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LITHIUM IN HEAVY-METAL RED GIANTS

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ABSTRACT

Abundance ratios of Li/Ca are determined for seven Ba II stars, five MS stars, and eight S stars from spectrograms with dispersions between 6.7 and 15 Å mm. The Li content of the Ba II stars is similar to that of normal G–K giants. The MS stars and four of the S stars resemble M giants in their Li abundance. Three S stars have 1–2 orders of magnitude more Li than typical M stars, but can probably be understood as the descendants of lithium-rich main-sequence stars. T Sgr has more Li than the T Tauri stars. The interpretation of such a large amount of Li is complicated by the presence of strong lines of Tc I which imply that deep convection takes place in this star.

I. INTRODUCTION

In addition to the normal G, K, and M giants, there are two main classes of peculiar giants: the carbon stars and the heavy-metal stars. The temperature sequence of these two groups corresponds to G5–M8. The heavy-metal stars are divided into two groups, the Ba II stars and the S stars. Discussions and analyses of these stars can be found in papers by Bidelman and Keenan (1951), Keenan (1954), and Warner (1965), among others.

Lithium has been studied in both normal stars and carbon stars. The Li content of about 100 normal late-type giants has been determined by Bonsack (1959) and Merchant (1967). Lithium was first discovered in carbon stars by McKellar (1940). A survey for Li in carbon stars was done by Torres-Peimbert and Wallerstein (1966), whose estimates of the Li content indicate that some carbon stars may have 3–4 orders of magnitude more Li than the Sun. These papers are reviewed by Wallerstein and Conti (1969).

According to Keenan and Teske (1956) the Li line is consistently enhanced in S stars relative to normal stars. A very strong line has been found in T Sgr by Keenan (1967). The strength of the Li line has been reported to be variable in the S star T Cam by Bretz (1966) from observations at three successive maxima. Warner (1965) found the Li abundance in two Ba II stars to be about 5–10 times greater than in his standard star. Lithium abundances for a survey sample of twenty heavy-metal red giants including seven Ba II stars, five MS stars, and eight S-type stars are determined in this paper for comparison with those found in the other late-type giants.

II. DATA REDUCTION AND RESULTS

a) *Observations*

Coudé spectrograms at 6.7 and 15 Å mm^{-1} on Kodak IIa-F and 103a-F emulsions were obtained with the 100-inch telescope at Mount Wilson Observatory. This material was supplemented by one coudé spectrogram at 8 Å mm^{-1} previously obtained with the 120-inch telescope at Lick Observatory and by spectrograms of five S stars at 6.8 and 13.5 Å mm^{-1} taken at the coudé focus of the 200-inch telescope and kindly made available to me by Dr. Jesse L. Greenstein. The spectroscopic information is summarized in Table 1. Portions of some of the spectra are reproduced in Figures 1 and 2 (Plates 12 and 13) showing that Li is either weak or absent in the MS stars and very strong in some S stars.

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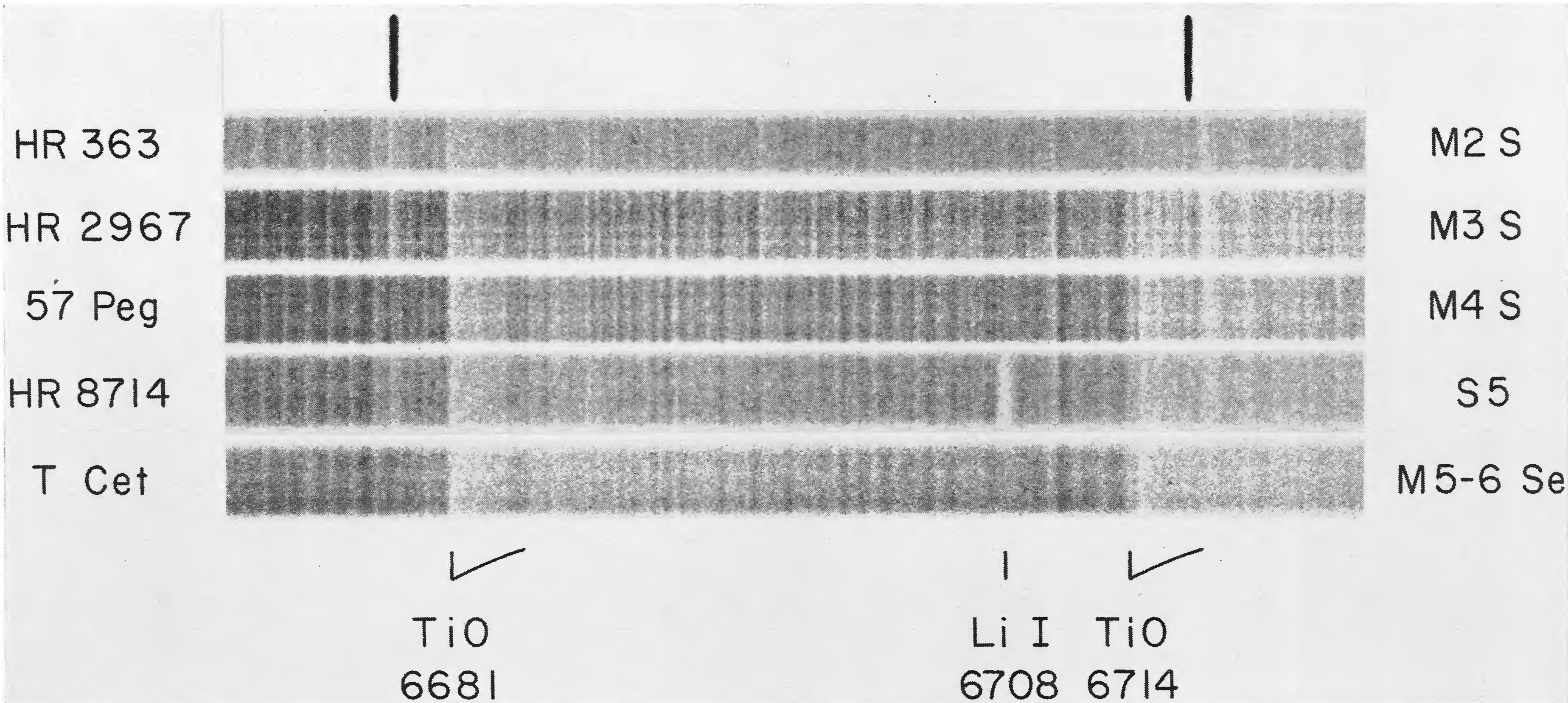

FIG. 1.—Enlargements of the Li region on five spectrograms taken with the coudé spectrograph of the 100-inch telescope. The Li line is barely detectable and is blended with TiO in the MS stars. It is very strong in the S star HR 8714.

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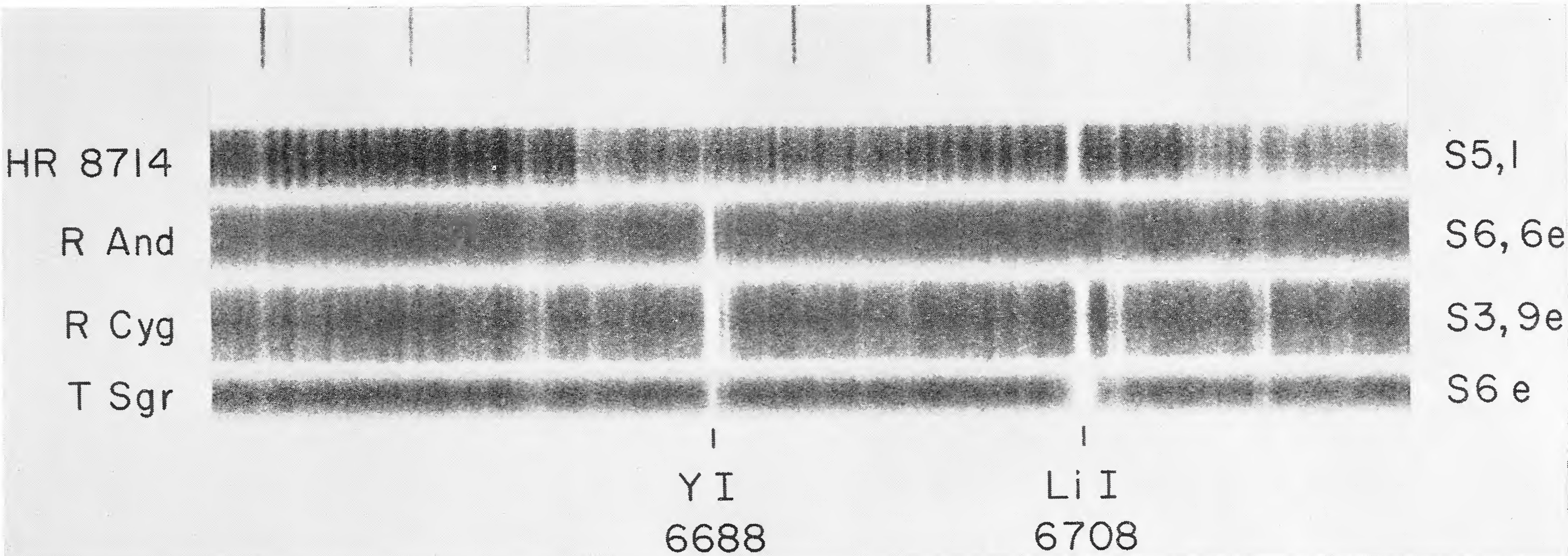

FIG. 2.—Enlargements of the Li region of four S stars. These spectrograms were obtained with the coudé spectrograph of the 200-inch telescope. Notice the great difference in strength of the Li I line, and also the Y I line.

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b) Analysis

Most of these same spectrograms were also used to determine the abundance ratio of Ti/Zr (Boesgaard 1970*a*). Measurement details, including the positioning of the continuum level, are presented in that paper. The abundance ratio of Li/Ca is determined in the present work; the equivalent widths of ten Ca I lines and one Li I line are given in Table 2.

A differential curve-of-growth technique was used which employs a succession of standard stars so that each star analyzed is very similar to its standard and the opacity is accounted for implicitly. Thus despite the wide range in temperature, the stars studied here are all on a consistent system. Excitation temperatures, $\theta_{\text{exc}} = 5040/T_{\text{exc}}$, and microturbulent velocities, ξ, were determined from curves of growth of Ti I lines. (Examples of these curves of growth are shown in Fig. 1 of the paper by Boesgaard [1970].) The shifts, $\Delta\log \eta_0$, of the Ca I and Li I curves of growth relative to the Ti I curve were found. A correction for the high thermal velocity of Li must be made as discussed by Merchant (1967). Following those results, Case II (the Li doublet seen as a blend due to low resolution or large-scale turbulence) is appropriate for giant stars and is used where the equivalent width of the Li line is greater than 125 mÅ. For lines weaker than that the two cases give identical results and often the Case I (intrinsic blending) technique was used as it is simpler. More detailed discussions of the analysis can be found in the papers by Merchant (1967) and Boesgaard (1970*a*).

TABLE 1

SPECTROSCOPIC DATA

Star	Spectral Type	Dispersion(s) (Å mm⁻¹)
Ba II stars:		
HR 2392	K0 Ba3	6.7, 6.7
HD 121447	K7 Ba5	15
HD 178717	K4 Ba4	15
HD 183915	K1 Ba2	15
HD 196673	K0 Ba2	15
HD 199394	G8 Ba1	15
ζ Cap	G5 Ba2	6.7, 6.7, 6.7
MS stars:		
T Cet	M5–6S	6.7, 6.7
HR 363	M2S	6.7
o^1 Ori	M3S	8
HR 2967	M3S	6.7, 6.7, 6.7
57 Peg	M4S	6.7, 6.7
S stars:		
R And	S6, 6e	6.8
HR 1105	S5, 3	6.8
HD 35155	S4, 1	6.7, 15
R CMi	Se	13.5
SU Mon	S3, 6	15
T Sgr	S5, 8e	6.8
R Cyg	S5, 8e	6.8
HR 8714	S5, 1	6.7, 6.7

For the majority of these stars the ratio of the number of ions to neutrals is $\gg 1$ for both Li and Ca. Therefore, the ionization correction can be easily incorporated into the final form of the logarithmic abundance ratio (Herbig 1965) as follows:

$$\log \frac{N(\mathrm{Li})}{N(\mathrm{Ca})} = \frac{\Delta \log \eta_0(\mathrm{Li\ I})}{\Delta \log \eta_0(\mathrm{Ca\ I})} + \log \frac{v(\mathrm{Li})}{v(\mathrm{Ca})} + \log \frac{u(\mathrm{Li\ II})}{u(\mathrm{Ca\ II})} - \theta_{\mathrm{ion}}[I(\mathrm{Li\ I}) - I(\mathrm{Ca\ I})]\,, \tag{1}$$

where $\Delta \log \eta_0$ refers to the horizontal shift to the Ti I curve of growth, v is the velocity, u is the partition function, θ_{ion} is the ionization temperature $= 5040/T_{\mathrm{ion}}$, and I is the ionization potential. Since the ionization potentials of Li I and Ca I differ by only 0.721 eV, the value of θ does not play an important role in equation (1), and its effect becomes smaller with smaller θ. The values used for θ_{ion} follow the results found by Merchant (1967): for stars with $\theta_{\mathrm{exc}} < 1.50$, $\theta_{\mathrm{exc}} - \theta_{\mathrm{ion}} = 0.25$; where $\theta_{\mathrm{exc}} > 1.50$, $\theta_{\mathrm{exc}} - \theta_{\mathrm{ion}} = 0.35$. The value of θ_{exc} is found individually for each star.

TABLE 2

EQUIVALENT WIDTHS: $-\log W/\lambda$

Element	λ(Å)	HR 2392	HD 121447	HD 178717	HD 183915	HD 196673	HD 199394	ζ Cap	T Cet	HR 363	o^1 Ori
Li I..........	6708	5.18	4.64	5.08	≤5.38	≤5.67	≤5.53	5.50	5.01	5.09	4.68
Ca I..........	6718	4.52	4.35	4.36	4.52	4.58	4.75	4.57	4.64	4.53	4.29
	6573	4.66	4.25	4.32	4.54	4.70	4.88	4.92	4.37	4.33	4.28
	6500	4.67	4.47	4.52	4.63	4.68	4.75	4.73	...	4.52	4.51
	6450	4.45	...	4.20	4.38	4.37	4.51	4.62	4.67	4.50	4.41
	6439	4.49	...	4.39	4.53	4.42	4.55	4.46	4.52	4.42	4.03
	6162	4.31	4.20	4.08	4.29	4.34	4.39	4.38	4.48	4.21	4.16
	6161	4.57	...	4.15	4.43	4.68	4.81	4.67	4.66	4.44	4.47
	6122	4.36	4.09	4.08	4.37	4.38	4.44	4.39	4.38	4.13	4.17
	6103	4.47	4.22	4.20	4.29	4.44	4.65	4.53	4.52	4.33	4.30
	5857	4.46	4.31	4.30	4.39	4.38	4.52	4.39	4.49	4.54	4.40

Element	λ(Å)	HR 2967	57 Peg	R And	HR 1105	HD 35155	R CMi	SU Mon	T Sgr	R Cyg	HR 8714
Li I..........	6708	5.25	5.19	≤5.16	5.01	4.90	4.25	4.11	3.66	4.21	4.11
Ca I..........	6718	4.52	4.83	4.64	4.46	4.57	4.37	4.22	4.62	4.51	4.35
	6573	4.30	4.48	4.21	4.24	4.33	4.03	4.03	4.05	4.08	4.25
	6500	4.65	5.01	4.72	4.58	4.64	4.28	4.08	4.56	...	4.46
	6450	4.45	4.60	4.48	4.36	4.47	4.12	4.12	4.41	4.23	4.47
	6439	4.38	4.43	4.54	4.37	4.46	4.23	4.19	4.40	4.19	4.41
	6162	4.32	4.50	4.18	4.28	4.39	4.19	3.92	4.34	...	4.22
	6161	4.60	5.03	4.65	4.72	4.59	4.59	4.15	4.60	...	4.50
	6122	4.20	4.33	4.08	4.18	4.33	4.21	3.83	...	4.13	4.12
	6103	4.32	4.42	4.25	4.34	4.44	4.24	3.87	...	...	4.24
	5857	4.52	4.83	4.40	4.50	4.64	4.21	4.41	4.72	...	4.40

For the stars with $\theta_{\mathrm{exc}} > 1.70$ the degree of ionization was found from the Saha equation. In all cases the electron pressure was assumed to be 0.01 dyn cm^{-2}. This value was chosen for these stars on the basis of the P_e values found for the M2–M4 stars by Merchant (1967) and P_e values summarized for other cool stars by Fujita and Tsuji (1966). The final $\log [N(\mathrm{Li})/N(\mathrm{Ca})]$ was found from the following equations:

$$\log \frac{N(\mathrm{Li\ I})}{N(\mathrm{Ca\ I})} = \frac{\Delta \log \eta_0(\mathrm{Li\ I})}{\Delta \log \eta_0(\mathrm{Ca\ I})} + \log \frac{v(\mathrm{Li})}{v(\mathrm{Ca})} + \log \frac{u(\mathrm{Li\ I})}{u(\mathrm{Ca\ I})}\,, \tag{2}$$

$$\log \frac{N(\mathrm{Li\ II})}{N(\mathrm{Li\ I})} = \log a = 9.08 + \log \frac{u(\mathrm{Li\ II})}{u(\mathrm{Li\ I})} - 5.39\,\theta_{\mathrm{ion}} - \tfrac{5}{2} \log \theta_{\mathrm{ion}} - \log P_e\,, \tag{3}$$

$$\log \frac{N(\mathrm{Ca\ II})}{N(\mathrm{Ca\ I})} = \log b = 9.08 + \log \frac{u(\mathrm{Ca\ II})}{u(\mathrm{Ca\ I})} - 6.11\,\theta_{\mathrm{ion}} - \tfrac{5}{2} \log \theta_{\mathrm{ion}} - \log P_e\,, \tag{4}$$

$$\log \frac{N(\mathrm{Li})}{N(\mathrm{Ca})} = \log \frac{N(\mathrm{Li\ I})}{N(\mathrm{Ca\ I})} + \log \frac{(1+a)}{(1+b)} . \tag{5}$$

Abundances for these stars were also calculated by using equation (1). In all cases except R Cyg, the results from equation (1) and equation (5) agree to within 0.04 in the log. Increasing the electron pressure used in equations (2) and (3) by a whole order of magnitude decreases the solution obtained by equation (5) by not more than 0.10 (except for R And, where it decreases by 0.25). The difference in the results from equations (1) and (5) for R Cyg is due to the low ionization temperature used ($\theta_{\mathrm{ion}} = 1.92$); the ionization equation gives more neutral atoms than ions of both Li and Ca. The value from equation (5) is more realistic.

TABLE 3

RESULTS

Star	θ_{exc}	ξ (km sec^{-1})	$\log \frac{1+a}{1+b}$	$\log \frac{N(\mathrm{Li})}{N(\mathrm{Ca})}$	Estimated p.e.
Ba II stars:					
ζ Cap	1.05	2.7	...	−4.6	0.2
HD 199394	1.12	1.9	...	≤−4.8	0.2
HR 2392	1.19	2.9	...	−4.7	0.2
HD 196673	1.27	2.9	...	≤−5.3	0.2
HD 183915	1.32	2.6	...	≤−5.2	0.2
HD 178717	1.57	2.8	...	−5.9	0.3
HD 121447	1.78	3.4	+0.45	−5.5	0.3
MS stars:					
HR 363	1.65	2.3	...	−6.2	0.3
o^1 Ori	1.86	2.8	0.49	−5.6	0.2
HR 2967	1.80	2.6	0.48	−6.1	0.1
57 Peg	1.80	1.8	0.48	−5.9	0.3
T Cet	1.79	1.8	0.46	−5.7	0.4
S stars:					
SU Mon	1.80	4.9	0.48	−4.4	0.4
HD 35155	1.72	1.7	0.42	−4.5	0.2
R CMi	1.90	3.7	0.56	−5.6	0.4
HR 8714	1.80	2.8	0.44	−4.1	0.2
T Sgr	1.93	4.1	0.55	−2.0	0.3
HR 1105	2.03	2.2	0.58	−6.3	0.4
R Cyg	2.27	3.2	0.17	−5.6	0.5
R And	2.01	2.9	+0.58	≤−5.9	0.4

c) Results

The atmospheric parameters, abundance results, and estimated probable errors are given for each star in Table 3. It is estimated that the error in abundance for most of the stars is a factor of 2–2.5, but some are probably in error by as much as a factor of 3 (± 0.5 in the log). An obvious error results from the determination of an abundance based on only one line of Li. For some of the stars there is more than one plate, so the measurement error can be estimated. The measurements agree to 10–20 percent. Another source of error is in the temperature, both the excitation and the ionization temperature. The mean excitation potential for the Ca lines is 2.1 eV whereas λ6707 of Li is a 0.0-eV line. Thus a probable error in θ_{exc} of 0.10 results in an error of 0.2 in the log of the abundance ratio. The probable errors of θ_{exc} are mostly below 0.12, but range from 0.03 to 0.21. The same probable errors, of course, are present in θ_{ion}. The probable error for each star given in Table 3 is estimated from (1) the error in the equivalent width of the Li line, (2) the product of the calculated probable error in θ_{exc} and the average excitation potential of the Ca lines, (3) the product of the same probable error for θ_{ion} and 0.72, the difference in ionization potential of Li I and Ca I, and (4) for the cooler stars, an estimate of the error due to an order-of-magnitude error in P_e.

III. DISCUSSION

Opportunity for comparison of these results with those found previously is limited. Warner (1965) has determined that the Li abundance in two Ba II stars, ζ Cap and HR 5058, is about 10 times greater than the solar value. This is in good agreement with the values found here for the hotter Ba II stars.

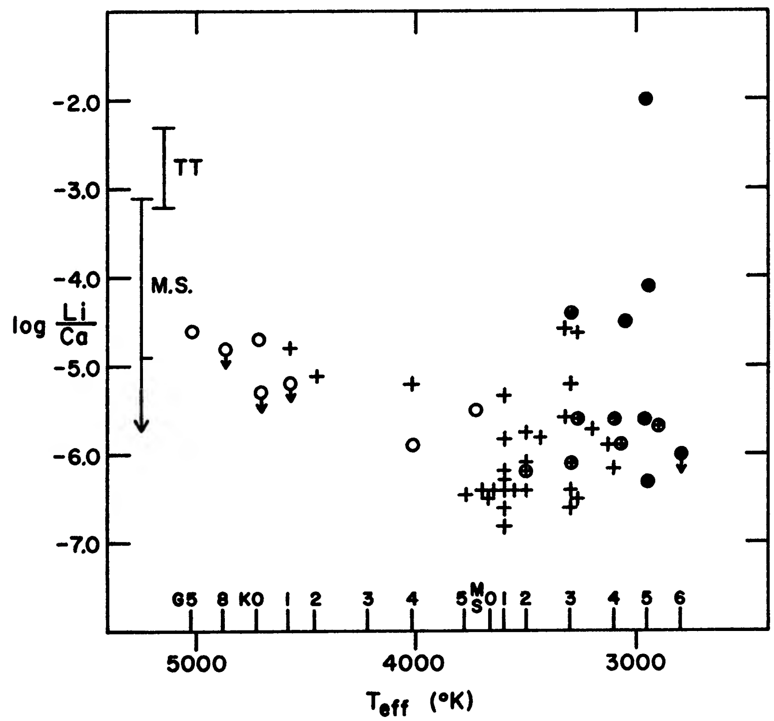

FIG. 3.—Logarithmic ratio of Li to Ca plotted against effective temperature. The temperature/spectral type scale is that of Johnson (1966). (The spectral type used for R CMi is consistent with its excitation temperature.) *Open circles*, Ba II stars; *filled circles*, S stars; *circled plus signs*, MS stars; *pluses*, normal K and M giants. Vertical bar in the upper left labeled TT shows range of values for the T Tauri stars. The long vertical bar labeled M.S. gives the range for main-sequence stars. This bar ends at Peach's (1967) photospheric limit for the Sun; the mark at −4.9 shows the Greenstein-Richardson (1951) solar value.

Figure 3 shows the abundance results for the heavy-metal stars plotted against spectral type. Included in this plot for comparison are the results for the K and M giants found previously (Merchant 1967), the range for the T Tauri stars (Bonsack and Greenstein 1960), and the range for main-sequence stars.

Several remarks can be made about Figure 3. (1) The majority of points, Ba II, K, M, MS, and S stars, fall along a sequence sloping from the middle left to the lower right. This slope has been interpreted as a result of increasing convective dilution, as first suggested by Iben (1965). (2) The Li/Ca ratios in most of the heavy-metal stars agree with those of their normal counterparts. The Ba II stars are similar to the K giants in Figure 3 and also to those given by Bonsack (1959) when compared through the solar value. The MS stars resemble typical M giants, as do four of the S stars. (3) There is a group of four S stars and two M stars that seem undeniably lithium-rich since the Li lines in these stars have equivalent widths near 400 mÅ or more. (4) The variable S star, T Sgr, has as much Li as typical T Tauri stars. If T Sgr has the solar Ca abundance, it has some 5000 times more Li than the solar photospheric limit (Peach 1968).

Since there are no a priori reasons to expect heavy-metal stars to have different Li contents from normal stars, there is no difficulty in understanding the first two points. (A plot similar to Fig. 3 given for normal stars in the review paper by Wallerstein and Conti [1969] shows a dip in the Li abundance near K4–K5. Boesgaard [1970*b*] pointed out that Warner's [1969] reanalysis of Bonsack's data removes this dip.)

The high Li content of some of the stars, particularly T Sgr, is puzzling, however. The six stars mentioned in point 3—T Sgr, HR 8714, SU Mon, R CMi, HR 2028, and 29 Cap—seem to have no other characteristics in common. R CMi has atomic-line strengths similar to type S but shows weak CN and C_2 bands and no ZrO bands (Keenan 1954). SU Mon and T Sgr are typical variable S stars; HR 8714 is a nonvariable. HR 2028 is a high-velocity M star whereas 29 Cap is a normal, perhaps slight variable, M3 giant. These five stars can be tentatively understood as the descendants of the Li-rich main-sequence stars. The highest values for log Li/Ca observed in main-sequence stars cooler than F0 (summarized by Herbig and Wolff 1966) are not more than 30 times higher than the five Li-rich stars, excluding T Sgr. Calculations of post–main-sequence Li dilution by Iben (1967) for stars of 1, 1.25, and 1.5 $M_{\odot}$ (main-sequence spectral types = F0–G2) show that such stars would have their Li content diluted by factors in excess of 20 before they reach $T_{\rm eff} = 4500°$ K. The factor is higher for higher masses. These models do not, however, represent stars with as cool surface temperatures as the M and S stars, so quantitative comparisons cannot be made.

T Sgr, however, is more difficult to understand. The fact that it has as much or more Li than even the T Tauri stars suggests that it must have made some Li during its evolution. However, Merrill (1952) found strong Tc lines in this star. If the Tc is made in the interior and carried to the surface by convection, then any Li present or created on the surface would be simultaneously transported to the interior regions and thereby diluted.

The observation of a variation in the Li line strength in successive maxima of the S star T Cam by Bretz (1966) suggests that Li production may be related to pulsation. Suppose that Li and Tc are both created as a result of a shock that produces the variation in brightness in this star. One should then ask if Li and Tc line strengths are related. For the four S stars common to this Li study and Merrill's Tc investigation, no correlation was found between the two elements. R And and R Cyg have strong Tc but little Li. HR 1105 has little Li or Tc. T Sgr has much Li and fairly strong Tc.

T Sgr then should join the super-lithium-rich carbon stars WZ Cas, WX Cyg, and T Ara. The presence of Tc in T Sgr and ^{13}C in WZ Cas (McKellar 1960) increases the difficulty in understanding these lithium-rich stars. Cameron's (1955) proposed mechanism, whereby ^{7}Be is produced and convected to cool temperatures before becoming ^{7}Li by electron capture, is inadequate for these four stars; as Wallerstein and Conti (1969) point out, these stars have too much Li by factors of 10–100. Although it is possible to understand qualitatively the Li history of most late-type giants, the high Li content in these four stars (representing 3 percent of the late-type giants studied) remains unexplained.

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