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BERYLLIUM IN MAIN-SEQUENCE STARS

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ABSTRACT

Beryllium abundances are determined in 38 stars of spectral types F and G, including the Sun. New observations in the ultraviolet at 6.7 Å mm^{-1} of 15 stars have been made with the coudé spectrograph of the 224 cm telescope at Mauna Kea. These data supplement values found in the literature. A model atmosphere analysis with Carbon and Gingerich (1969) models and the equivalent widths of one of the Be II resonance lines, 3131.064 Å, gives the Be abundance for each of the 38 stars. Effective temperatures were found from Hβ photometry; values of log g were estimated from the position of the star in the $(c_1, b - y)$ diagram.

The derived Be abundances show no dependence on stellar surface temperature or $B - V$, and the mean abundance is Be/H $= 1.31 \times 10^{-11} \pm 0.36 \times 10^{-11}$. The solar system abundances are similar. This value thus represents the cosmic or universal abundance, and the origin of Be can be explained by galactic cosmic-ray spallation reactions in the interstellar gas.

One-third of the stars in the temperature range 6600–7400 K have only upper-limit Be abundances and are Be-deficient. These stars are also Li-deficient. A discussion of the light-element depletion in terms of diffusion (including turbulent diffusion) and convective overshoot is given. Diffusion and rotational braking appear to offer the more promising explanation of the two.

Subject headings: nuclear reactions — stars: abundances — stars: atmospheres

I. INTRODUCTION

The light elements Li, Be, and B are readily destroyed by (p, α) reactions in stellar interiors where the temperatures are in excess of a few million degrees Kelvin. Bodenheimer (1966) has made calculations of the amount of pre–main-sequence destruction of Be by (p, α) reactions and finds that stars reaching the main sequence at spectral types earlier than K2 would not destroy any of their initial Be. A K2 dwarf would have destroyed 2 percent of its Be; a K5, 15 percent during pre–main-sequence evolution.

The surface Be would not be depleted during main-sequence evolution, since the temperature at the base of the convection zone is not high enough. Thus the observed Be abundances for main-sequence stars of type G and earlier should reflect the initial or cosmic Be abundance. However, as was pointed out by Conti (1968) and by Boesgaard (1968), observational results seemed to show that the abundance of Be decreased in main-sequence stars with earlier spectral type or increasing surface temperature. This conclusion was based on observations and analyses by Merchant (1966), Conti and Danziger (1966), and Conti (1968).

New observations of Be for 15 stars supplement the previous data, and an analysis which makes use of Carbon and Gingerich (1969) model atmospheres gives new Be abundances. The new results show that there is no dependence of Be abundance on temperature and that the mean Be abundance in F and G dwarfs is Be/H $= 1.3 \times 10^{-11}$.

II. OBSERVATIONS

New spectra have been obtained of 15 stars at 6.7 Å mm^{-1} with the 48 inch (122 cm) focal-length coudé camera and a 600 line mm^{-1} grating blazed in the second-order blue at λ4000 at the 88 inch (224 cm) telescope at the Mauna Kea Observatory. The spectra were taken on baked IIa-O plates behind a Corning 9863 filter and were widened to 0.55–0.70 mm on the plate. For three stars (τ^6 Eri, 110 Her, and ξ Peg), more than one spectrogram was obtained. The stars selected are all slow rotators ($\leqslant 20$ km s^{-1}), since the spectral region of the Be II resonance lines (λ3130.4 and λ3131.1) is crowded, and rotational broadening makes it impossible to measure the strength of the lines. Even for sharp-lined stars, the stronger line at λ3130.4 is too badly blended with V II at λ3130.2 to be measured. The spectral resolution is about 0.1 Å, and the smallest measurable equivalent width for the line at 3131 Å is about 10 mÅ. Table 1 lists the stars observed at Mauna Kea, their spectral types, rotational velocities, and the equivalent width at the Be II line at λ3131.

In addition I have reanalyzed the Be abundance in all genuine main-sequence F and G stars which have been observed previously at high dispersion at λ3131. To determine whether the stars are main-sequence stars, I have plotted their positions in $(c_1, b - y)$ diagram. This is shown in Figure 1. The main sequence given by Crawford (1975) is shown (log $g = 4.4$), as are lines given by Bell (1971) corresponding to log $g = 4.0$ and 3.6. Bell also plots the evolutionary tracks of Iben

TABLE 1

New Beryllium Observations

HR	Star	Sp	$v \sin i$ (km s^{-1})	W(Be) (Å)
818......	τ^1 Eri	F6 V	22	0.070
1173......	τ^6 Eri	F3 V	6	0.055
1543......	π^3 Ori	F6 V	16	0.070
3775......	θ UMa	F6 IV	13	0.130
4054......	40 Leo	F6 IV	16	$\leq$0.012
4540......	β Vir	F8 V	$\leq$6	0.079
5338......	ι Vir	F7 IV	15	$\leq$0.005
7061......	110 Her	F6 V	14	0.034
7534......	17 Cyg	F5 V	9	0.082
7955......	...	F8 V	0	$\leq$0.014
8309......	μ^1 Cyg	F6 V	18	$\leq$0.015
8430......	ι Peg	F5 V	7	0.074
8447......	τ PsA	F5 V	...	0.087
8665......	ξ Peg	F7 V	7	0.090
8969......	ι Psc	F7 V	6	0.092

(1967) for stars of mass 1.0, 1.25, and 1.5 $M_{\odot}$, and points out that there is little variation in $\log g$ during much of the evolution. The stars with $\log g$ values near 4.4 to 4.0 will be considered to be main-sequence stars.

III. ANALYSIS

An LTE abundance analysis was done with a program and opacity code developed by Drs. F. Praderie and M. Spite and adapted by Dr. C. Pilachowski (1975, 1977). Standard model atmospheres of Carbon and Gingerich (1969) were used. A set of atmospheres was interpolated from them to correspond to $\log g = 4.4$ for $T_{\rm eff} = 8000, 7500, 7000, 6500, 6000$, and 5780. The abundance program requires an atmosphere specified by $T_{\rm eff}$ and $\log g$, a microturbulent velocity, and various atomic parameters for the lines to be considered. Herbig (1965) has found little variation in the velocity parameter for F and early G dwarfs, so the value he used for the microturbulent velocity, ξ, of 2.3 km s^{-1}, has been used here. The results are not sensitive to the value of ξ selected; in this temperature range the thermal velocity of Be atoms is about 3.5 km s^{-1}, and this component dominates. The value of $\log gf = -0.46$ for the line at 3131 Å from Wiese, Smith, and Glennon (1966) was used.

The abundance program prints the coordinates for the line profile and gives a list of equivalent widths corresponding to various abundance ratios of the element to hydrogen. Figure 2 shows an example of a straightforward curve of growth where the equivalent width of the Be II line at λ3131 is plotted against the abundance ratio Be/H for several temperatures. Interpolation between these curves for the appropriate temperature was done to determine the Be abundance for those stars with $\log g \approx 4.4$. Notice that the curves for 5780, 6000, and 6500 are very close together. In fact, the curve for 5780 is in between the two hotter ones. This is due to the competition between the degree of ionization and the continuous opacity. In this temperature range, even though the ratio of Be II/Be I increases with temperature, we see through less stellar material, since the opacity increases, and thus see fewer Be atoms. The practical result is that the Be equivalent widths and abundances are not very sensitive to temperature between 5700 and 6600 K. There is little saturation for equivalent widths less than about 80 mÅ; above this the shoulder of the curve of growth begins to become evident.

Figure 3 shows the sensitivity to $\log g$. The abundance curves are plotted for two different gravities at two representative temperatures. In the *worst* case, an incorrect gravity can give an abundance error of a factor of 2.

The effective temperatures were determined from values given in the literature for Hβ photometry and the calibration of Hβ, $T_{\rm eff}$ of Bell (1971). The appropriate value of $\log g$ for each star was judged from the position of the star in Figure 1 relative to the lines representing $\log g = 4.4$, 4.0, and 3.6.

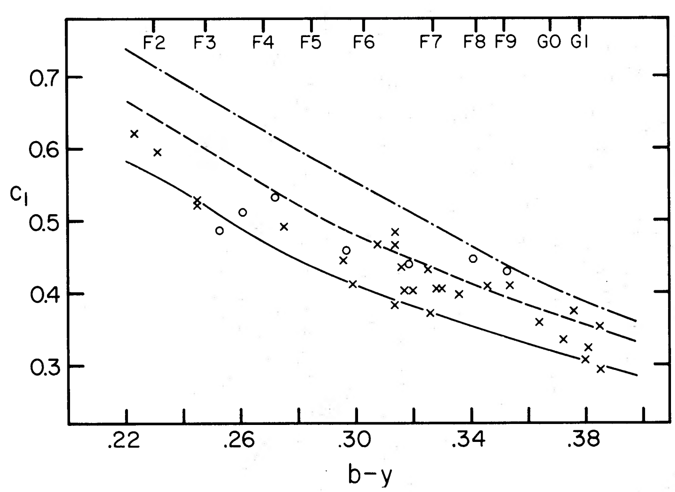

Fig. 1.—The Strömgren (c_1, $b-y$) diagram corresponding to luminosity and temperature shows the positions of the stars observed for Be abundances. *Solid line*, zero-age main sequence or $\log g = 4.4$ (Crawford 1975); *dashed line*, $\log g = 4.0$; *dashed-dotted line*, $\log g = 3.6$ (Bell 1971). The open circles show the positions of the Be-deficient stars.

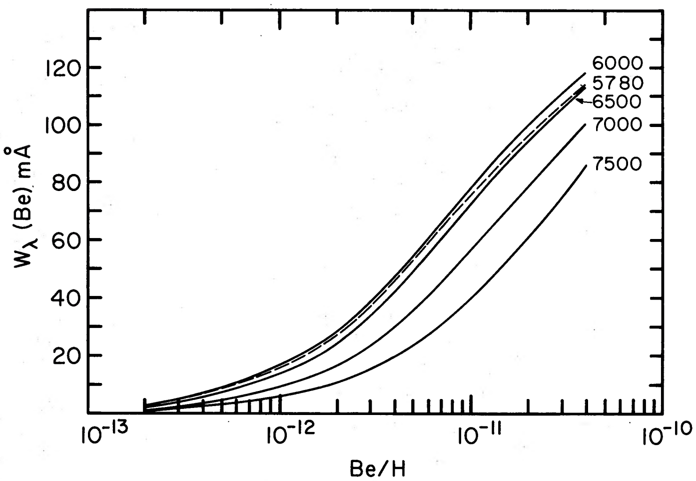

FIG. 2.—Simplified curves of growth from the model atmosphere analysis for Be II λ3131. The dashed line corresponds to the Sun. The close correspondence of the curves for 5780, 6000, and 6500 K is discussed in the text.

IV. ABUNDANCES

Table 2 lists all the F and G stars of luminosity classes V and IV-V for which Be observations have been made. The *uvby* indices $b - y$ and c_1 are given, and the estimate of log g if it differs from ~ 4.4. The Hβ photometric index and resulting T_{eff} are presented in the next two columns. The value of the Be II λ3131 equivalent width is a weighted average of all measurements where there is more than one observation. The last two columns give the derived value of Be/H and the logarithmic ratio relative to the Sun, [Be].

This method of analysis and the Be II λ3131 equivalent width in the Sun measured by Greenstein and Tandberg-Hanssen (1954), $W = 79$ mÅ, give a solar abundance of Be/H $= 1.13 \times 10^{-11}$. This is in good agreement with the value found by Ross and Aller (1974) of 1.2 (± 0.2) $\times 10^{-11}$ from the method of spectrum synthesis. More recently, Chmielewski, Müller, and Brault (1975) have made high-resolution, center-to-limb observations of the Sun and have done a non-LTE analysis. They find a solar Be abundance of $1.4 \times 10^{-11} \pm 0.6 \times 10^{-11}$. This good agreement provides confidence that the LTE approach used here produces reliable results. For consistency, the value of 1.13×10^{-11} was used to determine the numbers in the last column, [Be].

Figure 4 shows the Be abundance for each star plotted against its effective temperature. It is clear that, for the stars with known Be abundances (not upper limits), there is no discernible dependence of Be abundance on temperature. This results partly from the fact that a consistent method of analysis was applied to all the observations. Also, temperatures used here from Hβ photometry are typically 200 K hotter than those derived from $B - V$, and this tends to increase the Be abundance in the hotter stars. The Be content of some of the cooler stars was reduced some-

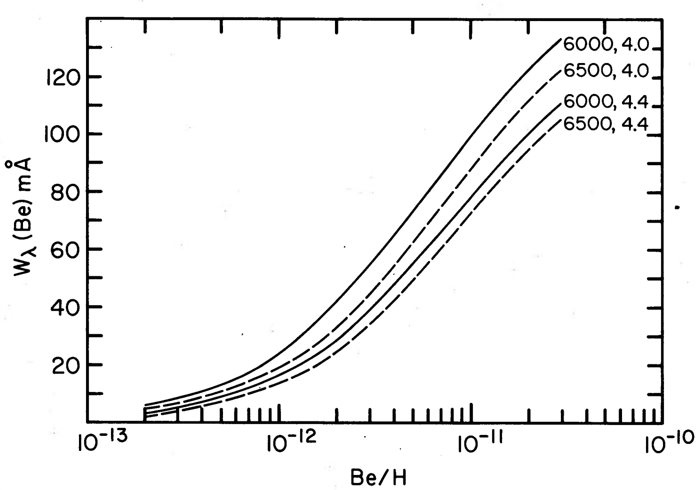

FIG. 3.—Simplified curves of growth showing the gravity dependence. The solid lines are for $T_{\text{eff}} = 6000$ and log $g = 4.0$ and 4.4. The dashed curves show $T_{\text{eff}} = 6500$ K and log $g = 4.0$ and 4.4.

TABLE 2

STELLAR PARAMETERS AND BERYLLIUM ABUNDANCES

HR	Star	Sp.	$b - y$*	c_1*	log g†	β*	$T_{\rm eff}$ (K)	W (Be)(mÅ)	Be/H	[Be]
458.......	ϵ And	F8 V	0.346	0.410	4.0	2.629	6420	80	0.8×10^{-11}	−0.15
646.......	η Ari	F8 V	0.308	0.466	4.0	2.647	6610	73	0.7×10^{-11}	−0.21
799.......	θ Per	F7 V	0.326	0.373	...	2.625	6370	100:	2.3×10^{-11}	+0.31
818.......	τ^1 Eri	F6 V	0.328	0.406	...	2.646	6610	70	1.0×10^{-11}	−0.05
937.......	ι Per	G0 V	0.376	0.376	3.8	2.605	6090	107	1.05×10^{-11}	−0.03
1101.......	10 Tau	F8 V	0.364	0.361	(4.2)	2.617	6270	97	1.41×10^{-11}	+0.10
1173.......	τ^6 Eri	F3 V	0.275	0.492	...	2.668	6840	55	0.8×10^{-11}	−0.15
1292.......	45 Tau	F2 V	0.231	0.592	...	2.694	7070	59	1.1×10^{-11}	−0.01
1543.......	π^3 Ori	F6 V	0.299	0.413	...	2.654	6690	67	1.0×10^{-11}	−0.05
1983.......	γ Lep A	F6 V	0.317	0.404	...	2.630	6430	70:	0.9×10^{-11}	−0.10
2047.......	χ^1 Ori	G0 V	0.380	0.307	...	2.599	5980	68	0.74×10^{-11}	−0.18
2085.......	η Lep	F0 V	0.223	0.621	...	2.716	7280	50:	1.1×10^{-11}	−0.01
2943.......	α CMi	F5 IV–V	0.272	0.532	4.0	2.674	6880	≤ 5	$\leq 0.25 \times 10^{-12}$	≤ −1.66
3262.......	χ Cnc	F6 V	0.314	0.384	...	2.636	6500	89	1.7×10^{-11}	+0.18
3775.......	θ UMa	F6 IV	0.314	0.463	4.0	2.646	6610	105	1.8×10^{-11}	+0.20
4054.......	40 Leo	F6 IV	0.297	0.459	4.2	2.654	6690	≤ 15	$\leq 0.8 \times 10^{-12}$	≤1.15
4374.......	ξ UMa A	G0 V	...	...	...	...	5900	100	2.0×10^{-11}	+0.25
4540.......	β Vir	F8 V	0.354	0.412	3.8	2.628	6410	79	0.61×10^{-11}	−0.27
4785.......	β CVn	G0 V	0.385	0.296	...	2.600	6000	101	2.1×10^{-11}	+0.27
4825.......	γ Vir N	F0 V	0.245	0.528	...	2.694	7060	47	0.8×10^{-11}	−0.15
4826.......	γ Vir S	F0 V	0.245	0.528	...	2.694	7060	40:	0.6×10^{-11}	−0.27
4983.......	β Com	G0 V	0.372	0.336	...	2.609	6150	100	2.1×10^{-11}	+0.27
5185.......	τ Boo	F7 V	0.319	0.439	4.1	2.656	6680	≤ 22	$\leq 1.5 \times 10^{-12}$	≤ −0.88
5338.......	ι Vir	F7 IV	0.341	0.448	3.7	2.622	6340	≤ 5	$\leq 0.13 \times 10^{-12}$	≤ −1.94
5447.......	σ Boo	F2 V	0.253	0.488	...	2.681	6950	≤ 20	$\leq 0.22 \times 10^{-11}$	≤ −0.71
5868.......	λ Ser	G0 V	0.385	0.354	4.0	2.608	6140	93	1.0×10^{-11}	−0.05
5914.......	χ Her	F9 V	0.381	0.323	...	2.601	6010	100	2.0×10^{-11}	+0.25
5933.......	γ Ser	F6 V	0.320	0.403	...	2.633	6460	70:	0.9×10^{-11}	−0.10
7061.......	110 Her	F6 V	0.314	0.484	3.8	2.648	6630	35	0.19×10^{-11}	−0.77
7469.......	θ Cyg	F4 V	0.261	0.506	...	2.689	7020	≤ 12	$\leq 0.14 \times 10^{-11}$	≤ −0.91
7534.......	17 Cyg	F5 V	0.316	0.435	4.1	2.646	6610	82	1.1×10^{-12}	−0.01
7955.......	...	F8 IV–V	0.353	0.431	3.6	2.635	6480	≤ 14	$\leq 0.42 \times 10^{-12}$	≤ −1.43
8309.......	μ^1 Cyg	F6 V	...	...	4.0:	...	6690	≤ 15	$\leq 1.0 \times 10^{-11}$	≤ −1.05
8430.......	ι Peg	F5 V	0.296	0.446	...	2.670	6850	80	1.7×10^{-11}	+0.18
8447.......	τ PsA	F5 V	0.326	0.435	4.0	2.659	6750	87	1.2×10^{-11}	+0.03
8665.......	ξ Peg	F7 V	0.330	0.407	...	2.626	6380	99	2.2×10^{-11}	+0.29
8969.......	ι Psc	F7 V	0.336	0.399	...	2.622	6330	84	1.3×10^{-11}	+0.06
....	Sun	G2 V	...	...	...	...	5780	79	1.13×10^{-11}	0.00

* Photometric indices $b - y$, c_1, and β are taken from the various references given in Crawford 1975.

† If different from 4.4.

what by the effect of the increased continuous opacity. The average Be content for the 27 stars with log $g \geq 4.0$ is Be/H $= 1.31 \times 10^{-11} \pm 0.36 \times 10^{-11}$. The scatter seen in the upper part of Figure 4 can be attributed to errors in measuring the equivalent width and/or knowledge of $T_{\rm eff}$ and log g that specify the model atmosphere. Errors of 20 percent in the equivalent width can explain the observed scatter; values measured on different spectrograms show that such variations are possible, since the spectrum is crowded and the position of the continuum difficult to determine.

The mean Be/H abundance is the same as the solar value within the errors of the determinations. It is also the same as the meteoritic Be abundance (Buseck 1971). The observed upper limit for interstellar Be, $\leq 5 \times 10^{-11}$, is consistent with these values also (Boesgaard 1974). Table 3 summarizes these Be abundances in various sources. As pointed out by Chmielewski, Müller, and Brault (1975), there is no conflict between the solar and the meteoritic Be abundance within the errors. However, the fact that the majority of the F and G stars also have the same abundance is what shows that this is indeed the primordial or cosmic abundance. Thus the cosmic abundance is 1.3×10^{-11} for Be/H. Since we can account for the observed scatter observationally, it is difficult to know if any of the scatter represents intrinsic or cosmic variation in initial Be content.

V. SYNTHESIS OF THE LIGHT ELEMENTS

Meneguzzi, Audouze, and Reeves (1971) have proposed a model to account for the origin of the light elements by spallation reactions caused by bombarding

TABLE 3

BERYLLIUM ABUNDANCES

Object	Be/H	Reference
F and G Stars.....	1.3×10^{-11}	This paper
Sun..............	1.2×10^{-11}	Ross and Aller 1974
Sun..............	1.4×10^{-11}	Chmielewski *et al.* 1976
Meteorites........	2×10^{-11}	Buseck 1971
Interstellar gas.....	$\leq 5 \times 10^{-11}$	Boesgaard 1974

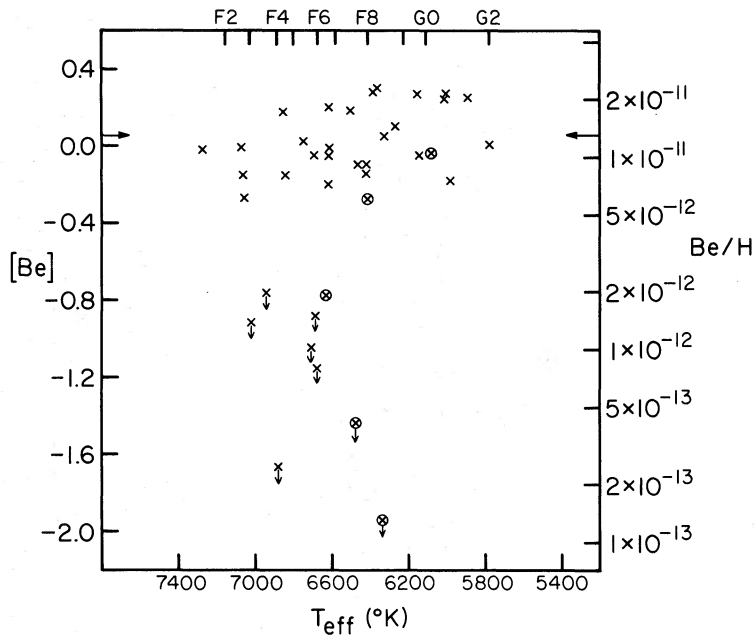

FIG. 4.—Beryllium abundances as a function of temperature. *Crosses*, dwarf stars; *circled crosses*, subgiants; *arrows*, upper limits. The arrows on the *y*-axes show the position of the mean Be abundance, 1.3×10^{-11}.

elements like C, N, and O with galactic cosmic rays (hereafter GCR). The energy spectral shape in the form $W^{-2.6}$ is found to give consistency with observations of the GCR and other properties of the interstellar gas.

According to Reeves (1974), the rate of formation of ^{9}Be can be written

$$\frac{d(^9\mathrm{Be/H})}{dt} = \phi_{30} \cdot \sigma \cdot \left(\frac{\mathrm{CNO}}{\mathrm{H}}\right)$$

where ϕ_{30} is the flux of protons and α-particles with the requisite energy (> 30 MeV) to break up C, N, and O nuclei, σ is the average cross section of C, N, O plus p, α to yield ^{9}Be, and CNO/H is the abundance ratio of the targets to hydrogen in the interstellar gas. With Reeves's values, $\phi_{30} = 10\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, $\sigma = 5 \times 10^{-27}\,\mathrm{cm}^2$, and C + N + O/H = 10^{-3}, then $d(\mathrm{Be/H})/dt = 5 \times 10^{-29}\,\mathrm{s}^{-1}$. If the energy spectrum of GCR has been reasonably constant and if the average exposure time of the interstellar gas is 10^{10} years, then the predicted ratio Be/H = 1.5×10^{-11}. An additional contribution from decelerated cosmic-ray atoms of light elements is of less importance.

The predicted Be/H ratio is so consistent with the observed ratio for stars of 1.3×10^{-11} that other sources for the origin of Be are unnecessary and improbable. Whereas some Li may be produced in the big bang (e.g., Wagoner 1973) and/or by nuclear reactions (Cameron and Fowler 1971), and Li and probably B can be made by low-energy spallation in the interstellar gas and supernova envelopes (e.g., Meneguzzi and Reeves 1975; Audouze and Truran 1973), these sources do not produce ^{9}Be. Reeves (1974) accounts for much of the ^{7}Li by production in the big bang.

The B/H ratio has been determined in one normal star, Vega, to be $\sim 1 \times 10^{-10}$ by Boesgaard *et al.* (1974) from *Copernicus* observations of B II. (It should be mentioned that a determination of B in several normal stars with higher resolution data is at present under way.) Boesgaard *et al.* (1974) argue that Vega should contain the primordial or cosmic B abundance. That abundance is very similar to that predicted by the GCR theory, B/H = 3×10^{-10}. The predicted ratio of B/Be is about 20, which, considering the uncertainties in both theory and observation, is not much different from the observed cosmic B/cosmic Be.

This all appears to substantiate the GCR theory for the origin of Be and B. The Be content in a variety of astronomical objects is very consistent. However, there remains the problem of the stars in Table 2 and Figure 4 which appear to be Be-deficient.

VI. BERYLLIUM-DEFICIENT STARS

Several of the stars in Figure 4 are plotted with upper limits for the Be abundance. This group falls considerably below the others by about an order of magnitude, or more. Of the 33 stars with $\log g \geq 4.0$ (i.e., dwarf stars), six—or 18 percent—are deficient in Be (HR 7955 and ι Vir are considered subgiants). The Be-poor stars are plotted in Figure 1 as open circles; their positions in the H-R diagram give no clue to the cause of the lack of Be.

As many of the physical data as possible were assembled for these stars in order to establish a "personality profile" which could be useful in interpreting the Be deficiency. Table 4 gives several of these

TABLE 4

BERYLLIUM-DEFICIENT STARS

HR	Star	Sp.	Be/H	Mass* ($M_\odot$)	Age† (yrs.)	T_{eff} (K)	δm_1‡	[Fe/H]§	Duplicity	Li/H‖	$v \sin i$# (km s^{-1})
2943..........	α CMi	F5 IV–V	$\leq 2.5 \times 10^{-13}$	1.4	1×10^9	6880	+0.0035	+0.16	VB, SB	$< 6.4 \times 10^{-11}$	≤ 6
4054..........	40 Leo	F6 IV	$\leq 8.0 \times 10^{-13}$	1.2	2.5×10^9	6690	+0.005	+0.15	...	$< 1.7 \times 10^{-10}$	16
5185..........	τ Boo	F7 V	$\leq 1.5 \times 10^{-12}$	1.25	2×10^9	6680	−0.004	+0.24	VB	$\leq 1.3 \times 10^{-10}$	14
5338..........	ι Vir	F7 IV	$\leq 1.3 \times 10^{-13}$	1.25	2×10^9	6340	+0.032	−0.12	...	$< 7.9 \times 10^{-11}$	15
5447..........	σ Boo	F2 V	$\leq 2.2 \times 10^{-12}$	1.35	5×10^9	6950	+0.035	−0.15	...	$< 2.5 \times 10^{-10}$	≤ 10
7469..........	θ Cyg	F4 V	$\leq 1.4 \times 10^{-12}$	1.35	5×10^9	7020	+0.0125	+0.08	VB	$< 2 \times 10^{-10}$	7
7955..........	...	F8 IV–V	$\leq 4.2 \times 10^{-13}$	1.4	2.5×10^9	6480	−0.011	+0.32	...	$\leq 1.6 \times 10^{-10}$	0
8309..........	μ^1 Cyg	F6 V	$\leq 1.0 \times 10^{-12}$	1.35	3.2×10^9	6690	...	...	VB	$< 1.5 \times 10^{-10}$	18

* Kraft 1967; Meneguzzi *et al.* 1971; Cayrel de Strobel, private communication.

† Meneguzzi *et al.* 1971; Cayrel de Strobel, private communication.

‡ Crawford calibration 1975.

§ Cayrel and Cayrel de Strobel 1966.

‖ Meneguzzi *et al.* 1971; Danziger and Conti 1966; new Mauna Kea observations at 6.7 Å mm^{-1} give W(Li) $\leq$ 11 mÅ for HR 7955 and W(Li) $<$ 7 mÅ for μ^1 Cyg.

\# Uesugi and Fukuda 1970; Kraft 1967.

characteristics for the eight stars—including the subgiants ι Vir and HR 7955. There is nothing that sets this group apart from the others studied in their masses or ages. As a group they are neither metal-poor nor metal-rich as measured by (1) the Strömgren m_1 index and the value δm_1 derived from calibration with Hβ photometry (Crawford 1975); and (2) the calibration of δm_1 with Fe/H from the tabulation of Cayrel and Cayrel de Strobel (1966). At least half are double stars —mostly wide visual pairs—and that is the expected proportion for field stars. All are fairly slow rotators—less than 20 km s^{-1}—but all the stars observed are slow rotators; much greater rotational velocity would smear the blended spectral lines too much for the Be abundance to be determinable.

There are two discernible patterns for these stars, however. There appears to be a temperature dependence. The coolest dwarf star that is Be-deficient has $T_{\rm eff} = 6680$ K. In the temperature range 6600–7400 K there are 18 dwarfs, and six are Be-deficient—that is, one-third of the stars. On the other hand, none of the 15 dwarfs in the temperature range 5800–6600 K shows a Be deficiency.

The second pattern relates to the Li abundance. The Li abundance has been determined for all the stars in Table 2 except τ PsA. Of the dwarf stars (log $g \geq 4.0$), 12 of 32 have only upper-limit Li abundances, or 38 percent. (Of the total sample, there are 16 of 37 stars, or 43 percent.) However, 100 percent of the Be-deficient stars have only upper-limit Li abundances. Li depletion is a function of mass (and age), and the ability to detect a Li I line decreases with increasing temperature. To determine whether the upper limits are significant, each Li upper limit for the stars in Table 4 has been compared with the mean Li/H in its spectral range for the stars with detectable Li. Thus the mean for spectral types F4–F6, 5×10^{-10}, is compared to the value $\leq 6.4 \times 10^{-11}$ for α CMi (F5), etc. On the average, for the Be-deficient stars the upper limits on the Li abundances are about a factor of 4 times less than the mean Li abundances, whereas the standard deviation of the mean Li abundances is a factor of ± 1.8. So the upper limits for Li in the Be-deficient stars are significant to at least the 2 σ level.

The fact that the stars are deficient in both Li and Be suggests that the same mechanism is responsible for the deficiency of both elements. The situations for the two elements are not quite parallel, though: (1) As seen in Figure 4, the difference between the Be "haves" and "have-nots" is quite marked; there are no transition stars. However, the Li abundances show a continuum from the Li-rich stars ($\sim 10^{-9}$) to those with little or no Li ($\sim 10^{-11}$) (see, e.g., Fig. 1 of Herbig and Wolff 1966). (2) Beryllium is destroyed by (p, α) reactions at hotter temperatures than Li is: 3.2×10^6 K versus 2.4×10^6 K. (3) None of the dwarf stars cooler than 6600 K are Be-deficient, but no such temperature dependence is seen for Li.

Two of the most promising mechanisms for main-sequence light-element depletion are convective overshoot (Weymann and Sears 1965; Straus, Blake, and Schramm 1976) and diffusion below the bottom of the convection zone (Schatzman and Vauclair 1973). The depth of the convection zone and the amount of convective overshoot determine the minimum extent of the surface mixing from convection. Additional mixing may be achieved through diffusion and the effects of rotational braking.

Weymann and Sears (1965) have made calculations indicating the depth to which convective overshoot is energetically possible. The degree of overshoot that is actually achieved, however, is unknown. Using a dynamical approach to describe convection, Straus, Blake, and Schramm (1976) conclude that the amount of overshoot energetically allowed is sufficient to account for the observed Li depletion in low-mass main-sequence stars. They also find that the amount of overshoot that is permitted by the energetics increases with increasing stellar mass. This is necessary to explain the depletion in higher-mass stars and the gradual (rather than rapid) decrease of Li with stellar mass. They do not discuss whether convective overshoot might cause depletion of Be. Intuitively, it seems to require a delicate balance to achieve enough overshoot to burn Be in 30 percent of the stars hotter than 6600 K and not in any of the others and simultaneously deplete Li readily in the cooler stars. But perhaps this fraction of the hotter stars possess the "giant" convective cells which Straus, Blake, and Schramm expect would show considerable overshoot, while more pedestrian conditions of overshoot exist in the lower-mass stars. The prevalence of giant cells may result from conditions relating to hydromagnetics, meridional circulation, macroturbulence, etc.

Schatzman and Vauclair (1973) and Vauclair (1972, 1973) have discussed the effects of both microscopic and turbulent diffusion on the abundances of Li and Be in F and G stars. Microscopic diffusion is a separation of elements due to effects of gravity, a temperature gradient, and radiation pressure; it takes place in stable, nonrotating atmospheres. Schatzman and Vauclair find that, with microscopic diffusion, the Li abundances will decrease with time and with spectral type from F to G. They also suggest that, if there is little or no turbulent diffusion, the Be abundance will increase with decreasing surface temperature; this tendency is smoothed out in the presence of mild turbulent diffusion. Variations in the Li abundances at a given temperature can be attributed to variations in the effectiveness and duration of microscopic diffusion. The Be abundance should not change much with surface temperature or age, as observed in the stars of normal Be content.

To explain the Be-deficient stars, it is necessary to invoke turbulent diffusion to transport the Be, and Li, down to temperatures hot enough to destroy them by nuclear burning. Since Li is destroyed at cooler temperatures than Be, some stars that are deficient in Li could be expected to have a normal surface Be content, as observed. Li destruction will take place in lower-mass stars where the mixing may not extend so deeply into the star. (The mass fraction of main-sequence stars in which Be survives is about twice that in which Li can survive [see Boesgaard and Chesley

1976].) Apparently the conditions for the burning of Be are not favored for stars cooler than 6600 K. (Li will be depleted in these hotter stars too; the fact that Li is depleted in more stars and in cooler stars could be due to the action of the two types of diffusion.) Inside the star the transition regions are very sharp between Li and no-Li and Be and no-Be at the critical temperatures for nuclear burning. Thus nuclear burning can explain the sharp segregation of the stars with Be from those without; nuclear burning would result in a rapid and complete destruction of Be. The segregation would not show up for Li, since both microscopic and turbulent diffusion act in combination or separately to reduce the Li differently in different stars. Thus, these ideas suggest that diffusion can explain the existence of the Be-deficient stars, their relation to surface temperature, and the marked segregation of the stars with Be from those without Be.

Schatzman and Vauclair attribute high turbulent diffusion to differential rotation or meridional circulation. Goldreich and Schubert (1967) discuss some conditions under which stars would have transferred angular momentum, through turbulent diffusion or spin-down, and have transported Li and Be down to temperatures where they are destroyed by nuclear burning. (Large turbulent eddies may be set up if the interior of the star is rotating rapidly.) These conditions could occur in stars with high initial angular momentum that are now slow rotators—and now deficient in both Li and Be. Initial angular momentum can be shared between two (or more) stars forming together. It may be relevant that seven of the eight Be-deficient stars have constant radial velocities, according to Abt and Levy (1976), while only 53 percent of the F and G dwarfs they surveyed have constant velocity, and only 50 percent of the stars with normal Be have constant velocities. (The Be-deficient star that is the exception is α CMi, which is a spectroscopic binary and has a white dwarf companion.) This indirect evidence may be interpreted to mean that these currently slow rotators were not able to share their initial angular momentum with a nearby (SB) companion.

Both these ideas, diffusion and convective overshoot, are very difficult problems theoretically. Both require a major advance in our understanding of turbulent convection. Details of stellar structure models and knowledge of the depth of the convection zone need to be more secure. Revisions of the mixing-length theory are implied. For the present, it appears that diffusion, including large turbulent diffusion, explains both the Be-deficient stars and the trends of Li depletion in the more consistent way.

VII. CONCLUSIONS

The results as plotted in Figure 4 show that there is no dependence of Be abundance on temperature for F and G dwarfs, contrary to earlier results. From these stars that have Be, an average value for Be/H of $1.31 \times 10^{-11} \pm 0.36 \times 10^{-11}$ is derived. This abundance represents the universal or cosmic abundance of Be. The Be abundances in stars, the Sun, meteorites, and the interstellar gas are all consistent with a Be/H ratio of $1\text{–}2 \times 10^{-11}$.

This universal Be abundance can be readily explained by the galactic cosmic-ray theory of Meneguzzi, Audouze, and Reeves (1971), where C, N, and O atoms in the interstellar gas are bombarded by cosmic rays and break up into fragments including ^{9}Be. The observed and predicted abundances agree perfectly and no other source is required for the origin of Be. In addition, the B abundance for Vega (Boesgaard *et al.* 1974) and the B/Be ratio are consistent with the GCR theory.

Some of the dwarf stars in Figure 4 are clearly deficient in Be; these are all hotter than 6600 K or spectral type F6. In that temperature range one-third of the stars are Be-deficient, while none of the cooler main-sequence stars show deficiencies. All the Be-deficient stars are also Li-deficient. Microscopic and turbulent diffusion appear to offer the most promising way to account for the observed depletions of both Li and Be in main-sequence stars.

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REFERENCES

Abt, H. A., and Levy, S. G. 1976, *Ap. J. Suppl.*, **30**, 273.
Audouze, J., and Truran, J. W. 1973, *Ap. J.*, **182**, 839.
Bell, R. A. 1971, *M.N.R.A.S.*, **155**, 65.
Bodenheimer, P. 1966, *Ap. J.*, **144**, 103.
Boesgaard, A. M. 1968, in *Highlights of Astronomy*, ed. L. Perek (Dordrecht: Reidel), p. 237.
———. 1974, *Astr. and Ap.*, **34**, 9.
Boesgaard, A. M., and Chesley, S. E. 1976, *Ap. J.*, **210**, 475.
Boesgaard, A. M., Praderie, F., Leckrone, D. S., Faraggiana, R., and Hack, M. 1974, *Ap. J. (Letters)*, **194**, L143.
Buseck, P. R. 1971, in *Handbook of Elemental Abundances in Meteorites*, ed. B. Mason (New York: Gordon & Breach), p. 73.
Cameron, A. G. W., and Fowler, W. A. 1971, *Ap. J.*, **164**, 111.
Carbon, D. F., and Gingerich, O. C. 1969, in *Proceedings of the Third Harvard-Smithsonian Conference on Stellar Atmospheres*, ed. O. Gingerich (Cambridge: MIT Press), p. 377.
Cayrel, R., and Cayrel de Strobel, G. 1966, *Ann. Rev. Astr. and Ap.*, **4**, 1.
Chmielewski, Y., Müller, E. A., and Brault, J. W. 1975, *Astr. and Ap.*, **42**, 37.
Conti, P. S. 1968, *Ap. J.*, **151**, 567.
Conti, P. S., and Danziger, I. J. 1966, *Ap. J.*, **146**, 383.
Crawford, D. L. 1975, *A.J.*, **80**, 955.
Danziger, I. J., and Conti, P. S. 1966, *Ap. J.*, **146**, 392.
Goldreich, P., and Schubert, G. 1967, *Ap. J.*, **150**, 571.
Greenstein, J. L., and Tandberg-Hanssen, E. 1954, *Ap. J.*, **119**, 113.
Herbig, G. H. 1965, *Ap. J.*, **141**, 588.

Herbig, G. H., and Wolff, R. J. 1966, *Ann. d'Ap.*, **29**, 593.
Iben, I. 1967, *Ap. J.*, **147**, 624.
Kraft, R. P. 1967, *Ap. J.*, **150**, 551.
Meneguzzi, M., Audouze, J., and Reeves, H. 1971, *Astr. and Ap.*, **15**, 337.
Meneguzzi, M., and Reeves, H. 1975, *Astr. and Ap.*, **40**, 99.
Merchant, A. E. 1966, *Ap. J.*, **143**, 336.
Pilachowski, C. 1975, unpublished Ph.D. thesis, University of Hawaii.
———. 1977, *Astr. and Ap.*, submitted.
Reeves, H. 1974, *Ann. Rev. Astr. and Ap.*, **12**, 437.
Ross, J. E., and Aller, L. H. 1974, *Solar Phys.*, **36**, 11.
Schatzman, E., and Vauclair, S. 1973, *Comments Ap. and Space Sci.*, **5**, 159.
Straus, J. M., Blake, J. B., and Schramm, D. N. 1976, *Ap. J.*, **204**, 481.
Uesugi, A., and Fukuda, I. 1970, *Contr. Inst. of Ap. and Kwasan Obs.*, No. 189.
Vauclair, S. 1972, in *IAU Colloquium 17*, *L'âge des étoiles*, ed. G. Cayrel de Strobel and A. M. Deplace (Paris: Meudon Obs.), pp. 38–1.
———. 1973, unpublished preprint.
Wagoner, R. V. 1973, *Ap. J.*, **179**, 343.
Weymann, R. J., and Sears, R. L. 1965, *Ap. J.*, **142**, 174.
Wiese, W. L., Smith, M. W., and Glennon, R. M. 1966, *Atomic Transition Probabilities*, Vol. **1**, H *through* Ne (NSRDS-NBS 4).

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