLAR PARAMETERS AND ABUNDANCES FOR COMA BERENICES CLUSTER ([Fe/H] = −0.06)

Star ID	T_{eff} (K)	Source[a]	log g	ξ (km s^{-1})	$v \sin i$ (km s^{-1})	A(Li)	A(Be)	σ
Tr 19	6730	1	4.30	2.09	<12	<0.70	0.65	0.07
Tr 53	6165	1	4.35	1.58	<12	2.92	1.15	0.06
Tr 58	6200	1	4.34	1.62	12	2.58	1.10	0.07
Tr 65	5985	1	4.39	1.38	12	2.53	1.15	0.09
Tr 76	6060	1	4.38	1.45	12	2.16	0.90	0.08
Bou 49	6113	2	4.38	1.50	...	1.81	<0.10	0.20
Tr 101	6535	1	4.32	1.91	20	2.68	1.10	0.11
Tr 114	6400	1	4.33	1.79	<12	2.68	1.10	0.07
Tr 118	6495	1	4.33	1.87	<12	2.40	1.05	0.07
Tr 141	5616	3	4.43	1.03	<6	2.04	1.30	0.06
Bou 50	5788	2	4.39	1.22	...	2.43	1.25	0.06
HD 111878	6091	3	4.36	1.51	10	2.73	1.20	0.07
HD 114400	5866	3	4.39	1.29	<15	2.41	1.35	0.06

[a] (1) Boesgaard 1987; (2) Jeffries 1999; (3) Ford et al. 2001.

TABLE 4
Stellar Parameters and Abundances for UMa Cluster ([Fe/H] = −0.09)

Star ID (HR)	T_{eff} (K)	Source[a]	log g	ξ (km s^{-1})	$v \sin i$ (km s^{-1})	A(Li)	A(Be)	σ
531B	5820	1	4.48	1.13	. . .	2.48	1.25	0.06
1321	5500	2	4.44	0.93	<6	2.17	1.25	0.06
1322	5940	2	4.41	0.89	4	2.71	1.10	0.06
2047A	5900	1	4.39	1.32	9	2.75	1.20	0.06
3391	5850	1	4.41	1.25	9	2.70	1.20	0.07
4867	6360	2	4.38	1.69	36	2.53	1.30	0.21

[a] (1) Boesgaard 1988a; (2) Soderblom et al. (1993).

the atomic and molecular line list used by Boesgaard & King (2002) for the Hyades and by Boesgaard et al. (2003) for the Pleiades and α Per. (See the discussion of the line list in García López et al. 1995; King, Deliyannis, & Boesgaard 1997; Boesgaard & King 2002.) To achieve a good match between the observed and synthetic spectra, we smoothed the synthetic spectra with a Gaussian and multiplied the observed spectrum by a constant (usually 0.85–0.95) to align the continua. The fit was done outside the Be II region. Then the Be abundance was adjusted to achieve the best fit. The Be II line at λ3131 is relatively clear of blends, and we relied more heavily on the fit of that line than on the stronger line of the doublet at λ3130 in our abundance determinations.

The spectrum synthesis fits for two stars in Coma are shown in Figure 4. These two stars differ in temperature by nearly 500 K, but the syntheses yield the same Be abundance. The observed points for HD 111878 are seen to be well matched by the adopted synthetic spectrum in spite of its $v \sin i$ value of 10 km s^{-1}. Figure 5 shows two examples of the observed and synthetic spectra for two solar-temperature stars in Coma. Examples of the spectrum synthesis fits for two early G dwarfs in UMa are shown in Figure 6.

The adopted Be abundances, as A(Be), along with the estimated errors, are given in Tables 3 and 4, for Coma and UMa, respectively, in the last two columns. A more complete discussion of the error estimates is given in Boesgaard et al. (2003). The uncertainties in A(Be) result from a combination of the errors in T_{eff} (typically $\pm$80 K, giving $\pm$0.01 dex), log g (typically $\pm$0.1 dex, giving $\pm$0.04–0.05), [Fe/H] (typically 0.05 dex, giving $\pm$0.02), ξ [typically 0.25 km s^{-1}, giving 0.03, independent of temperature and A(Be)], the S/N of the observed spectrum (typically giving $\pm$0.02–0.04), and the "goodness of fit," which is an estimate influenced by the amount of rotational broadening (ranging from $\pm$0.02 to $\pm$0.15 dex).

An astrometric and photometric analysis of *Hipparcos* data has been done of the field around the Coma cluster by Odenkirchen, Soubiran, & Colin (1998). Proper motions in the cluster field have been cataloged by Abad & Vicente (1999). Some of the stars we observed were identified in these programs and were studied for Li by Jeffries (1999)

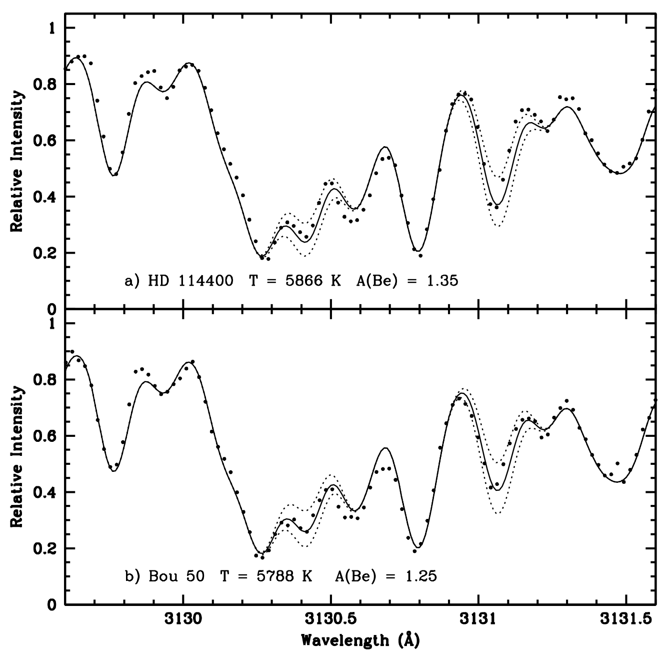

Fig. 4.—Examples of the spectrum synthesis for two Coma stars. The dots are the observed spectrum points; the solid line is the best-fit Be abundance, and the dotted lines are for Be abundances a factor of 2 higher and lower. These stars differ in temperature by 475 K but have virtually the same Be abundance. In spite of a $v \sin i$ value of 10 km s^{-1}, a good synthesis fit could be achieved for HD 111878.

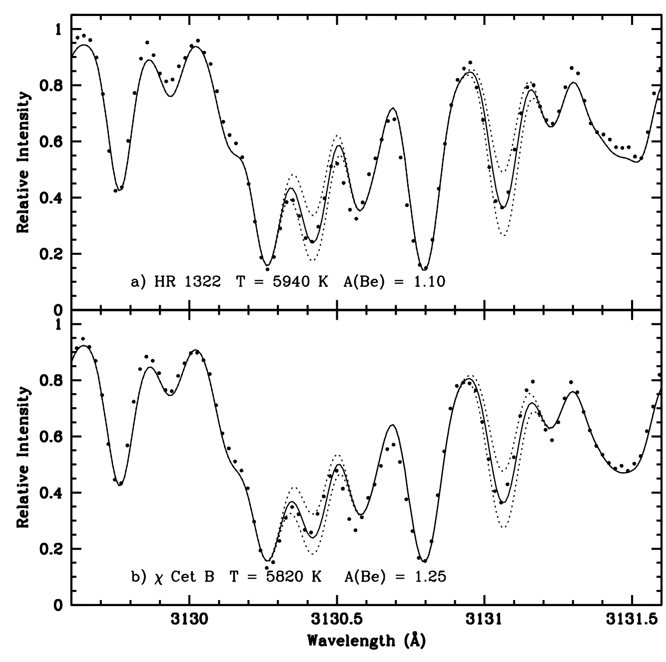

Fig. 5.—Examples of the spectrum synthesis for two Coma stars. The lines and symbols are the same as in Fig. 4. These two stars have similar temperatures and Be abundances.

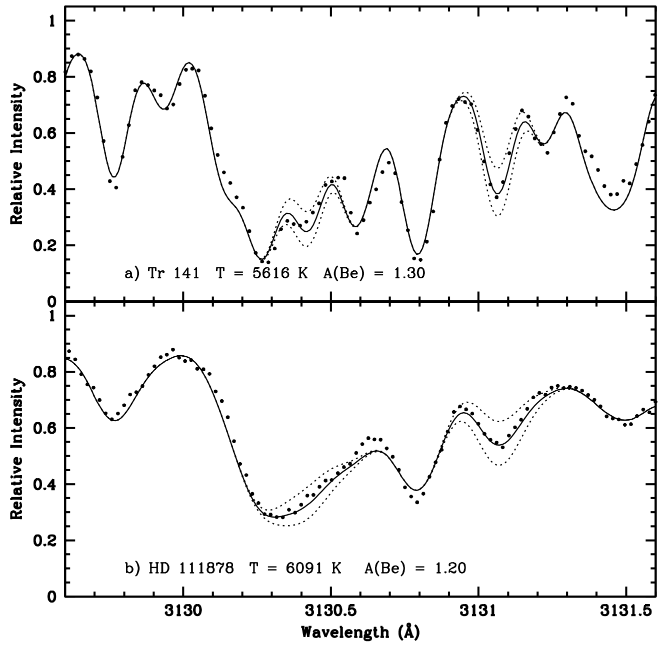

FIG. 6.—Examples of the spectrum synthesis for two UMa stars. The lines and symbols are the same as in Fig. 4.

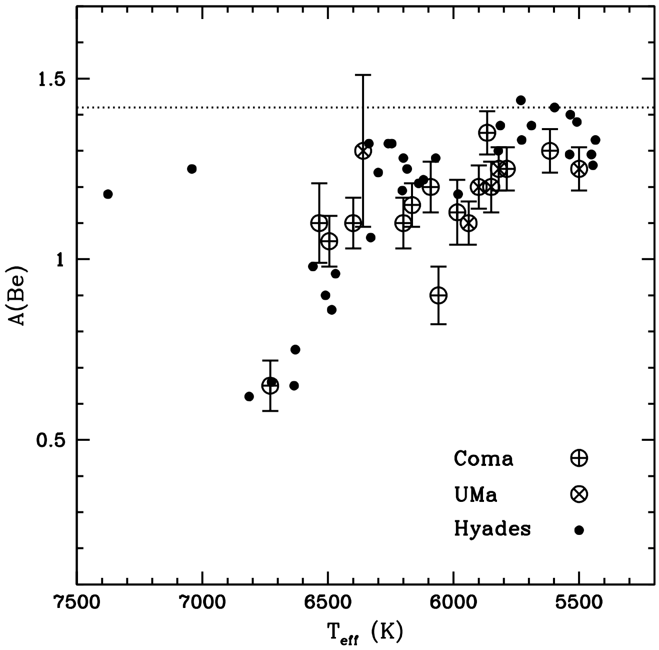

FIG. 7.—Be abundances in the Coma and UMa dwarfs are plotted vs. temperature. The results for Coma are the open circles with plus signs, and those for UMa are open circles with crosses. For comparison, the Be abundances from the Hyades (Boesgaard & King 2002, revised) are shown as small dots. Like the Hyades, the mid-F star " Li dip " shows its counterpart " Be dip " in the more youthful Coma cluster. (We have observed no " dip " stars in UMa.)

and Ford et al. (2001). Of those newly identified stars, we tried to observe Be only in those that were members according to Ford et al. (2001). We have found, however, that one of the stars from Jeffries (1999), Bou 49 (from Bounatiro 1993), is probably not a bona fide Coma member. Its radial velocity of -4.2 km s^{-1} (Jeffries 1999) is not in good agreement with the cluster mean of -0.4 (± 1.6) km s^{-1} (Trumpler 1938), and its membership was questioned by Jeffries. For the temperature found by Jeffries of 6113 K, its A(Li) of 1.81 shows it to be very depleted for a young cluster star. We have found this star to have very weak Be lines and suggest that its membership is also questionable on the basis of its light-element abundances.

4. RESULTS AND DISCUSSION

Figure 7 shows the presence of a mid-F star Be dip in younger Coma cluster like the Hyades Be dip, which is shown for comparison in the figure. (The Hyades points have all been reanalyzed with the latest MOOG version that has the UV opacity edges included; the Be abundances in the Hyades stars have increased slightly, typically by 0.04 dex, ranging from 0.00 to 0.12 dex.) There is only one star in the center of the dip, but several others lie along the cool edge of the dip and agree with the Hyades trend. The UMa stars show Be deficiencies that are consistent with the trend, but we have not observed stars hot enough to be near the center of the dip. The younger Pleiades stars do not show this dip, and we can conclude that Li and Be are depleted during the main-sequence phase and that the effects of this depletion are noticeable after some 300 Myr of main-sequence evolution.

We show definitive evidence of the Be depletion in the Coma star at the center of the Li dip, Tr 19, in Figure 8. The best synthetic spectrum has $A(\text{Be}) = 0.65$, which is down by a factor of 6 from the meteoritic value. Figure 8 shows a synthesis with a Be abundance like that found for the Sun by Chmielewski, Müller, & Brault (1975), which clearly does not fit the Tr 19 spectrum. The figure also shows a synthesis with essentially no Be, and this clearly does not fit Tr 19 either. We can conclude that Tr 19 has detectable but

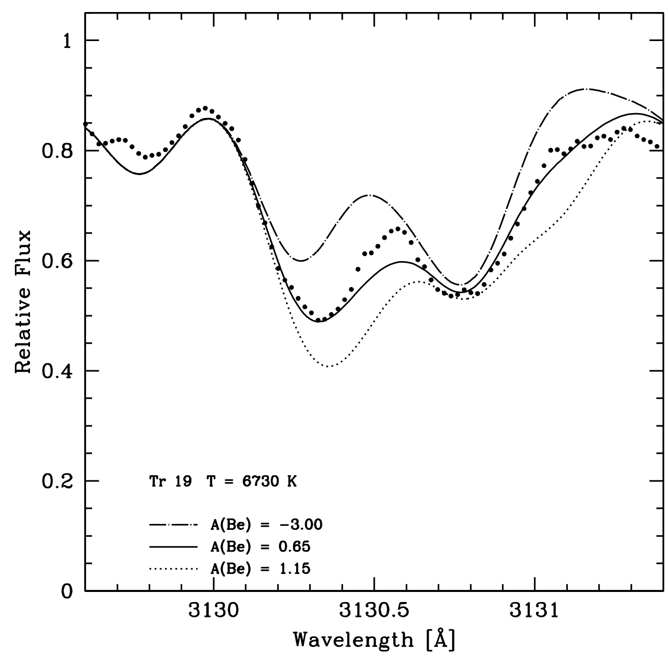

FIG. 8.—Synthetic spectrum of Be in the Li- and Be-depleted star, Tr 19, which is the low point in Fig. 7 at [6730, 0.65] near the center of the Li dip. The dots are the observed spectrum, and the solid line is the synthesis with the best fit, $A(\text{Be}) = 0.65$. The dotted line shows the synthesis with solar Be abundances of Chmielewski et al. (1975). The dot-dashed line corresponds to essentially no Be. Although the $v \sin i$ of $\sim$12 km s^{-1} broadens the spectral features, it is clear that this star retains some Be but is Be-deficient.

depleted Be; it retains some but not all of its Be. In contrast, it seems to have retained no Li, as the upper limit on A(Li) is less than 0.70, a 400-fold decrease from meteoritic Li.

As can be seen in Figure 1, Coma is lacking in stars near 6000–6300 K that have A(Li) near the meteoritic value of A(Li). Figure 2 shows that the certified members of UMa are few in number, with none near the Li peak at 6000–6300 K. Both the younger Pleiades and the older Hyades have stars in this temperature range, with A(Li) close to the meteoritic value. The stars in both Coma and UMa on the hot side of the dip do reach Li abundances close to those for the meteorites, so perhaps the lower Li values at the Li peak result from Li depletion. More elaborate explanations, which are difficult to explore here, might include (1) a "metallicity" dependence to factors that set the Li peak depletion rates, (2) differing detailed opacity mixtures, important in PMS standard Li burning, for UMa and Coma relative to the Hyades and Pleiades (e.g., Piau & Turck-Chieze 2002), and (3) more rapid initial rotation for stars in Coma and UMa and some early Li depletion. Whatever the cause, it apparently does not affect the Be abundance in the same way: The Coma and UMa Be abundances in the range 6000–6300 K are indistinguishable from their Hyades and Pleiades counterparts. Indeed, whereas the mechanism of Galactic Be production is limited to spallation reactions in the interstellar medium, suggested sources of Li production are myriad; thus, Li and Be production need not precisely track each other in principle.

The abundances of both Li and Be in Coma and UMa are shown on the same scale in Figure 9, where they are normalized to their respective meteoritic values. For each A(Be) point, the A(Li) point is lower, i.e., in each star, there is more Li depletion than Be depletion. In Coma, both elements show a trend from 6200 to 6800 K of decreasing abundance toward the center of the Li-Be dip near 6650 K. For the cooler stars (<6000 K), A(Li) decreases with decreasing temperature, but A(Be) remains high, with little scatter. The mean A(Be) for the four G stars ($T_{\rm eff} \leq 6030$ K) in Coma is 1.26 ± 0.09 and for the five UMa G stars is 1.20 ± 0.06. These values compare well to the 13 G dwarfs in the Hyades at $A(\rm Be) = 1.33 \pm 0.07$ and the seven Pleaides G stars at 1.26 ± 0.10. For the G dwarfs in the four clusters, the "initial" Be abundance is apparently $A(\rm Be) = 1.28$, regardless of age or metallicity.

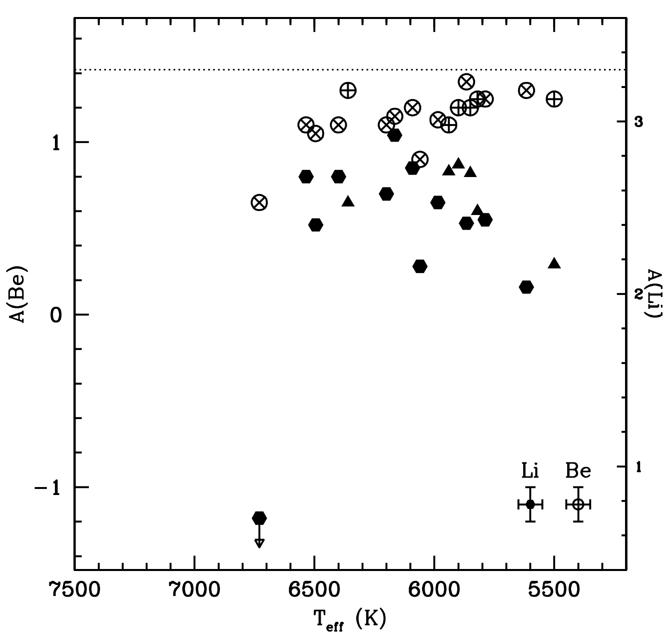

Fig. 9.—Abundances of both Li and Be plotted on the same scale, each normalized to its respective meteoritic abundance. The Li abundances are the solid symbols: Coma (*hexagons*) and UMa (*triangles*). The Be abundances are open circles: Coma (*cross*) and UMa (*plus*). For each star, the corresponding Li abundance is below the Be abundance. For the F stars, there is a downward trend in both Li and Be from 6200 to 6800 K. For the G stars, while Li is increasingly depleted with decreasing temperature, Be stays near the initial value (Boesgaard & King 2002, revised).

Figure 9 reveals one Coma star, Tr 76 at $T_{\rm eff} = 6060$ K, that is lower in both Li and Be than its counterparts. (Fig. 7 also shows that the Be in this star lies below the trend.) Both Boesgaard (1987) and Jeffries (1999) determined the Li abundance of this star and found $A(\rm Li) = 2.15$ at $T_{\rm eff} = 6060$ K and 2.16 at $T_{\rm eff} = 6088$ K, respectively, i.e., in excellent agreement. The value for A(Be) is 0.90 ± 0.08. This star is different from those of similar temperatures in the Hyades and Pleiades. Those stars in the Hyades and Pleiades that were somewhat deficient in Li had normal Be, so this Be deficiency in Tr 76 is unusual.

The three coolest stars in our samples (5500–5800 K) demonstrate Li abundances 10–20 times lower than the meteoritic value. However, there is no clear evidence of Be depletion in these stars; the Be abundances agree with the photospheric solar Be as well as the Be abundance in Hyades and Pleiades dwarfs of similar temperatures.

It was discovered by Deliyannis et al. (1998) and confirmed with additional data by Boesgaard et al. (2001) that in field stars, the abundances of Li and Be are correlated on the cool edge of the Li-Be dip, from 5900 to 6680 K. Boesgaard & King (2002) found the same correlation in the Hyades, perhaps surprisingly, as the Hyades is so much younger than typical field stars. We have looked for this effect in these younger clusters and find that it is present for them as well. Figure 10 shows the correlated abundances of Li and Be in Coma and UMa, compared to those in the Hyades (from the new MOOG). The diagonal dash-dotted line shows the relationship for the field stars. The stars between 5900 and 6650 K in these even younger clusters, Coma and UMa, fall on same line as field stars and Hyades in A(Li) versus A(Be). This implies that the mixing mechanism acts slowly and simultaneously, circulating the atoms of the two elements to deeper interior layers of the star. If the depletion of Li and Be results from rotationally induced mixing, as strongly suggested by the work of Deliyannis & Pinsonneault (1997) and the observations of Deliyannis et al. (1998), Boesgaard et al. (2001), and Boesgaard & King (2002), then a spread in A(Li) and A(Be) would be caused by a spread in the initial rotation velocities of the stars.

5. SUMMARY AND CONCLUSIONS

We have made high-resolution spectroscopic observations in the UV with Keck + HIRES of F and G dwarfs in the young clusters, Coma and UMa, to determine Be abundances, to compare with the published Li abundances, and to compare these with similar Li and Be observations in the older, more metal-rich Hyades and the younger Pleiades and α Per clusters. The spectral resolution is $\sim$47,000, and the median S/N is $\sim$65. Abundance analyses were done by spectrum synthesis for 14 Coma stars and six UMa stars utilizing MOOG2002 with Kurucz UV opacity edges.

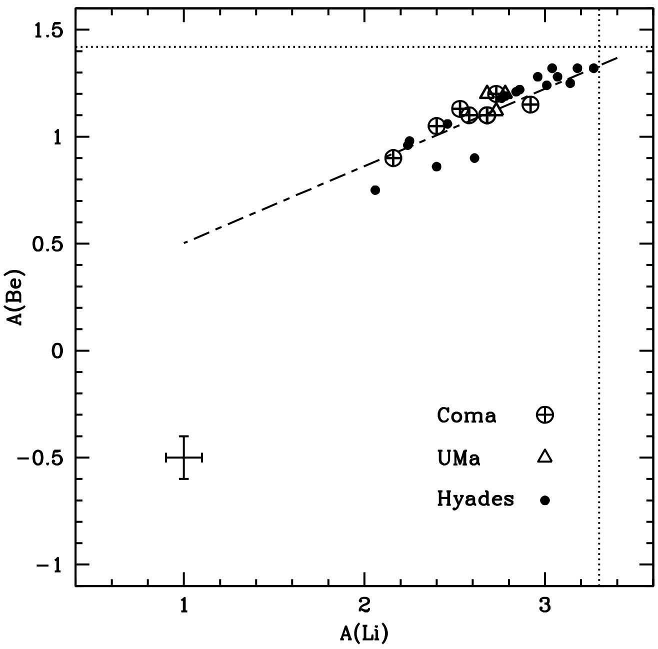

FIG. 10.—Li-Be relation for hot Coma stars (*open circles with plus signs*) and UMa stars (*open triangles*). The Hyades (*small filled dots*) are from Boesgaard & King (2002). The stars plotted here all have temperatures between 5850 and 6650 K. The vertical and horizontal dotted lines are meteoritic abundances. The dot-dashed line corresponds to the fit for the field stars in Boesgaard et al. (2001). A typical error bar is shown in the bottom left. The Coma and UMa stars fit the field-star relationship well.

There is a Be dip in the mid-F dwarfs in Coma (Fig. 7) matching its Li dip in temperature but not in the depth of the depletion (Fig. 1). The reality of the Be depletion in Tr 19 is illustrated in the synthesis fit (Fig. 8). The Be dip is not present in the younger Pleiades but is present in the older Hyades. (For Li, the Pleiades shows only a small dip, while in the Hyades, Li shows a pronounced chasm.) This indicates that the Be (and Li) depletion is taking place during main-sequence evolution and does not become evident until after the age of 200–300 Myr.

For each star, A(Li) is below A(Be) when the abundances are normalized to their respective meteoritic abundances. This is expected, as Li is more readily destroyed than Be. [We note that, unlike the Hyades and Pleiades, the mean A(Li) is a factor of 4 below the meteorite value in the temperature range 5900–6200 K.] Both Li and Be decrease toward the F star dip from 6000 to 6650 K. For G dwarfs, A(Li) decreases with decreasing temperature, but A(Be) remains near the meteoritic value. For stars cooler than 6000 K, the mean A(Be) is 1.26 ± 0.09 for Coma and 1.20 ± 0.06 for UMa, compared to 1.33 ± 0.07 for Hyades and 1.26 ± 0.10 for Pleiades. For these cool dwarfs, all the clusters have the same $\langle A(\mathrm{Be}) \rangle = 1.28$, independent of age and metallicity.

For the hotter stars in the sample, those on the cool edge of the Li-Be dip, A(Li) and A(Be), are correlated for Coma and UMa and follow the relationship found for field stars (Fig. 10). This correlation is similar to that found for the Hyades and implies a simultaneous depletion of the two light elements. The best explanation for these related depletions, as presented in Deliyannis et al. (1998), is slow mixing induced by rotation.

The Hyades are older by a few hundred megayears and more metal-rich by +0.2 dex than Coma and UMa. The pattern of Li and Be depletion in the F star dip is similar. In all three clusters, the G stars have increasing Li depletion with decreasing temperature but show no Be deficiencies. The Pleiades with solar metallicity is younger than Coma and UMa but shows no evidence of Be depletion in either F or G dwarfs, and the F star Li depletion is mild, perhaps only 0.2 dex. The effects of the slow mixing in main-sequence middle F stars begin to be noticeable only after an age of about 200–300 Myr. For G stars in both young clusters and older field stars, there are no Be deficiencies, even though there are large depletions in Li. Either different mixing mechanisms are at work in the hotter F stars than the G stars, or the prevailing mixing mechanism does not reach the same temperature layer in the G dwarfs.

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