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ABUNDANCES IN BERYLLIUM-DEFICIENT F STARS

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ABSTRACT

Abundances of a number of elements have been determined in six Be-deficient F dwarfs and in a comparison group of 13 normal F5–G0 dwarfs. The observations were made at high spectral resolution (0.06–0.11 Å) and high signal-to-noise ratios (350–800) at the Canada-France-Hawaii telescope. Model atmosphere abundance analyses were done for 28 lines of seven elements: Li, Na, Mg, Si, Ca, Sc, and Fe. By analogy with the Am stars and the Fm stars, excesses of Na and Si and deficiencies of Mg, Ca, and Sc might be expected if diffusion processes are responsible for the light element depletion. No difference was found in the distribution of any of these element abundances between the Be-deficient and the Be-normal stars. Two of the Be-deficient stars are slightly metal poor, two are normal, and two are slightly metal rich. Among the Be-normal stars virtual twins in temperature, gravity, and composition can be identified for the Be-deficient stars. All of the Be-deficient stars were found to be very Li deficient. We suggest that it is unlikely that diffusion is responsible for the Li and Be anomalies. Transport of Li and Be by extra mixing, such as convective overshoot, meridional circulation, turbulence, etc., could deplete the surface content of the light elements while not affecting the abundances of the other elements. For F dwarfs cooler than 6600 K, high activity and high rotation may be connected to very *low* abundances of Li and Be.

Subject headings: diffusion — stars: abundances

I. INTRODUCTION

Main-sequence F stars are generally thought to be uniform in chemical composition. However, there is a wide range in the abundance of the light elements, Li and Be. As shown by Herbig and Wolff (1966) and Boesgaard and Tripicco (1986*a*), F and G main-sequence field stars shown a range of two orders of magnitude in Li abundance. The largest abundances are found in the early F stars where presumably there has been no depletion of Li during pre–main-sequence or main-sequence evolution via convective circulation to temperatures sufficient for (p, α) reactions to occur. At all spectral types there were stars where the Li abundance was so low that the resonance line of Li I was too weak to detect. The abundance of Be has been found to be a uniform Be/H $= 1.3 \times 10^{-11}$ in a sample of 29 F0–G2 stars but deficient by factors of 6 and more in nine of the F stars (Boesgaard 1976; Boesgaard and Chesley 1976). The six Be-deficient *dwarfs* were all in the hotter one-third of the sample of dwarfs and all were Li-deficient also.

The mechanism by which Li and Be could be depleted in F stars is still not well understood, although various mechanisms for transporting these elements to high-temperature regions have been suggested, e.g., convective overshoot (Weymann and Sears 1965; Straus, Blake, and Schramm 1976) and diffusion below the convection zone (Schatzman and Vauclair 1973; Vauclair *et al.* 1978). Be can be destroyed by (p, α) reactions but at higher temperatures (i.e., deeper in the stellar interior) than Li. The approximate temperature for Li destruction via (p, α) reactions is 2.4×10^6 K, while for Be it is 3.2×10^6 K.

Vauclair *et al.* (1978) suggest that the Be-deficient F stars may be the result of a transport of Be to hotter temperatures (and nuclear destruction) via convective overshoot and then microscopic diffusion. They conclude that the Be-deficient F stars are a prolongation of the Am star sequence to Fm. The Be-normal stars could *not* have undergone meridional circulation or microscopic diffusion according to their ideas. They make no detailed predictions of the effects of microscopic diffusion on other elements because of uncertainties in the computations of radiative forces of a factor of ~ 3. They do claim that normal abundances for other elements would be difficult to reconcile with the explanation of microscopic diffusion for the Li, Be-deficient stars. They expect a general overabundance of metals in some, a general underabundance in others, or enhancements of light metals and deficiencies of heavy ones in others. Tomkin, Lambert, and Balachandran (1985) have done an abundance analysis of the Be-deficient F star, σ Boo, and comment on the lack of evidence for microscopic diffusion in that star.

We lack theoretical guidance but can turn to empirical guidance. Smith (1973) has studied abundances in Fm stars from spectrograms of 0.20 Å resolution. He found deficiencies for Mg, Ca, and Sc of $\sim$0.5–1.0 dex and excesses for Na and Si of 0.05–0.5 dex. He cautions that the Si excess may be spurious and remarks that the Ca and Sc deficiencies are even more extreme than they are in the Am stars.

We have chosen to examine the abundances of these elements, along with Li and Fe for comparison, in the Be-deficient F stars and a sample of Be-normal stars. The effects of diffusion may be subtle, so we have made our observations at high spectral resolutions with a high signal-to-noise (S/N) ratio. Beyond being a test of the Vauclair *et al.* (1978) explanation for the Be-deficient stars, this work is an examination of the effects of diffusion on the abundances in main-sequence F stars.

II. OBSERVATIONS AND DATA REDUCTION

The observations were made with the coudé spectrograph of the Canada-France-Hawaii 3.6 m telescope of the Mauna Kea Observatory, with the f/7.4 camera and an 830 line mm^{-1},

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TABLE 1

Stars Observed, Physical Characteristics, and Signal-to-Noise of Observed Spectra

Star (1)	HR (2)	Spectral Type (3)	V (4)	T_e (5)	log g (6)	$v \sin i$ (km s^{-1}) (7)	Signal-to-Noise Ratio Region 1 (8)	Region 2 (9)	Region 3 (10)	Region 4 (11)
υ And	458	F8 V	4.1	6050[a]	4.0[a]	9.2	...	220	...	570
β Vir	4540	F8 V	3.6	6100[a]	4.1[a]	4.0	560	430	740	1200
β CVn	4785	G0 V	4.3	5870[a]	4.4[a]	1.8	...	...	...	775
β Com	4983	G0 V	4.3	5960[a]	4.4[a]	4.3	...	...	...	760
τ Boo	5183	F7 V	4.5	6390[a]	3.8[a]	17.0	440	510	720	790
ι Vir	5338	F7 IV	4.1	6120[a]	3.8[a]	17.0	360	470	650	820
σ Boo	5447	F2 V	4.5	6700[b]	4.4[c]	7.5	...	470	680	830
ϵ Lib	5723	F5 V	4.9	6370[d]	3.85[c]	8:	...	...	...	780
λ Ser	5868	G0 V	4.4	5870[a]	4.0[a]	2.4	...	...	...	770
χ Her	5914	F9 V	4.6	5830[a]	4.0[a]	2.2	...	...	...	790
γ Ser	5933	F6 V	3.9	6270[a]	4.0[a]	8	...	...	...	730
110 Her	7061	F6 V	4.2	6250[b]	3.8[c]	14	...	460	710	770
θ Cyg	7469	F4 V	4.5	6650[b]	4.4[c]	5.3	390	350	750	820
17 Cyg	7534	F5 V	5.0	6240[a]	4.05[a]	9	335	350	675	765
	7955	F8 IV–V	4.6	6110[b]	3.6[c]	5:	365	390	750	800
μ^1 Cyg	8309	F6 V	4.7	6130[a]	4.3[a]	4:	325	350	700	765
τ PsA	8447	dF5	4.9	6370[d]	4.0[c]	10:	...	...	...	565
ξ Peg	8665	F7 V	4.2	5980[a]	4.1[a]	8.9	350	380	656	770
ι Psc	8969	F7 V	4.1	5960[a]	4.0[a]	5.7	380	380	310	790

[a] Duncan 1980.
[b] $R-I$.
[c] $b-y$.
[d] $B-V$.

mosaic grating blazed in the first order red at 8000 Å. The detector was a nitrogen-cooled 1872 photodiode Reticon array (Campbell *et al.* 1981). Spectra were obtained on 1981 June 16, 17, 18, 19 UT of six Be-deficient stars and 13 normal stars. Some of the stars were observed in the second-order blue in a 65 Å region centered at 4300 Å where lines of Ca I and Sc II occur. Three spectral regions in the first-order red were observed on the last three nights, including the Li region at 6700 Å, covering ~135 Å in each region. All the observations were made at high signal-to-noise with continuum S/N typically between 350 and 800.

The stars observed, their HR numbers, their spectral classes, and apparent visual magnitudes are given in columns (1)–(4) of Table 1. Columns (5) and (6) give the effective temperature and surface gravities used in the analysis of the stars and column (7) the published $v \sin i$ values (Hoffleit 1982; Soderblom 1982) discussed in § III. Columns (8)–(11) give the signal to noise of the spectrograms in the various wavelength regions observed. Table 2 gives the spectral regions observed, their dispersion and resolution (from the projected slitwidth).

The stellar exposures were divided by the mean of four flat-field exposures of equivalent stellar continuum exposure level in order to remove pixel-to-pixel variations of the individual photodiodes. A four-channel normalization procedure was then applied to remove the minor differences not accounted for by the flat-fielding procedure. Sample spectra, after flat-field division, of the 6700 Å region are shown in Figure 1.

TABLE 2

Spectral Regions Observed

Region	Wavelength Range (Å)	Dispersion Å mm^{-1}	Dispersion Å pixel^{-1}	Resolution (Å)
1	4265–4330	2.4	0.035	0.06
2	5680–5815	4.8	0.072	0.11
3	6135–6270	4.8	0.072	0.11
4	6630–6765	4.8	0.072	0.11

Most of the features chosen for the abundance analysis were in spectral regions where the continuum level was easy to locate and there were no blending features; the equivalent widths could be readily measured by a computer routine. The lines in the 4300 Å region were quite blended in spite of the higher spectral resolution, and special care was taken in measuring the Ca I and Sc II equivalent widths in that region with reference to spectra of very sharp-lined stars. The equivalent widths measured for 28 lines from the spectra are given in Table 3 along with an index of the quality for each feature (1 = excellent to 3 = somewhat blended) based on considerations of the continuum location and adjacent neighboring line blends. Values for gf and their source are also listed. A total of 341 equivalent widths were determined. Solar equivalent widths are taken from Moore, Minneart, and Houtgast (1966). Lunar spectra were taken at CFHT of the 6200 Å region, and those measured equivalent widths show good agreement with the published values.

The Be-deficient stars show very low upper limits for the Li equivalent width. A line that is twice the peak-to-peak noise would be detectable. The minimum detectable equivalent width in a spectrum with S/N = 700 would be 0.3 mÅ.

III. ABUNDANCE ANALYSIS

The stellar effective temperatures (T_e) given in Table 1 are mean values from Duncan (1981) who derives temperatures primarily from $(R-I)$ colors and the relation $T_e = 3.934$–0.51 $(R-I)$ and from Hearnshaw's (1974) calibrations of $(R-I)$ colors and the Strömgren β index: $\theta_e = 5040/T_e = 0.955$ $(R-I) + 0.56$ and $\theta_e = -1.232\beta + 4.067$. All but three of our stars have $(R-I)$ colors and all but one have β values. The three temperatures rarely disagree by as much as 30°. Values

TABLE 3

EQUIVALENT WIDTHS

λ	QUALITY	gf VALUE[a]	REFERENCE[b]	W_λ (mÅ) Sun	υ And	β Vir	β CVn	β Com	τ Boo[c]	ι Vir[c]	σ Boo[c]
Li I:											
6707.83..........	1	1.51	1	<2	32	25	14	59	≤4	≤1	≤4
Na I:											
5688.20[d].........	1	4.24 (−2) 3.80 (−1)	2	121	143	157	...	...	155	133	76
6154.23..........	2	2.69 (−2)	2	27	...	39	...	...	40	22	10
6160.75..........	2	5.37 (−2)	2	44	...	60	...	...	...	...	18
Mg I:											
5711.08[d].........	1	3.715 (−2)	3	107	101	102	...	...	93	85	53
Si I:											
5690.47..........	1	1.35 (−2)	4	53	52	57	...	...	54	39	20
5772.15..........	1	4.17 (−2)	2	47	61	62	...	...	70	52	23
5793.13..........	2	3.31 (−2)	2	38	49	53	...	...	56	41	21
Ca I:											
4283.01..........	3	5.970 (−1)	2	133	...	143	...	...	135	114	
4289.37..........	3	4.977 (−1)	2	131	...	136	...	...	...	...	...
4318.65..........	2	6.194 (−1)	2	116	...	136	...	...	131	113	...
6162.17..........	2	5.623 (−1)	5	222	...	200	...	...	203	168	128
6166.44..........	1	5.012 (−2)	5	54	...	63	...	...	68	53	27
$6169^{0.06\mathrm{b}}_{0.56}\}$	2	{1.175 (−1) {1.906 (−1)	5	183	...	194	...	...	196	172	103
6717.68..........	1	1.585 (−1)	5	120	113	118	96	113	119	98	58
Sc II:											
4294.78..........	2	5.370 (−2)	6	62	...	100	...	...	79	89	...
4314.09..........	3	7.943 (−1)	6	108	...	144	...	...	152	171	...
4320.74..........	3	6.026 (−1)	6	94	...	147	...	...	170	164	...
6245.63..........	2	8.913 (−2)	6	30	...	...	...	...	...	...	20
Fe I:											
5741.86..........	1	1.862 (−2)	7	31	30	33	...	...	28	22	9
5752.04..........	1	1.000 (−1)	7	56	50	54	...	...	52	38	20
6173.34..........	1	1.318 (−3)	8	50	...	61	...	...	63	55	18
6213.44..........	1	2.138 (−3)	7	61	...	77	...	...	71	64	29
6265.14..........	1	2.818 (−2)	8	72	...	83	...	...	78	74	30
6703.57..........	1	7.413 (−4)	7	32	28	33	27	31	28	19	6
6705.12..........	1	6.761 (−2)	9	42	53	47	33	48	44	32	13
6726.67..........	1	6.918 (−2)	7	50	39	47	33	43	43	32	11
6750.16..........	1	2.399 (−3)	8	75	65	69	64	69	63	52	24

[a] Values in parentheses are powers of 10.

[b] References for *gf* values: (1) Gaupp, Kuske, and Andra 1982; (2) Wiese, Smith, and Miles 1969; (3) Warner 1968*a*; (4) Garz 1973; (5) Holweger 1972; (6) Warner 1968*b*; (7) Gurtovenko and Kostik 1981; (8) Blackwell *et al.* 1982; (9) Andersen, Gustafsson, and Lambert 1984.

[c] Be-deficient star.

[d] Blend of two lines of the same element.

for log g were taken from Perrin *et al.* (1977) or Duncan (1981) or were found from the Strömgren indexes, $b-y$ and c_1, and the calibrations of Crawford (1975) and Bell (1971) as in Boesgaard (1976). The temperatures from Hβ photometry and the Bell (1971) calibration used by Boesgaard (1976) are systematically higher by 200°–300° than those used here from the Duncan or Hearnshaw relationships. The recent Hβ–T_e calibration by Saxner and Hammärback (1985) gives temperatures that are less than 80 K hotter than those used here.

An LTE abundance analysis was done with an atmosphere/abundance routine and opacity code developed by Drs. M. Spite and F. Praderie and adapted by Dr. W. D. Heacox, described in Heacox (1979). A set of model atmospheres of Kurucz (1979) were used with the following log g and T_e values: log $g = 4.5$, $T_e = 6000$, 6500, and 7000 K; log $g = 4.0$, $T_e = 6000$, 6500, and 7000 K; log $g = 3.5$, $T = 6000$ and 6500 K; and a solar atmosphere with log $g = 4.44$ and $T_e = 5770$ K. Nissen (1981) has derived a relation for microturbulence as a function of T_e and log g: $\xi = 3.2 \times 10^{-4}$ ($T_{\rm eff} = 6390$) -1.3 (log $g - 4.16$) + 1.7, which is for stars in the $T_{\rm eff}$ range 5800–7200 K. We have calculated ξ for each of our stars and used the mean value, 1.8 km s^{-1}, in the abundance calculations. The code includes radiation, thermal, van der Waals, and Lorentz broadening calculations. Equivalent widths for all the lines in Table 3 were calculated for all nine atmospheres for nine (usually) abundances ranging from ~20 times less than solar to 20 times more. The three blended features (Na I λ5688, Mg I λ5711, and Ca I λ6169) were specially treated and synthesized by the routine for direct comparison with the observed line. Examples of the resultant curves of growth for λ6727 of Fe I and the blend of λ5688 of Na I are shown in Figures 2 and 3. For each star each measured equivalent width was compared

TABLE 3—*Continued*

W_λ (mÅ)											
ϵ Lib	λ Ser	χ Her	γ Ser	110 Her	θ Cyg[c]	17 Cyg	HR 7955[c]	μ^1 Cyg[c]	τ PsA	ξ Peg	ι Psc
71	22	58	18	5	≤0.8	24	≤0.5	≤2	25	29	26
...	...	...	...	123	108	112	155	111	...	107	120
...	...	...	...	22	22	21	45	19	...	20	22
...	...	...	...	...	27	35	63	29	...	36	36
...	...	...	...	83	71	83	100	74	...	73	82
...	...	...	...	44	36	42	55	32	...	33	43
...	...	...	...	53	34	42	62	42	...	37	40
...	...	...	...	40	34	37	54	35	...	32	36
...	...	...	...	...	120	104	148	110	...	125	126
...	...	...	...	...	124	108	136	132	...	115	126
...	...	...	...	...	108	113	134	103	...	110	112
...	...	...	...	167	155	178	197	159	...	159	176
...	...	...	...	51	42	55	65	46	...	45	52
...	...	...	...	163	146	169	199	146	...	150	173
95	117	81	89	94	83	95	118	83	109	85	95
...	...	...	...	...	60	79	89	79	...	84	73
...	...	...	...	...	143	153	188	137	...	137	133
...	...	...	...	...	130	165	194	...	...	126	165
...	...	...	...	...	35	45	54	41	...	34	39
...	...	...	...	20	15	20	34	16	...	14	17
...	...	...	...	37	35	40	55	31	...	33	38
...	...	...	...	51	35	46	73	37	...	44	45
...	...	...	...	60	48	62	79	51	...	56	57
...	...	...	...	64	51	65	55	57	...	65	68
14	32	18	15	16	13	18	34	13	24	14	22
27	41	22	27	30	24	30	46	23	40	25	28
27	45	24	30	32	27	29	45	24	44	23	31
46	68	48	48	49	37	36	67	44	59	44	53

with the calculated values from the curves of growth and with interpolation for the appropriate temperature and gravity. Thus an abundance was determined for each line measured for each star. To cancel out the effect of errors in the *gf*-values, the abundance found for each line was compared to that derived for the Sun from the solar equivalent widths of Moore, Minneart, and Houtgast (1966). The mean solar abundance found from the appropriate subset of lines was used to find the ratio of the mean stellar to the mean solar abundance.

Iron abundances were determined for each star in the usual logarithmic notation $[\mathrm{Fe/H}] = \log\ (\mathrm{Fe/H})_*/\log\ (\mathrm{Fe/H})_\odot$. These can be compared with published means compiled by Cayrel de Strobel and Bentolila (1983) from the [Fe/H] catalog of Cayrel de Strobel *et al.* (1980) and updates from the Stellar Data Center in Strasbourg and with [metal/H] values found by Nissen (1981). Figure 4 shows the good agreement between the two sets of results.

Elemental abundance ratios were formed, [X/Fe], for all the stars in the sample. Tomkin, Lambert, and Balachandran (1985) have shown that the Sun and disk stars with $[\mathrm{Fe/H}] \geq -0.4$ have the same composition, i.e., the mean $[\mathrm{X/Fe}] = 0.00$. This result was used to calibrate our [X/H] since those numbers are subject to possible systematic shifts in $(\mathrm{X/H}_\odot)$ because of the small number of solar lines, the dependence on microturbulence, ξ, etc. For example, the mean [Ca/Fe] was $+0.09$ instead of the expected 0.00, so 0.09 was subtracted from the stellar [Ca/H] values. Our abundance results are compared in Table 4 with those of Spite (1968) and Tomkin *et al.* (1985), who did detailed, high-resolution analyses of some of the same stars for the same elements. The general agreement in both temperature and composition is excellent.

Abundances of Li/H were determined from the Li-Fe blend as described in detail by Boesgaard and Tripicco (1986*a*). The curve with the appropriate [Fe/H] value was used, or appropriate interpolation was done between [Fe/H] curves, from the derived [Fe/H] values. There is virtually no absorption at the position of the Li I line in the Be-deficient stars, and only for τ Boo and HR 7955 is there any believable Fe I absorption. Abundances were redetermined for Be/H because the tem-

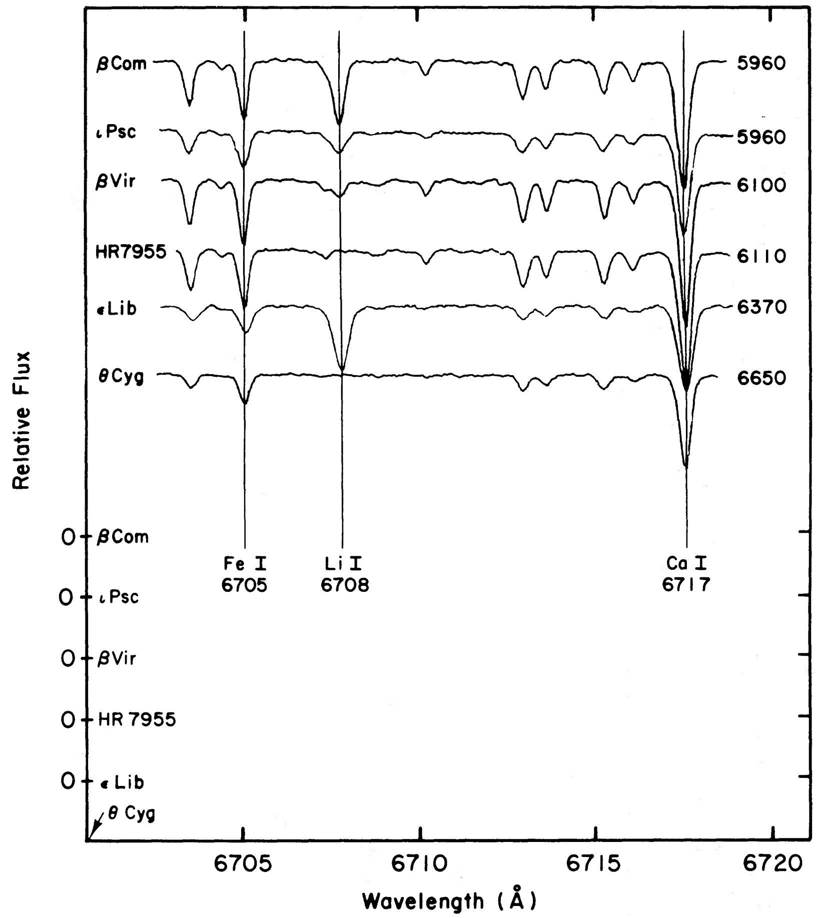

FIG. 1.—Sample spectra showing part of the Li region in representative stars. The S/N ratio of the spectra is typically ~800. The stars are arranged in order of increasing temperature. The Li feature is strong in β Com and ϵ Lib and clearly completely absent in the Be-deficient stars, HR 7955 and θ Cyg. The Fe I feature which blends with the Li I line can be seen clearly in β Vir and as a contributor to the blend in β Com and ι Psc; the Fe I line alone can be seen in HR 7955.

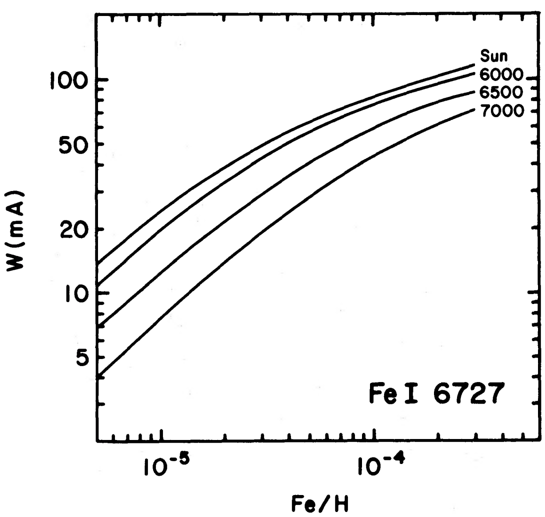

FIG. 2

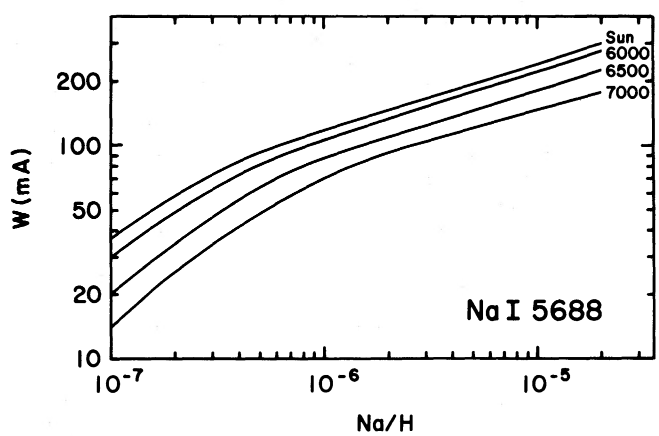

FIG. 3

FIG. 2.—Sample curves of growth for Fe I λ6727 for log $g = 4.0$ for three different temperatures with $\xi = 1.8$ km s^{-1}. The curve labeled "Sun" is for the Kurucz model atmosphere $T_e = 5770$, log $g = 4.44$ with $\xi = 1.5$ km s^{-1}. The solar curve for $\xi = 1.2$ km s^{-1} is shifted slightly to the right so that a given equivalent width would give an abundance that is larger by ~0.03 dex.

FIG. 3.—Sample curves of growth for the blended line of Na I at 5688.2 Å. This set of curves is for log $g = 4.5$ and $\xi = 1.8$ km s^{-1}; there is a slight gravity dependence for this feature. The solar curve is as specified in Fig. 2.

TABLE 4

COMPARISONS WITH OTHER RESULTS

LOGARITHMIC ABUNDANCE RATIO (Star-Sun)	β VIR			σ BOO		τ BOO		γ SER			β COM	
	BL	TLB	S	BL	TLB	BL	S	BL	TLB	S	BL	TLB
	(6100 K)	(6010 K)	(6150 K)	(6700 K)	(6710 K)	(6390 K)	(6460 K)	(6270 K)	(6130 K)	(6380 K)	(5960 K)	(5910 K)
[Fe/H]	0.18	0.15	0.25	−0.18	−0.26	+0.30	+0.28	−0.13	−0.21	−0.07	+0.02	−0.03
[Na/H]	0.27	0.09	0.36	−0.32	−0.31	+0.40	+0.42	...	...	...	...	...
[Mg/H]	0.19	0.19	0.26	−0.27	−0.45	+0.25	+0.24	...	...	...	...	...
[Si/H]	0.17	0.18	0.22	−0.29	−0.21	+0.27	+0.32	...	...	...	...	...
[Ca/H]	0.18	0.05	0.32	−0.21	−0.30	+0.41	+0.22	−0.18	−0.15	−0.01	−0.01	+0.04
[Si/H]	0.21	0.18	...	−0.38	−0.51	+0.03	...	...	...	...	...	...

KEY.—BL = this work; TLB = Tomkin, Lambert, and Balachandran 1985; S = Spite 1968.

peratures used here are systematically lower and the gravities somewhat different than those used by Boesgaard (1976). For these 11 Be-normal stars the mean Be/H = 1.26×10^{-11} with the Chmielewski, Muller, and Brault (1975) solar Be/H = 1.4×10^{-11}. (We exclude 110 Her from this mean because it appears to be deficient, although not totally depleted, in both Li and Be.)

The final abundance results are presented in Table 5, listed separately for the Be-deficient stars and the Be-normal stars in order of decreasing temperature. While most abundances are given as the logarithmic ratio [X/H], the Li abundances are given as log N(Li) where log N(H) = 12.00, because of the well-known solar Li depletion. Solar Li/H is 10^{-11} according to Muller, Peytremann, and De La Reza (1975).

IV. RESULTS AND DISCUSSION

a) Metals

The abundance of Fe was determined in this sample of stars in order to provide a basis of comparison both with other Fe/H determinations for these stars and with the elements that may be found to be enhanced or depleted in Fm stars. The derived [Fe/H] values are given in Table 5 and are shown against temperature in Figure 5; there is no apparent distinction in the distribution of the Be-deficient stars versus the normal stars. The other abundances are plotted against temperature in Figures 6*a*–6*e*. These figures show that their is no difference in the distribution of element abundances between the Be-deficient stars and the Be-normal stars. The Be-deficient stars are not, as a group, systematically enhanced in Na and Si, or systematically deficient in Mg, Ca, and Sc. There is no discernible difference between Be-normal and Be-deficient stars, as might be predicted the latter represented an extension of the Am and Fm star sequences with abundance anomalies due to diffusion.

The six Be-deficient stars divide themselves into three pairs according to their abundances. (1) The pair θ Cyg and ι Vir both have normal, solar abundances although their temperatures are different by more than 500 K. (2) The pair σ Boo and μ^1 Cyg have abundances that are ~2 times less than solar and have a temperature difference of more than 500 K. (3) The pair τ Boo and HR 7955 are both slightly metal rich (a factor of ~2) with a 300 K temperature difference. (See the upper part of Table 4.) Another way to state the comparison is to note that the three Be-deficient stars with $T_e \approx 6100$ K, ι Vir, μ^1 Cyg, and HR 7955, show normal, slightly deficient, and slightly enriched metal contents, respectively. These comparisons show that the Be-deficient stars are not a homogeneous group with respect to chemical composition.

Furthermore, among the Be-normal stars, virtual twins in temperature, gravity, and composition can be identified for the

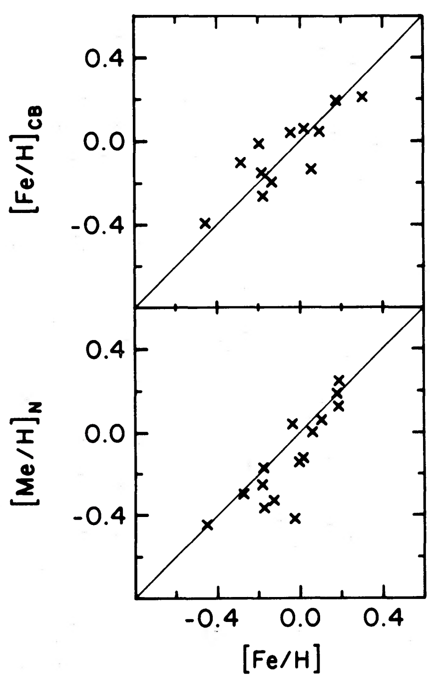

FIG. 4.—Our [Fe/H] abundances compared with those of the Cayrel and Bentolila (1983) catalog (*upper*) and those of Nissen (1981) from photometry (*lower*). The discrepant point at (−0.03, −0.41) in the lower diagram is ι Vir.

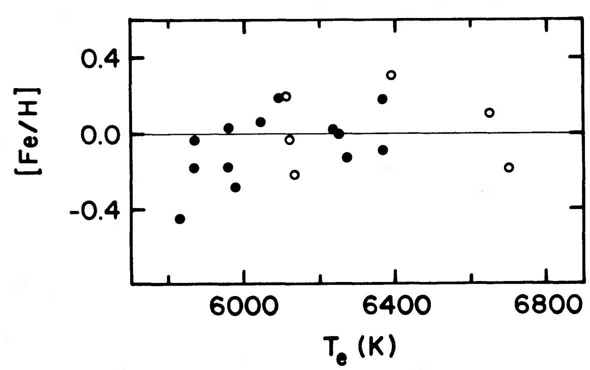

FIG. 5.—[Fe/H] abundances plotted against stellar effective temperature. The Be-deficient stars are the open circles and the Be-normal stars are the filled circles. The cool, metal-deficient star in the lower left is χ Her.

TABLE 5

ABUNDANCE RESULTS

Star	T_e	log N(Li)	[Be/H]	[Na/H]	[Mg/H]	[Si/H]	[Ca/H]	[Sc/H]	[Fe/H]
				Be-deficient Stars					
σ Boo	6700	≤1.51	≤ −0.77	−0.32	−0.27	−0.29	−0.21	−0.38	−0.18
θ Cyg	6650	≤1.0	≤ −1.05	−0.01	−0.02	+0.01	+0.12	+0.07	+0.10
τ Boo	6390	≤0.6	≤ −1.10	+0.40	+0.25	+0.27	+0.41	+0.03	+0.30
μ^1 Cyg	6130	≤0.3	≤ −1.08	−0.24	−0.23	−0.14	−0.19	−0.03	−0.22
ι Vir	6120	≤0.72	≤ −1.85	+0.02	0.00	−0.03	+0.01	+0.21	−0.03
HR 7955	6110	≤0.4	≤ −1.35	+0.37	+0.30	+0.17	+0.30	+0.12	+0.19
				Be-normal Stars					
τ PsA	6370	2.27	−0.10	...	...	...	+0.21	...	+0.18
ϵ Lib	6370	2.88	...	...	...	...	−0.05	...	−0.09
γ Ser	6270	2.04	−0.31	...	...	...	−0.18	...	−0.13
110 Her[a]......	6250	1.15	−0.82	0.00	+0.03	+0.04	0.00	...	−0.01
17 Cyg	6240	2.16	−0.15	−0.13	0.00	−0.02	+0.03	+0.02	+0.01
β Vir	6100	2.04	−0.20	+0.27	+0.19	+0.17	+0.18	+0.21	+0.18
υ And	6050	2.15	−0.25	...	+0.09	+0.07	+0.01	...	+0.06
ξ Peg	5980	2.00	−0.01	−0.25	−0.27	−0.25	−0.25	−0.13	−0.28
β Com	5960	2.44	+0.25	...	...	...	−0.07	...	+0.02
ι Psc	5960	2.01	−0.21	−0.19	−0.14	−0.10	−0.14	−0.26	−0.18
β CVn	5870	1.56	+0.25	...	...	...	−0.31	...	−0.19
λ Ser	5870	1.78	−0.12	...	...	...	+0.03	...	−0.04
χ Her	5830	2.34	−0.05	...	...	...	−0.52	...	−0.45

[a] This star is somewhat deficient in both Li and Be, but is not as depleted as the Be-deficient stars listed above.

Be-deficient stars. Some examples are given in Table 6. In the case of β Vir versus HR 7955 which are different in Be by a factor of at least 15 and in Li by at least 40, the other elements are similar to 0.07 dex or an average of a factor of 1.2. These comparisons and those shown in Figure 6 show that the Be-deficient stars are not different from dwarfs with normal light-element contents.

b) *Lithium*

All 19 stars were observed in the region of the Li I doublet λ6707 at very high S/N ratios (600–800; see Table 1) to determine tighter limits on the Li depletion discussed by Boesgaard (1976) in the Be-deficient stars. Those six stars had Li equivalent widths of less than 4 mÅ, while the 13 normal stars (with the exception of 110 Her) showed measurable Li lines from 15 to 71 mÅ. The abundances were calculated for the blend Li doublet and include the effect of the very weak line of Fe I at 6707.441 that appears in the solar spectrum. The values found for log N(Li) (= log Li/H + 12.00) appear in Table 5. Figure 7 shows those log N(Li) values plotted against temperature, and here a clear dichotomy appears between the Be-deficient and the normal stars. In this sample most of the normal stars are depleted in Li by factors of 4–20 relative to the F field star maximum of Boesgaard and Tripicco (1986*a*), but the Be-deficient stars have upper limits on Li that show depletions of more than 30 to more than 400. (Note the light line in Fig. 7 that corresponds to the abundances that stars of various temperatures would have with Li equivalent widths of 5 mÅ; this shows the temperature sensitivity of Li detectability.) Clearly the Be-deficient stars are severely deficient in Li.

Figure 8 shows the newly calculated Be abundances and the newly observed Li abundances. The accuracy of the latter is greater by a factor of ~2 because of the difference in the detector (photographic plate vs. Reticon) and signal to noise (~30 vs. ~700). The Be-normal stars can be depleted in Li, the more susceptible of the two elements to (p, α) reactions. The reverse is not found: there are no stars in the lower right with depleted Be and normal Li. The stars in the lower left are potentially *devoid* of both Li and Be. One star, 110 Her, is possibly a transition case; it appears to show very weak, but not absent, spectral features of both elements. Its mean metal content is [Z/H] = +0.01. It may provide some interesting clues to the process of depletion of Li and Be in main-sequence stars.

c) *Activity and Rotation*

Values of the projected rotation, $v \sin i$, primarily from Soderblom (1982), are given in Table 1. For the Be-deficient stars the mean is 9.3 ± 6.1 and for the eight Be-normal stars in

TABLE 6

BE-DEFICIENT AND NORMAL PAIRS

Star	T	[Be/H]	[Fe/H]	[Na/H]	[Mg/H]	[Si/H]	[Ca/H]	[Sc/H]
β Vir	6100	−0.20	+0.18	+0.27	+0.19	+0.17	+0.18	+0.21
HR 7955	6110	≤ −1.35	+0.19	+0.37	+0.30	+0.17	+0.30	+0.12
17 Cyg	6240	−0.15	+0.01	−0.13	0.00	−0.02	+0.03	+0.02
110 Her	6250	−0.82	−0.01	0.00	+0.03	+0.04	0.00	...
τ PsA	6370	−0.10	+0.18	...	...	...	+0.21	...
τ Boo	6390	≤ −1.10	+0.30	+0.40	+0.25	+0.27	+0.41	+0.03
ξ Peg	5980	−0.01	−0.28	−0.25	−0.27	−0.25	−0.25	−0.13
μ^1 Cyg	6130	≤ −1.08	−0.22	−0.24	−0.23	−0.14	−0.19	−0.03

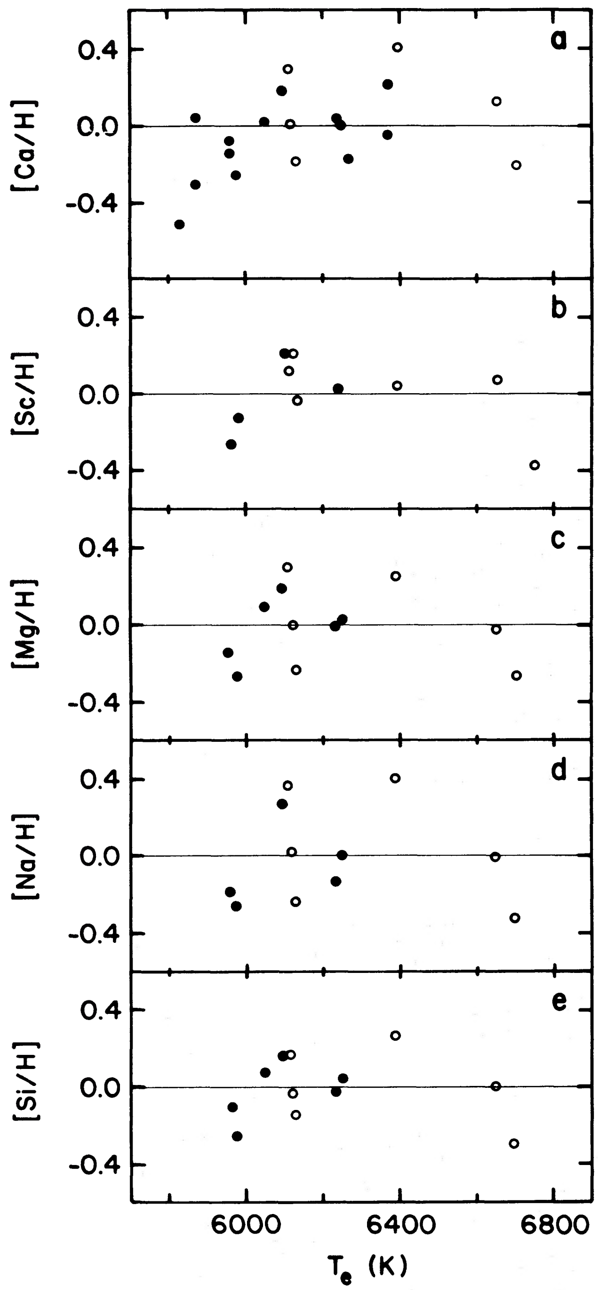

FIG. 6.—Abundances of the other elements determined in this study against temperature. The open circles are the Be-deficient stars, while the filled circles are the Be-normal stars. Deficiencies of Ca, Sc, and Mg and excesses of Na and Si might have been expected in the Be-deficient stars by analogy with the Am and Fm stars. There appear to be no differences in the distribution in the elemental abundances in the Be-deficient stars compared with the normal stars.

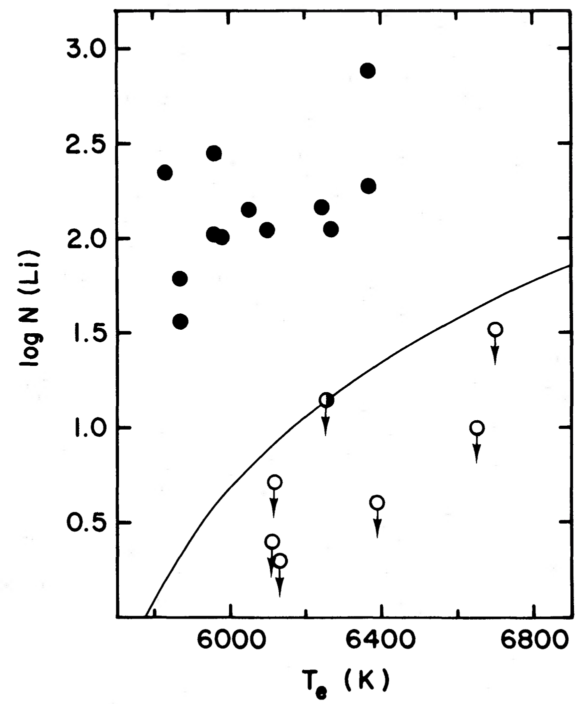

FIG. 7.—Lithium abundances as log N(Li), where log N(H) = 12.00, in this sample of Be-deficient stars (*open circles*) and normal stars (*filled circles*). The half-filled circle is 110 Her which could be a transition case, depleted in, but not devoid of, Li and Be. The light line shows the locus of Li abundances corresponding to a line strength of 5 mÅ in a star with solar Fe/H. All of the Be-deficient stars show marked deficiencies of Li, and only upper limit values were measurable.

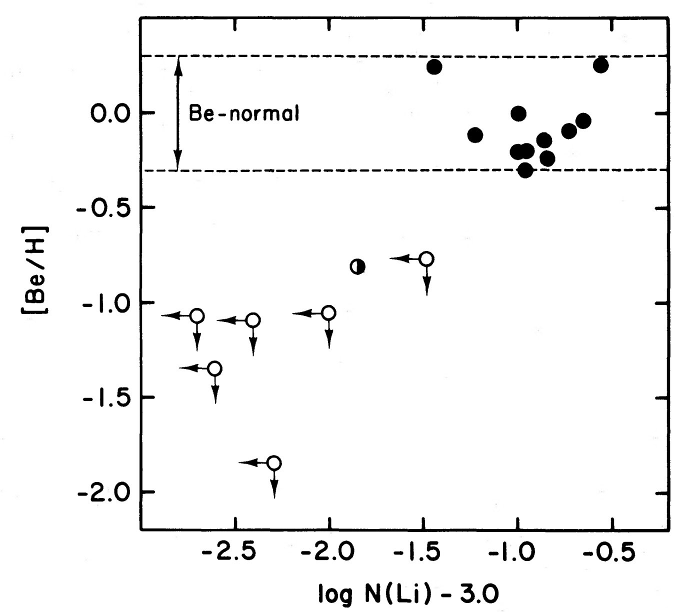

FIG. 8.—Be abundances compared to Li abundances. The Li abundances are shown as log N(Li)–3.00 to indicate the depletion level from the Population I star maxima found in F dwarfs, meteorites, T Tau stars, etc. Stars with normal (solar) Be are to be found in the region of [Be/H] = +0.3 to −0.3, which represents the approximate accuracy of the Be abundances determination. These stars show the well-documented range of Li abundances found in F and G dwarfs. Due to the fact that Li is destroyed in stellar interiors more readily than Be, there are no stars in the lower right part of the diagram with high Li and low Be. True Li and Be values in those stars with only upper limit measurements may be far lower than the one–two orders of magnitude depletion shown here.

this sample for which Soderblom measured it is 4.8 ± 2.9. Even though the error bars overlap, we point out that none of the latter eight stars has a projected rotation as high as the mean for the Be-deficient stars. (Those eight stars are all somewhat cooler than the six Be-deficient stars and that might be responsible for the lower $v \sin i$ values.) It is possible then that the light element deficiencies are associated with higher rotation, which could have affected the depth of the convective motions during pre–main-sequence or main-sequence evolution. The possibility of such a connection between rotation and light element depletion was put forward by Boesgaard and Tripicco (1986*b*) in the context of the large Li depletions that they discovered in the Hyades F stars in the narrow temperature range 6500–6800 K. According to Thévenin, Vauclair, and Vauclair (1986), Li and Be-deficient F field dwarfs with $T_{\rm eff} < 6500$ K are deficient through nuclear destruction and are more rapid rotators than those with normal light element contents, while those hotter than $T_{\rm eff} = 6500$ K are deficient through diffusion processes and are slower rotators.

A companion study on activity in F stars with known light element deficiencies has been completed recently by Wolff, Boesgaard, and Simon (1986). They find a possible connection between the Be abundance and the activity level in the chromosphere, as measured by the He I λ5876 line and by transition region feature, C IV λ1549 line. For stars cooler than 6600 K, two-thirds of those which are severely Li-deficient or Be-deficient (or both) are active, whereas only two of 11 Be-normal stars are active. While G dwarfs show a Li-activity-rotation connection, high activity and high rotation may be connected to *low* values of Li and Be in middle and late F dwarfs.

V. CONCLUSIONS

For a number of Be-deficient stars and a comparison group of normal stars we have examined the abundances of several elements that have been found to show anomalies in Am and Fm stars. Even subtle differences should be detectable since we have high-resolution and high S/N data, and we have taken care to reduce all systematic errors and to treat all the data in a consistent fashion. We found no difference in the array of Fe/H abundances between the normal stars and the Be-deficient stars (and both groups of stars are distributed normally about the solar abundance). Excesses were expected in Na/H and Si/H (or Na/Fe and Si/Fe) in the Be-deficient stars but not found. Similarly, the expected deficiencies in Mg/H, Ca/H, and Sc/H (or Mg/Fe, Ca/Fe, Sc/Fe) were not revealed in the group of Be-deficient stars. In fact, we can find "twins" at the same temperature for the Be-deficient stars (except for the high temperature one, σ Boo) for which the pattern of abundances is virtually identical (for example, see Table 6)—except, of course, for Be and Li. It is clear that there is no pattern of abundances that distinguishes the Be-deficient stars as a group from the Be-normal stars. Therefore it seems unlikely that diffusion is responsible for the Be and Li anomalies. We return to the depletion of Li and Be through nuclear destruction rather than through element transport by gravitational settling, i.e., microscopic diffusion.

Mechanisms of light element transport to temperatures high enough to destroy Li and Be by nuclear reactions include convective overshoot, meridional circulation (Eddington-Sweet-Vogt circulation), turbulence (for example, from differential rotation), magnetically induced mixing, etc. Abundances of other elements would not be disturbed by these transport mechanisms because they are not susceptible to nuclear reactions at 10^6 K, or even 10^8 K in most cases.

One recent interesting suggestion is that of Parker (1984), who has discussed forced convection which occurs in the thermal shadows of magnetic fields at the base of the convection zone and which could result in Li transport and depletion in the Sun. He estimates that magnetic inhomogeneities of 4×10^5 Gauss and a vertical circulation of 10^{-7} cm s^{-1} over a vertical distance of 3×10^4 km would give a characteristic mixing time of 10^9 yr. He uses the nondepletion of solar Be to provide an upper limit on the magnetic inhomogeneity. For the severely Li- and Be-depleted F dwarfs, Parker's mechanism could be operating in addition to convective overshoot. Turbulence induced by internal gravity waves, as discussed by Press (1981) for the Sun, is another exotic possibility for the Be-deficient F stars. Other mixing schemes resulting from hydrodynamical instabilities which break down into turbulence have been discussed by Zahn (1983) and by Baglin, Morel, and Schatzman (1985). The observational data presented here on the Li and Be depletion amounts should help constrain these theories.

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