

THE ABUNDANCE OF LITHIUM IN T TAURI STARS AND RELATED OBJECTS*

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ABSTRACT

Spectrograms of four T Tauri stars involved in nebulosity and eight stars possibly similar in some respects to T Tauri stars have been examined for the presence of the resonance doublet of Li I at λ 6708. A very strong feature at this wave length was found in the spectra of the four T Tauri stars and of SU Aur, which differs from Herbig's definition of the T Tauri class only in having a somewhat higher spectroscopic luminosity. Spectrophotometric analysis showed that the lithium/metals ratio in these five stars exceeds the solar ratio by a factor of 100 and approximately equals the terrestrial value. No Li I was detected in the other seven stars; except for the few hot stars included, these cannot then have lithium/metals ratios much in excess of the solar value.

These results suggest that young stars have approximately 1 lithium atom per 10^9 hydrogen atoms, at least in their atmospheres. Primary cosmic rays appear to be incapable of contaminating the interstellar medium, and then the entire protostar, with this amount of lithium. However, if a sufficiently efficient mechanism for the production of lithium at the surface of a star can be found, this result can be accomplished without the appearance of a large fraction of the star's energy as high-energy surface phenomena. The magnetic energy content of a protostar is sufficiently large that, if forced to the surface during the contraction and there dissipated in accelerating protons, the quantity of lithium required by the observations can be formed by spallation reactions in the atmosphere.

I. INTRODUCTION

Hunger's observation (1957) that the resonance doublet of Li I at λ 6708 is strongly present in the spectra of T Tauri and RY Tauri, together with the failure of features of similar strength to appear in spectra of normal stars of types G8-M0 (Bonsack 1959), suggests that this interesting element may be significantly overabundant in these peculiar stars. This suggestion is strengthened by the relatively early spectral types assigned to the blue region of the absorption spectra, G5 for T Tau and G0 for RY Tau. If lithium is indeed overabundant in these and other T Tauri stars, then perhaps the circumstellar envelopes of these stars are seats of lithium production. In addition, one might conclude that they have not destroyed their surface lithium by whatever process operates in the sun and cooler normal stars (Greenstein and Richardson 1951; Bonsack 1959). If these stars are in the first stages of Kelvin contraction, as convincingly argued by Herbig (1958*a*), then their failure to destroy lithium can be simply interpreted as a lack of sufficient time to do so. This interpretation suggests a method of classifying T Tauri stars according to age.

In order to test such interpretations it is necessary to determine (*a*) the abundance of lithium in the stars with the strong Li I feature, (*b*) whether this feature is common to all stars classified as T Tauri type according to Herbig's (1958*b*) criteria, and (*c*) whether other stars also exhibit this peculiarity. The present paper reports the results of a first attack on these problems. Spectrograms of the red region were obtained for twelve stars having at least some features in common with the T Tauri group. Five of these were found to have strong lines of Li I. The abundance of lithium relative to the sun was determined for four of these by an approximate curve-of-growth analysis, and their spectra were compared visually with the other stars observed. The abundance of barium relative to the sun was also determined for these four stars.

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II. OBSERVATIONS AND MEASUREMENTS

Table 1 lists the spectrograms examined in this investigation; some of them were originally obtained for other programs but are included here because the stars exhibit some similarity to the T Tauri group. The columns of the table give, successively, the name (or HD number) of the star, the BD number, the co-ordinates for the epoch 1900, the spectral classification, the plate numbers, and the date. The spectral classifications, except for +24°2742, are taken from the literature. The symbol "(n)" following the classification indicates that the star is intimately involved with nebulosity. The plate numbers with the prefix "Pd" were obtained with the 200-inch telescope and have a dispersion of 27 Å/mm. The prefix "Ce" indicates plates from the coudé spectrograph of the 100-inch telescope; the dispersion here is 31 Å/mm. The star 61 UMa is a normal G8 V star which was used as a control in the spectrophotometric analysis.

TABLE 1
STARS OBSERVED

Name	BD	α (1900)	δ (1900)	Spect.	Plate No.	Date
RY Tau	+28° 645	4 ^b 15 8 ^m	+28° 12'	dG0 (n)	Pd 4230	12-17-58
T Tau	+19 706	4 16.2	+19 18	dG5 (n)	Pd 4233	12-18-58
					Ce 12163	9-29-58
SU Aur	+30 743	4 49 6	+30 24	gG2 (n)	Pd 4242	12-20-58
RW Aur.	+30 792	5 01 4	+30 16	dG5e	Pd 4234	12-18-58
GW Ori.	+11 819	5 23 4	+11 47	dK3 (n)	Pd 4377	2-26-59
					Ce 12425	1-23-59
CQ Tau.	+24 873	5 29.8	+24 41	F2	Ce 12430	1-24-59
V380 Ori	- 6 1253	5 31 6	-06 47	A (n)	Pd 4382	2-27-59
PZ Mon	+ 1 1522	6 43 2	+ 1 20	K2Ve	Ce 12437	1-26-59
.....	+37 2318	12 40.0	+37 17	K2+B5	Pd 3712	4- 7-58
					Pd 3840	6- 6-58
HD 117555.....	+24 2592	13 26 0	+24 44	gG8pe	Pd 3675	2- 9-58
					Pd 3852	6-25-58
.....	+24 2742	14 31.2	+23 53	gG+B	Pd 3391	8-16-57
AG Dra.	+67 922	16 01.1	+67 05	K1 IIpe	Pd 4494	5-16-59
61 UMa	+35 2270	11 35.8	+34 46	G8V	Ce 12357	1- 1-59

Of the program stars listed, four are regarded as bona fide T Tauri stars by Herbig (1958b) and Joy (1945, 1949): T Tauri, RY Tauri, RW Aurigae, and GW Orionis (designated "MH α 265-2" by Joy). The red spectrum of SU Aur is quite similar to that of T Tau, but Herbig excludes it from the T Tauri group because of the high luminosity indicated by its blue absorption-line spectrum. V380 Ori has an emission spectrum quite similar to RW Aur, but the A-type absorption spectrum excludes it from Herbig's T Tauri group. The remaining stars listed which have variable-star designations, except AG Dra, were included in the program because of their RW Aur-type light-variation. HD 117555 was discussed briefly by Merrill (1948). It is a late G-type star with very broad lines and emission at H α and the Ca II resonance lines. The stars +37°2318 and +24°2742 are composite objects with strongly variable H α emission; the former star has been called a variable of the Z Andromedae type (Cowley 1956; Mumford 1956). AG Dra shares with the T Tauri stars a G-type absorption-line spectrum and strong variable emission in H, He, and Ca II and in an overlying violet continuum (see Roman 1953; Mirzoyan 1957). The light-variation resembles that of Z And, according to the *General Catalog of Variable Stars* (Kukarkin *et al.* 1958). The latter four stars are at high galactic latitudes.

Five of these stars have strong lines of Li I—T Tau, RY Tau, RW Aur, SU Aur, and

GW Ori. Portions of their spectra from H α longward are reproduced in Figure 1. In these stars the strength of the feature is similar to that of the strongest metallic lines in the yellow-red region of the spectrum, excluding only the Na I D lines. In order to obtain estimates of the lithium abundance corresponding to these line strengths, equivalent widths were measured for all lines, from the D lines to the sensitivity limit of the Kodak F-type emulsions, which were sufficiently strong and unblended for meaningful measurement. In RW Aur, the few visible absorption lines are so broad and weak that no measurements were possible. In the other stars, only nine lines, including the Li I doublet, satisfy these criteria at this rather low dispersion. These lines are listed in Table 2, which gives the wave length, identifications, multiplet number in the *Revised Multiplet Table*, ionization potential, and excitation potential. The spectrograms were calibrated for photometry with plates exposed in the auxiliary wedge-slit spectrographs; equivalent widths were measured on intensity-scale tracings made with the California Institute of Technology microphotometer which has been modified by the addition of a Moseley electronic curve-following device. The equivalent widths of the blended Li I doublet ranged from 150 mÅ in GW Ori to 450 mÅ in T Tau. The spectrogram of T Tau made at the 100-inch was not used in the photometric analysis because of its insufficient width; the two spectrograms of GW Ori were reduced independently.

TABLE 2
LINES MEASURED

No	λ	Ident.	Mult.	I (ev)	E (ev)
1	5889 95	Na I	1	5 12	0 00
2	5895 92	Na I	1	5 12	0 00
3	6122 22	Ca I	3	6 09	1 88
4	6141 72	Ba II	2	9 96	0 70
5	6393 62	Fe I	168	7 86	2 42
6	6430 85	Fe I	62	7 86	2 17
7	6439 07	Ca I	18	6 09	2 51
8	6609 11	Fe I	206	7 86	2 55
9	6707 79	La I	1	5 37	0 00

An estimate of the errors in photometry may be derived from the two plates of GW Ori. A comparison of the measured intensities indicates that the lines in the 100-inch spectrogram were measured 15 per cent stronger, on the average, than those in the 200-inch spectrogram. This may reflect systematic errors in the photometry, but the difference is more likely due to a real change in the spectrum during the month that elapsed between the taking of the plates. After allowing for the systematic difference, the probable error in a single measurement of $\log W$ was computed to be 0.08, i.e., about 20 per cent.

III. ANALYSIS

The abundance of lithium relative to the heavier metals and relative to the sun has been estimated for each of the four stars with detectable Li I features and measurable comparison lines by a rough curve-of-growth analysis. While high accuracy is not to be expected from the limited material available, certainly order-of-magnitude values can be obtained. Since all the lines involved are of similar strengths, the significant part of the curve of growth is fairly well defined. Further, it will be shown that the results are quite insensitive to errors in estimating the temperature and electron pressure in the stellar atmospheres.

The seven lines of calcium, iron, and sodium listed in Table 2 were used to establish

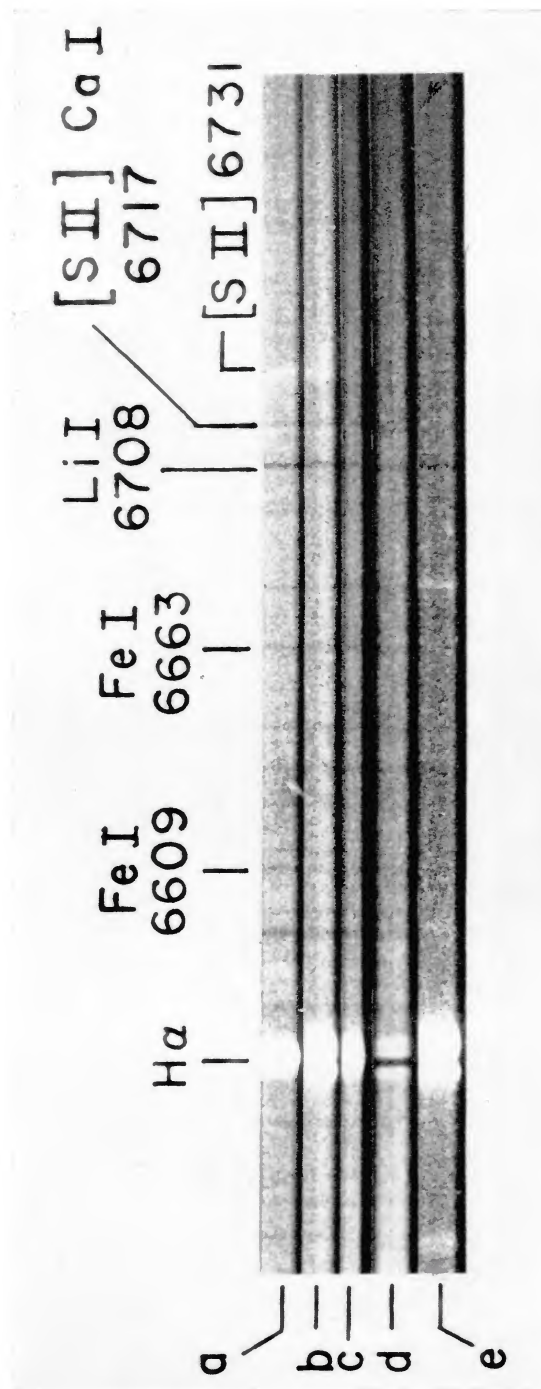


FIG. 1.—Spectra of the stars found to show Li I, from H α longward. The stars are (a) T Tau, (b) RY Tau, (c) GW Ori, (d) SU Aur, and (e) RW Aur.

a curve of growth for each star and for the control star 61 UMa. Caution must be exercised in using the strengths of the D lines in the T Tauri stars, since these lines often have emission or interstellar or circumstellar absorption components. For example, in T Tau itself the extrastellar D lines are stronger than those originating in the stellar atmosphere. But, since the D lines define the strong-line end of the segment of the curve of growth used and the Li I line falls at the weak-line end, the effect of such errors in the D-line strengths is not serious. In order to construct the curve of growth, the relative abundances of Ca, Fe, and Na were assumed to be the same in the program stars as the sun. Values of the abscissae of the solar curve of growth for the seven lines were obtained by fitting one of Wrubel's (1949) curves of growth for $B^{(0)}/B^{(1)} = \frac{2}{3}$ to Wright's (1951a) empirical solar curve of growth and using Wright's and Allen's (1934) equivalent widths to read off the corresponding $\log \eta_0$'s for all the lines listed except Li I. To obtain the solar $\log \eta_0$ for Li I, Greenstein and Richardson's (1951) value of the equivalent width in the sun was corrected for blending (see below) and applied to the same theoretical curve. Note that the equivalent width of the Li I doublet in the sun is less than one one-hundredth that in T Tau, which has been assigned to a similar spectral class.

As a first trial, the values of $\log W/\lambda + 6$ from the four program stars and the control star were plotted against unmodified solar $\log \eta_0$'s. These plots each appeared to define rather well the transition portion of a curve of growth, and it was possible to represent each by a theoretical curve from Wrubel's computations. Scatter about each theoretical curve was well within the estimated errors of photometry. These statements cannot be made with as much certainty about SU Aur as about the remaining stars, since the spectrogram of this star was overexposed and did not permit measurement of lines 5, 6, and 7 in Table 2. Figure 2 presents the observed points and the adopted theoretical curves for these five stars.

The reason for the apparent adequacy of the solar $\log \eta_0$'s can be seen from the following argument. In the sun and similar stars the elements considered here are mostly singly ionized in the line-forming layers. Thus if one assumes that the number of neutral atoms is small compared with the number of singly ionized atoms and that the number of doubly ionized atoms is negligible, one may introduce the Boltzmann and Saha equations into Wrubel's definition of η_0 and obtain, for the difference between the stellar and solar $\log \eta_0$'s for a given line,

$$\log \eta_0^* - \log \eta_0^\odot = \log \frac{\kappa_\odot}{\kappa_*} + \frac{5}{2} \log \frac{T^\odot}{T_*} - \log \frac{P_e^\odot}{P_e^*} + \log \frac{N^*}{N^\odot} + (\theta^* - \theta^\odot)(I - E) - \log \frac{v^*}{v^\odot}. \quad (1)$$

Here, as usual, κ is the continuous-absorption coefficient, T is the temperature, $\theta = 5040/T$, P_e is the electron pressure, N is the number of atoms of the given element per gram of stellar material, I and E are, respectively, the ionization and excitation potentials in electron volts, and v is the most probable velocity for small-scale motion. It has been assumed that the partition functions are not significantly different in the star and the sun and that the same temperature can be used to describe both the ionization and the excitation equilibria. The only term on the right of equation (1) which will produce a different shift between the values of $\log \eta_0^*$ for different lines is the term involving the ionization and excitation potentials. Inspection of Table 2 shows that $I - E$ for all the lines of neutral elements except the two of Ca I falls in the range 5.1–5.6 ev. Line 7 deviates most from the other lines; here $I - E$ is 3.6 ev. Thus small errors in θ would have little effect on the shape of the curve; slight changes in the plotted positions of the Ca I lines would not be noticed because they are on the "flat" part of the curve of growth. In dwarf stars significantly cooler than the sun, differences in the curve of

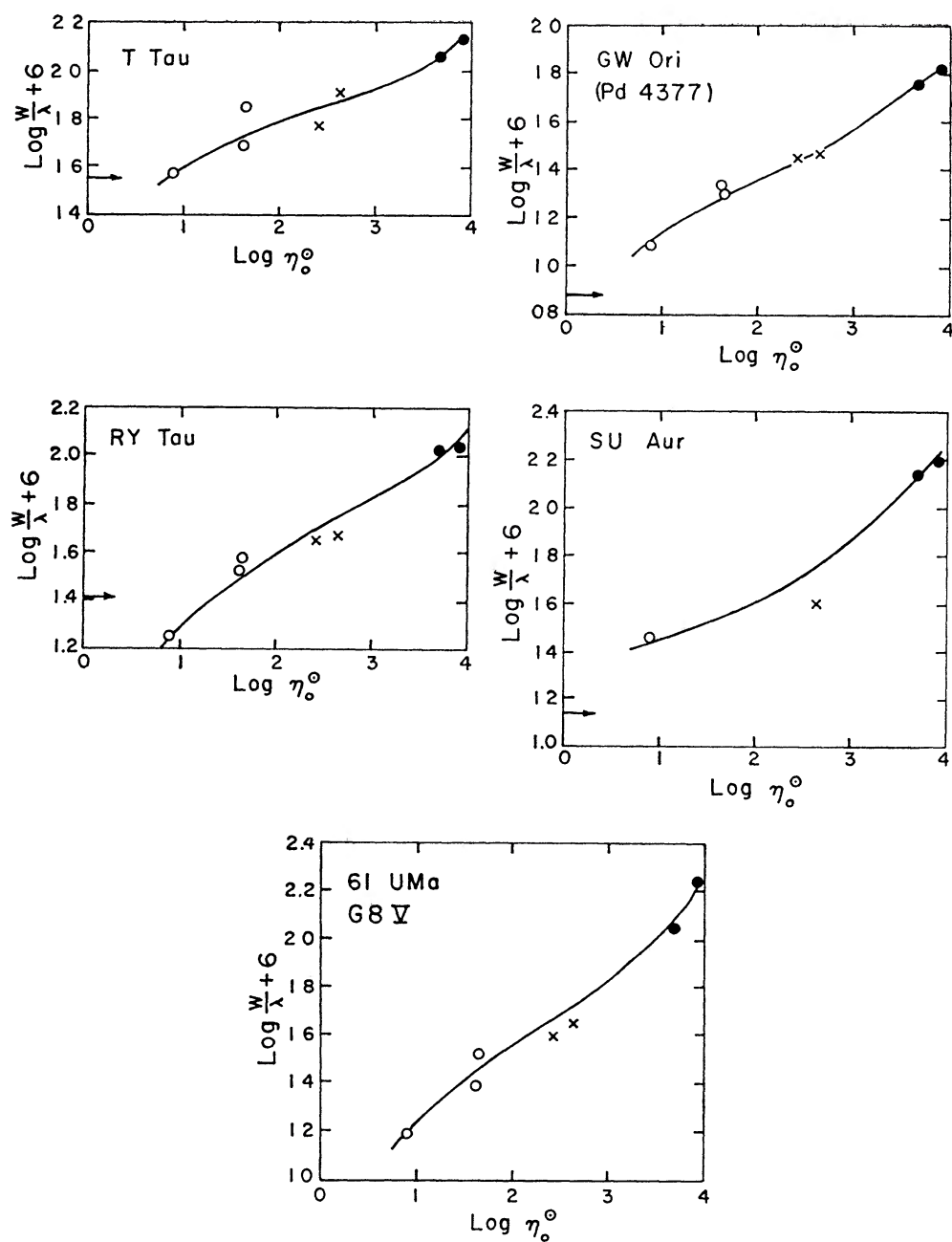


FIG. 2—Curves of growth for the four T Tauri stars and the standard star using solar abscissae. The open circles are lines of Fe I; the crosses, Ca I; and the filled circles, Na I. The arrows at the left indicate the adjusted equivalent widths for Li I. The solid curves are selected from Wrubel's M E-model curves of growth.

growth would arise because the iron atoms become mostly neutral and equation (1) no longer holds. Similarly, for giant stars sufficiently hotter than the sun, a significant number of calcium atoms become twice ionized, making the equation invalid. There is no evidence in Figure 2 that either of these events is occurring.

In order to determine explicitly what effects deviations from the solar $\log \eta_0$'s might have, values of $\log \eta_0^*$ were computed for four combinations of temperature and electron pressure which correspond to stellar atmospheres outside the range expected of the stars studied here. The values used were as follows: case 1, $T = 8000^\circ$, $\log P_e = 1.9$; case 2, $T = 8000^\circ$, $\log P_e = 2.2$; case 3, $T = 4000^\circ$, $\log P_e = 0.84$; and case 4, $T = 4000^\circ$, $\log P_e = -0.35$. The electron pressures were taken from Aller (1953, p. 225) for the high temperature and from Bonsack (1959) for the low temperature, to correspond with luminosity classes III and V. The spectral types corresponding with the four cases are, respectively, A8 III, A8 V, K5 V, and K2 III. In computing $\log \eta_0^*$ (which differs from the $\log \eta_0^*$ given in equation (1) by the omission of the term in v) the ratio $N^*/N^\odot$ was taken as unity, and the values of the continuous opacity were taken from the curves presented by Vitense (1951). Appropriate correction factors were applied to equation (1) to account for states of ionization different from those assumed in the derivation. These extra terms were computed by the Saha equation.

The measured values of $\log W/\lambda + 6$ for T Tau, GW Ori (from the Pd plate), and 61 UMa were plotted against these four sets of $\log \eta_0^*$. The diagrams for T Tau are presented in Figure 3 and for 61 UMa in Figure 4. One of Wrubel's theoretical curves has been fitted to the points in each case; these are also shown in the figures. The curves for cases 1, 2, and 4 have a normal appearance, but the curves required for case 3 had, in all three stars, unreasonably low damping constants—particularly so because conditions representing a cool dwarf atmosphere had been assumed. This result is not due to weak Na I D lines, possibly caused by incipient emission in the T Tauri stars; even ignoring the D lines, lines 3 and 7 of Ca I are sufficiently displaced to demand an excessively low value of the damping. Furthermore, low damping is also required in the curve derived from the equivalent widths of the normal star.

Three quantities of interest can be derived from the fit of the theoretical curve to the observed points. The first is the ratio of damping to Doppler width, a , which is determined by the length and slope of the horizontal part of the curve. The second is the most probable velocity, v , derived from the difference between the ordinates of the theoretical and empirical curves; the third is the ratio of mean abundances, $N^*/N^\odot$, obtained from the difference between the abscissae of the empirical and theoretical curves, after correcting for the difference in v . Recall that the empirical abscissa, $\log \eta_0^*$, is computed assuming $N^* = N^\odot$. Values of these quantities for each of the five stars obtained using the solar $\log \eta_0$'s are given in part *a* of Table 3, and the values obtained from T Tau, GW Ori, and 61 UMa for the four test cases are given in part *b*. The values of $\log a$ may be compared with a value of -1.6 obtained in fitting Wright's solar data, and a value of -3.0 obtained by Wright (1951*b*) for the K2 III star α Boo. The values of v , the thermal plus turbulent motion, may be compared with 2.0 km/sec obtained for the sun from Wright's data (a value which agrees adequately with numerous other investigators). It is obviously much smaller than the value 50 km/sec given by Herbig (1952) as the projected rotational velocity required to explain the observed width of the absorption lines in the T Tauri stars.

In obtaining the abundance of lithium relative to these other elements, the fact that the observed lithium feature is a blended doublet must be taken into account. At the velocities of small-scale motion encountered in these stars, the absorption coefficients of the lines are themselves significantly blended, and it cannot be assumed that the absorptions of the individual lines simply add. Thus in this analysis it was assumed that the effect of blending was to produce a total line-absorption coefficient which differed from the absorption coefficient of the stronger line of the doublet only in that it

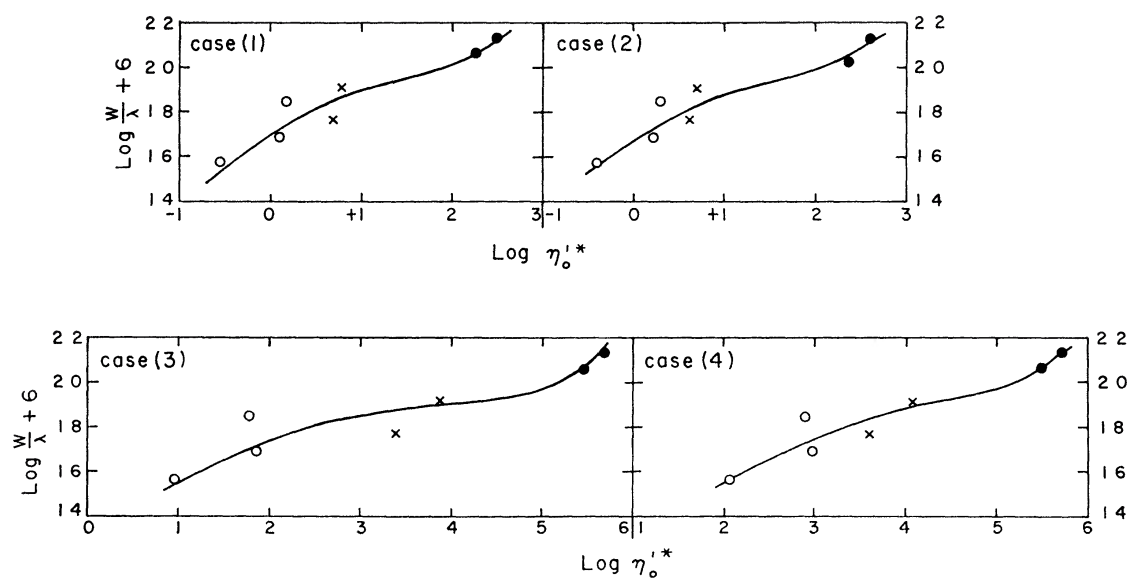


FIG. 3.—Curves of growth for T Tau, assuming four extreme models for the star (see text). Symbols and curves have the same meaning as in Fig. 2.

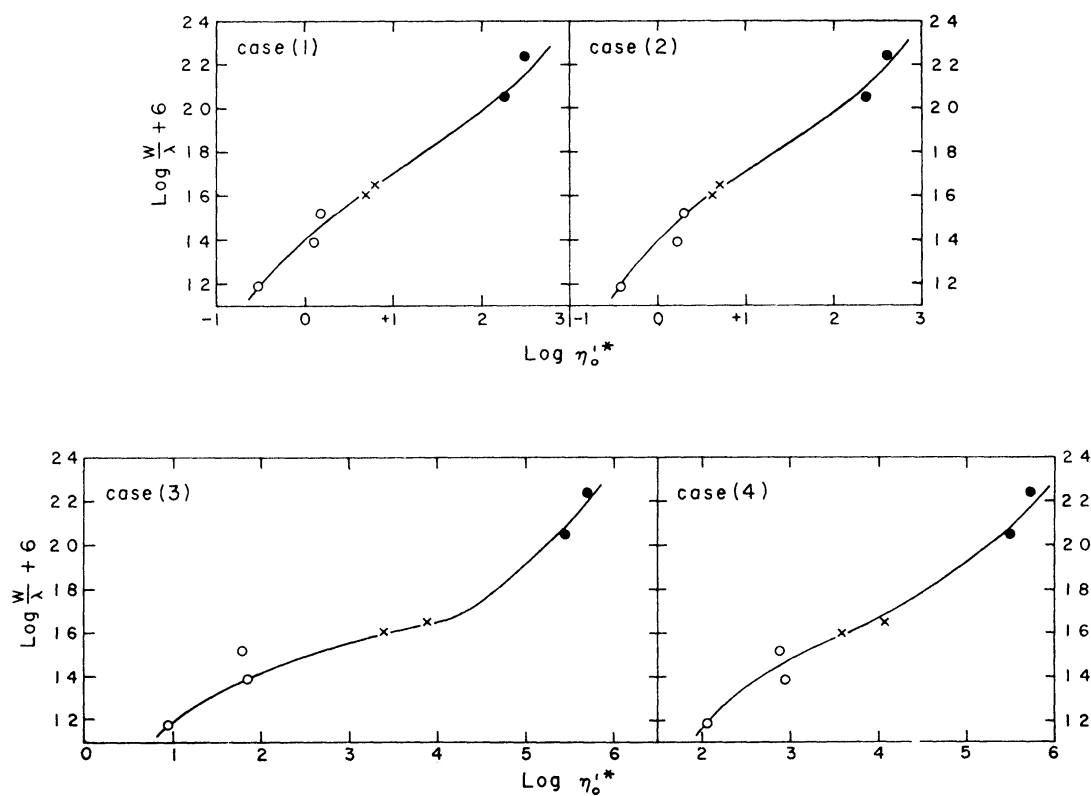


FIG. 4.—Curves of growth for 61 UMa (G8 V) corresponding to Fig. 3

was 50 per cent broader. This probably slightly exaggerates the effect, since it puts slightly more of the absorption-coefficient curve near the maximum than actually is the case. This correction was applied by simply increasing the value of v for lithium, computed from the value for the heavier elements found from the curve of growth and the temperature, by 50 per cent, and using the increased value both in correcting $W(\text{Li})$ for use with the curve of growth derived for the heavier elements and in the interpretation of the resulting value of $\log \eta_0^*(\text{Li})$. In the equations which follow, $v(\text{Li})$ includes this correction.

TABLE 3
RESULTS

STAR	$-\log a$	v (km/sec)	$\log N^*/N\odot$	$-\log$ $W/\lambda(\text{Li})$	$\log R(\text{Li})$	$-\log$ $W/\lambda(\text{Ba})$	$\log R(\text{Ba})/$ $r(P_e)$
a) Solar $\log \eta_0$							
RY Tau	2.2	4 0	0 0	4 29	2 6	4 68	-0 6
T Tau	3 0	4 4	0 8	4 17	2 2	4 46	- .7
SU Aur	2 6	2 6	1 0	4 44	1 7:	4 40	+ 2
GW Ori (Pd)	2 4	1 9	0 1	4 62	1 9	4 53	+ 3
GW Ori (Ce)	2 8	2 8	0 1	4 69	1 7	4 53	+ 2
61 UMa	1 8	3 0	0 0	≤ 5 28	≤ 0 8	4 59	-0 1
RW Aur				4 50	2:		
b) Test Cases							
T Tau {	1	+3 0	5 6	+1 9	4 17	+2 3	
	2	+3 0	5 7	+1 9	4 17	+2 2	
	3	+4 6	4 0	+0 8	4 17	+0 4	
	4	+3 6	4 4	-0 4	4 17	+1 6	
GW Ori {	1	+2 4	2 6	+1 3	4 62	+2 1	
	2	+2 4	2 7	+1 2	4 62	+2 2	
	3	+4 2	1 5	+0 3	4 62	-0 1	
	4	+3 0	2 0	-1 2	4 62	+1 3	
61 UMa {	1	+1 8	4 4	+1 2			
	2	+1 8	4 8	+1 1			
	3	+3 4	2 3	+0 1			
	4	+2 4	2 1	-1 2			

The low first ionization potential and the high second I.P. (75 ev) of lithium insure that in the stars considered here, even in the extreme test cases, the assumptions regarding the state of ionization applied in deriving equation (1) are valid. Then the abundance of lithium relative to that of some element Z is related to the difference between the $\log \eta_0^*$ for the lithium doublet and that for a line of Z I by

$$\log \frac{Li}{Z} = \log \eta_0^*(\text{Li}) - \log \eta_0^*(Z) + C(\text{Li}) - C(Z) - \theta [I(\text{Li}) - I(Z) + E(Z)] + \log \frac{v^*(\text{Li})}{v^*(Z)} \tag{2}$$

Here Li and Z are the numbers of the two atoms per gram. The constants C involve the statistical weights, wave lengths, f -values, and partition functions related to the two

transitions. In order to compare with the sun, one subtracts a similar equation for the solar atmosphere:

$$\begin{aligned} \log R = \log \frac{(Li/Z)^*}{(Li/Z)^\odot} = \log \eta_0'^*(Li) - \log \eta_0^\odot(Li) - \log \eta_0'^*(Z) + \log \eta_0^\odot(Z) \\ - (\theta^* - \theta^\odot) [I(Li) - I(Z) + E(Z)] + \log \frac{v^*(Li)}{v^*(Z)} - \log \frac{v^\odot(Li)}{v^\odot(Z)}. \end{aligned} \quad (3)$$

Since the quantity $\log \eta_0'^* - \log \eta_0$ has already been computed for each line, it is convenient to enter this quantity (eq. [1]) in equation (3), to give

$$\begin{aligned} \log R = \log \eta_0'^*(Li) - \log \eta_0^\odot(Li) + \log \frac{(\kappa/P_e)^*}{(\kappa/P_e)^\odot} + \frac{5}{2} \log \frac{T^*}{T^\odot} - (\theta^* - \theta^\odot) I(Li) \\ + \log \frac{v^*(Li)}{v^*(Z)} - \log \frac{v^\odot(Li)}{v^\odot(Z)}. \end{aligned} \quad (4)$$

Note that, although no quantities related to the line strengths of element Z enter the right side of equation (4), the assumption that the abundance of Z equals the solar abundance was made when applying equation (1); only when this assumption is valid, does R represent the abundance of lithium relative to the sun.

The values of $\log R$ for the four stars derived by using the solar $\log \eta_0$'s, along with the equivalent widths of the lithium lines, are given in Table 3. These values are also given for each test case for T Tau and GW Ori. No upper limits to $\log R$ were obtained for the stars in which no Li I was seen, except for the standard star 61 UMa, where an upper limit of 0.8 was derived (solar $\log \eta_0$'s).

Since the abundances of the heavy element are of interest in these stars, a quantity analogous to $\log R$ in equation (4) was obtained for barium, using the Ba II line at λ 6142 (No. 4 in Table 2). The interpretation of the equivalent width of this line is not complicated by blending, and the velocity v for Ba differs negligibly from that of the comparison elements; but, since in this case a line of the ionized atom is used, the approximations entering equation (1) are not valid. The equation analogous to equation (4) for barium is

$$\log R(Ba) = \log \eta_0'^*(Ba) - \log \eta_0^\odot(Ba) + (\theta^* - \theta^\odot) E(Ba) + \log \frac{\kappa^*}{\kappa^\odot}. \quad (5)$$

Values of $\log R(Ba)$ have been computed for the four program stars and for 61 UMa using the solar $\log \eta_0$'s. In this case the temperatures are taken equal to the solar value, so that the third term in equation (5) vanishes and the fourth reduces to the ratio of the electron pressures. From the appearance of the curves of growth (low damping) and the absolute magnitudes of the T Tauri stars, it seems likely that the electron pressures are lower than the solar value, but it is difficult to assign a number to each star. Therefore, the values of the abundance ratio R are presented in Table 3 as $\log R(Ba)/r(P_e)$, where $r(P_e)$ is the ratio of the stellar to the solar electron pressures.

IV. RESULTS

The values of $\log R(Li)$ listed in part *a* of Table 3 indicate that the abundance of lithium relative to the heavier metals in the four stars studied exceeds the solar value of this ratio by factors ranging from 50 to 400, provided that the use of solar $\log \eta_0$'s is a valid approximation. The agreement of the results from the two independently analyzed plates of GW Ori, which were taken by different telescopes at times separated by a month, indicates that the errors probably do not exceed a factor of 5.

The available evidence suggests that the use of unmodified solar values of the curve-

of-growth abscissae does not produce significant errors. From equation (1) it may be seen that only large deviations from solar conditions will produce relative changes in the abscissae for the lines used here; changes in the electron pressure alone will have no effect at all as long as the continuous opacity is due to H^- . The results of test cases 1 and 2 given in part *b* of Table 3 show that the assumption of an unreasonably high temperature does not increase the abundance of lithium relative to Ca, Fe, and Na but does require that all these elements be overabundant relative to the sun by factors from 10 to 100. Case 4 shows that if the T Tauri stars are assumed to be substantially cooler than the sun and above the main sequence, the high relative abundance of lithium is reduced, but in at least two stars the abundances of the metals are then reduced significantly below the solar values. If the "veiling" of the absorption spectrum by continuous emission described by Herbig (1958*b*) is significant in any of these stars, the abundances of the metals given by $N^*/N^\odot$ are too low, but the overabundance of Li relative to the other metals is unaffected. The star in which such an effect is most probably operating is GW Ori, which Joy (1949) classified as dK3 but which has line strengths appropriate to a G star. Test case 3, which represents the stars as K5 dwarfs, must be rejected because of the unreasonably low damping required by the curves of growth, as has been remarked. This case suggests that if the stars are dwarfs, as the spectral classifications of Joy and Herbig suggest (except for SU Aur), then they must be dwarfs of class G. If the stars are of class G and have luminosities somewhere in the range giant to dwarf, the solar log η_0 's will give adequately accurate results; possibly the metals in T Tau and SU Aur are somewhat overabundant, although in the latter the apparent overabundance may well be due to errors in fitting the curve of growth. Since the conversion of the quantity $R(\text{Li})$ into the abundance of lithium relative to the sun requires multiplication by the abundance of metals relative to the sun, it is possible that there may be 10^3 times as much lithium in T Tau as in the sun.

The abundance of Li in RW Aur could not be determined because of the weakness and breadth of the metallic lines. An estimate may be made, however, by comparison of the depth of the Li I feature with that of the Fe I line λ 6609.11, which has essentially the same temperature sensitivity as the Li I feature. The Fe I line cannot be identified with certainty in RW Aur, but it can be stated that the central depth of the Li I feature is at least 3.0 times that of the Fe I line. This ratio ranged from 1.2 to 2.8 in the four stars analyzed. Thus one may conclude that lithium has the same or greater abundance in RW Aur as in the other four stars studied.

It should be stated that there is no evidence that the Li I doublet originates in a circumstellar nebula and is thus enhanced relative to the other absorption lines by dilution of the radiation. If the Li I doublet were thus enhanced, the D lines would be similarly affected, but the D lines have normal or low intensities. The lines of Ca I and Fe I used for comparison, except for line 5, do not arise from metastable levels. In addition, the stellar component of the D lines, the Li I doublet, and the remaining absorption lines exhibit no detectable difference in radial velocity.

Thus all the T Tauri stars considered in this study and one star resembling T Tau except for its spectroscopic luminosity have abundances of lithium relative to the metals greater than the solar ratio by a factor of approximately 100. The other stars examined had no detectable lithium, but in stars of class F and earlier this does not necessarily imply an abundance lower than in the stars in which it is observed. In those classified as late G and K stars the abundance probably cannot much exceed the solar value.

The spectrogram of RW Aur used in this study differs conspicuously from those of T Tau and the other three stars having strong Li I lines. The absorption lines in RW Aur were extremely shallow and broad and, except for the very strong D lines, almost invisible. The lines of [O I] and [S II] found in the other stars were absent, and other broad emission lines—predominantly permitted transitions of Fe II—were strongly present. Strong emission in $H\alpha$ with a central reversal was present, as were weaker emissions at the D lines and He I λ 5876 and λ 6678. Only $H\alpha$, Na I, and He I λ 5876 were observed

in addition to the forbidden lines in the other stars. The spectrum of V380 Ori resembles RW Aur, except that the excitation in the Fe II emission spectrum is higher, D lines appear only in emission, and the He I emission is weaker. This star shows no Li I but is probably too hot to exhibit the line even if lithium is abundant in the atmosphere. Apparently, the circumstellar envelopes of V380 Ori and RW Aur are more dense, as indicated by the absence of forbidden lines, and more massive, as indicated by the presence of permitted lines, than those of the other T Tauri stars. Perhaps they represent a different stage of the evolution of a young star.

Of the remaining stars listed in Table 1, CQ Tau and PZ Mon were chosen because they were listed in the *General Catalog of Variable Stars* as being RW Aurigae stars, probably on the basis of their light-curves. PZ Mon has been investigated spectroscopically by L. and G. Münch (1955) and photometrically by S. Gaposchkin (1955). In both these studies the star is described as a flare star; the spectroscopic investigation revealed Ca II emission normally and H emission during outbursts. The spectrogram obtained for this study displayed a yellow-red spectrum agreeing with the K2 V classification of Münch and Münch, except that H α was too weak. No Li I could be seen. No spectroscopic information on CQ Tau was found in the literature; the spectrogram studied here shows a few broad and weak absorption lines longward of the D lines, fairly weak D lines, broad H α emission with an absorption core placed slightly longward of center, and an enormously broad (~ 100 Å at the continuum) underlying H α absorption. This star seems indeed peculiar but not related to the T Tauri class. No Li I is observable. Neither of these stars is connected with visible nebulosity, according to the *Catalog*.

The broad-line G star HD 117555 has broad and strong emission at H α with a strong central reversal. The relative positions of these components are quite different on the two plates studied; in one the shortward emission component is nearly invisible, while in the other the two have similar strengths. The rapid changes in H α and the width of the absorption lines suggest violent motions in the atmosphere and surrounding envelope, which might conceivably be a seat of lithium production. No Li I line is seen; however, a weak line would be obliterated by the broadening. The stars +24°2742 and +37°2318 have composite spectra with variable H α emission; the latter also had weak [O I] in emission in one plate studied. Both these objects are probably multiple-star systems with associated gaseous streams, which again could be seats of lithium production. But again no trace of the element was found.

Ambartsumian (1957) has suggested that the bright violet continuum in the T Tauri stars results from the direct injection into the lower chromosphere of energy from the stellar interior. He also proposes that such energy produces the Li and Be found in the solar atmosphere. If the Li found in the stars of this study has originated in this way, the absence of observable Li I in AG Dra, which has a G-type absorption-line spectrum and a bright violet continuum, indicates that veiling violet continua do not necessarily imply high-energy phenomena resulting in Li production.

The results of this small survey suggest that lithium is abundant only in very young stars. But before such a statement can be made with confidence, more stars must be studied. In particular, it is by no means established that all stars similar to those found to have strong lithium features share this property. Such further studies can profitably be carried out at lower dispersion, since lines of the strength found here will still be conspicuous on such spectrograms.

The final column in Table 3 gives the abundance of barium relative to the ordinary metals per unit stellar electron pressure, divided by the same quantity for the sun. For T Tau and RY Tau these numbers are significantly less than unity, and, since the electron pressure in these stars is probably somewhat less than in the sun, they indicate an underabundance of barium relative to the metals by a factor of the order of 10. This result is in the opposite sense from that of Wallerstein and Helfer (1959) who found barium overabundant by a factor of 2 in the Hyades dwarfs. The values obtained for

the other two program stars and the normal dwarf probably indicate abundances near the solar one; the result for the latter indicates that the abundance deficiencies of Ba in T Tau and RY Tau are probably significant. Consequently, processes involving slow neutron captures do not occur.

V. THE ORIGIN OF LITHIUM IN T TAURI STARS

When a young protostar condenses from a dense nebula of gas and dust, electromagnetic or other non-thermal phenomena may occur. Ambartsumian has discussed the possibilities of non-thermal phenomena in UV Cet and in RW Aur variables (1957); Greenstein has discussed the possible effects of flares (1950). Our observations indicate that lithium is not present in some stars suspected of showing non-thermal continuous emission—for example, AG Dra (Mirzoyan 1957) and other symbiotic, flaring stars.

The apparent overabundance of lithium in the primary cosmic radiation (CR) is such that $(Li/H)_{CR}$ is of the order of 10^{-3} . This high abundance is supposedly attained by a steady-state process in which heavy CR nuclei collide with the stationary interstellar protons and produce light fragments by spallation. Some variant of such a process might occur in the space near, or in the envelope of, a protostar.

The direct capture of CR Li nuclei can be evaluated. Even if not destroyed by collisions as they are brought to rest, the number of CR Li nuclei is small. The observed ratio $(Li/H)_{CR} = 10^{-3}$; in the volume of space, V , out of which the star is formed, there are $10^{-3} V \times u_{CR}/E$ CR nuclei of Li and $n_H V$ ordinary hydrogen atoms. Let the energy density of CR be 1 ev/cm^3 or $u_{CR} = 1.6 \times 10^{-12} \text{ erg/cm}^3$, the mean energy $\bar{E} = 10^9 \text{ ev} = 1.6 \times 10^{-3} \text{ erg}$ (Peters 1958), and the particle density of hydrogen $n_H = 1/\text{cm}^3$. Then the ratio of Li/H attained after condensation is

$$\frac{Li}{H} \leq 10^{-3} \frac{u_{CR}}{En_H} \leq 10^{-12}. \quad (6)$$

Since the solar abundance, Li/H is about 10^{-11} , condensation is insufficient to account for the solar value, and even more so for the T Tauri stars.

The abundance of interstellar atomic lithium (Spitzer and Field 1955) is not high; because of its high chemical activity, there is a possibility that a large fraction of Li exists as stable compounds in dust grains. The life of a dust grain has been estimated at 10^8 years, that of a cosmic ray at 10^6 years. If CR Li atoms are slowed without disintegration, they may be stored at 100 times higher concentration in the dust grains than in cosmic rays, compared to other metals. If T Tauri stars are formed out of interstellar matter of larger than normal dust concentration, the Li abundance can be increased appreciably. Let ϵ_d and ϵ_g be the abundance ratio of Li to a normal metal in the dust and gas, assuming that the normal metals show no abundance changes between the two phases. Let F be the fraction of a star's atoms originally contained in the dust phase; the usual assumption is that $F = 10^{-2}$ for normal stars. If star 1 originates in a dense cloud, it is possible that $F_1 \rightarrow 1$. The ratio of Li/metal abundances in two stars, then, is

$$R = \frac{(Li/Metal)_1}{(Li/Metal)_2} = \frac{\epsilon_d F_1 + \epsilon_g (1 - F_1)}{\epsilon_d F_2 + \epsilon_g (1 - F_2)}. \quad (7)$$

Since $(\epsilon_d/\epsilon_g)F_2$ may be large or small, we cannot simplify equation (7), except to note that the enhancement is R/F_2 . Only if $\epsilon_d/\epsilon_g > 10^3$, $F_2 < 10^{-2}$, and $F_1 = 1$ will the increase in Li abundance reach the desired value of 100. Thus, while this storage mechanism is effective, it does require an unreasonably high concentration of Li-rich dust in the formation of the T Tauri stars, unless other processes lead to an abnormally large abundance of Li in the dust cloud, or protostar.

Consideration of the energy available indicates several possibilities, if mechanisms can be found to convert energy into nuclear transmutations resulting in Li formation. First, what fraction of stellar energy needs to appear in high-energy form capable of producing Li? If our observed high-abundance $\text{Li}/\text{H} = 10^{-9}$ is taken as the primeval abundance in all stars, then each star destroys $10^{-9} M/m_{\text{H}}$ atoms of Li during its life. Assume that 100 Mev is needed in high-energy form, per synthesis, and that the actual yield is one Li atom per 100 Mev/ β^* . To keep Li at its observed abundance value, so that it may be cycled through interstellar space to form new stars, each star must expend energy

$$E_{\text{Li}} = 10^{-9} \frac{M}{m_{\text{H}}} \frac{100 \text{ Mev}}{\beta^*} = 1.6 \times 10^{-13} \frac{M}{m_{\text{H}}}. \quad (8)$$

The total energy release by the star, either on the p - p or CN cycles is 10^{-5} erg/proton, and we may assume that the average star burns 10 per cent of its protons. Then the total stellar energy is

$$Lt = 10^{-6} \frac{M}{m_{\text{H}}}, \quad (9)$$

and the fraction of energy for synthesis is

$$\frac{E_{\text{Li}}}{Lt} = \frac{1.6 \times 10^{-7}}{\beta^*}. \quad (10)$$

This number can also be estimated by using the total observed integrated luminosity of a volume of the Galaxy near the sun as compared to its Li content based on our high abundance value. The results are accordant. In this mechanism each Li atom requires 100 Mev/ β^* in energy. If β^* is near unity, the high-energy phenomena represent 10^{-7} of the total stellar energy, a not unreasonable value. However, no detail can be given as to how the stellar energy is transformed and appears in nuclear-building processes.

A concrete process, spallation, can be investigated quantitatively. Assume that both cosmic rays and magnetic fields exist in the volume of space out of which the protostar is being formed. Let the CR protons collide with stationary heavy nuclei, near the surface of the star, as it condenses. Since the center of mass in such a collision moves only slowly, the fragments of the heavy nucleus are nearly at rest and produce D, T, He^3 , Li, and Be which will not be further disintegrated, as well as numerous H, He^4 , and mesons, once the proton energy exceeds 500 Mev. We replace the actual cosmic-ray spectrum by protons of one energy $\bar{E} = 1$ Bev. The secondary processes involving mesons and γ -rays will be neglected. The following discussion is largely due to Dr. Matthew Sands, of the Physics Department, California Institute of Technology. Inelastic collisions and ionization losses are small at 1 Bev compared to nuclear collisions; the majority of collisions are with stationary hydrogen atoms and represent a serious inefficiency factor in spallation. If the abundance of a nucleus of atomic weight A is N_A , the cross-section for spallation of such nuclei is $A^{2/3} \alpha_A \sigma N_A$, and the yield is $\alpha_A A^{2/3} \sigma N_A$, where $\sigma \approx 10^{-27} \text{ cm}^2$. The fractional yield of Li per complete breakup of a nucleus is α_A ; in nuclear stars in emulsions, $\alpha_A \rightarrow 1$ for heavy nuclei struck by CR protons when $E < 600$ Mev. We may estimate $\alpha_A = 0.1$ for $A = 12$ and $\alpha_A = 1$ for $A = 20$, and interpolate. The normal abundances of the elements in the stars are used for N_A , and the summation is then carried out. The abundance ratio of Li/H is

$$\frac{\text{Li}}{\text{H}} = \frac{U_{\text{CR}}}{\bar{E}} \left[\frac{\sum_{A=12}^{56} N_A \alpha_A A^{2/3}}{N_{\text{H}}^2} \right], \quad (11)$$

and, since N_A is the abundance relative to H, N_H can be taken as unity. According to Sands, the major contributions to spallation are O and Ne, which are cosmically abundant and heavy enough to yield a Li nucleus when disrupted. The bracketed term in equation (11) is an efficiency factor, since most collisions are with H; its value is 4×10^{-3} based on stellar abundances by Greenstein (1956). Since a was taken rather high, $Li/H \leq 4 \times 10^{-12}$, and the predicted Li abundance is far too small. One Li atom is produced for 250 CR protons of 1-Bev energy, i.e., at a cost of 250 Bev.

The observed high value of Li/H requires a larger energy source than the normal energy density of cosmic rays or a selective process which brings this energy source, or the cosmic rays, to the surface layers of a contracting protostar. Under such circumstances, if the layers spectroscopically observable represent only the fraction $\Delta M/M$ of the total mass of the star, the observable Li/H abundance can reach the value $1/(\Delta M/M)$ times its mean value. The outer convective or unstable layers in normal main-sequence stars represent $\Delta M/M \approx 10^{-2}$; the spectroscopically observable layer, of course, is very thin, $\Delta M/M \approx 10^{-8}$. Thus a concentration of CR, or magnetic field energy (and presumably angular momentum), near the surface is required, just as in the theory of the formation of stars. We are forced to consider surface-formation processes, such as have been described for magnetic variable stars by Fowler, Burbidge, and Burbidge (1955) and by Biermann (1956). Fowler *et al.* reported Be II in the magnetic Ap star α^2 /CVn. This result has been confirmed by Bonsack (unpublished). Presumably, then, the differential energy spectrum of the CR must be taken into account, low-energy protons and alpha particles producing neutrons and building D and heavy elements, while high-energy CR produces spallation. The early production of He^3 , D, and Li may be important, taken in conjunction with the history of the planetary system. If the relative fractionation of such elements as D/H, He^3/He^4 , and Li/Na can be neglected, the terrestrial abundance ratios would indicate the conditions in the outer envelope of the sun and in the solar nebula which formed the planetary system. It should be remembered that our Li abundance in T Tauri stars is nearly the same as in the earth.

The trapped magnetic field will have ample energy to produce the observed Li abundance if a suitable conversion mechanism can be found and if the magnetic field energy is dissipated near the star's surface, so that $\Delta M/M$ will be small. In a volume of space containing 1 solar mass of gas and an initial magnetic field, H , the magnetic energy is $5 \times 10^{55} H^2$ ergs. At a cost of 250 Bev per Li nucleus, $10^{56} H^2$ Li nuclei could be produced, or an abundance ratio

$$\frac{Li}{H} = \frac{0.1 H^2}{\Delta M/M}. \quad (12)$$

Thus, for an interstellar magnetic field of 10^{-6} gauss, $Li/H = 10^{-13}/\Delta M/M$, and for 3×10^{-5} gauss, $10^{-10}/\Delta M/M$. With plausible assumptions on the depth $\Delta M/M$, the observed value, $Li/H = 10^{-9}$ is attainable.

VI. LITHIUM IN THE T TAURI NEBULA

It is of interest to estimate the abundance of lithium in the nebula surrounding T Tau, since presumably this material is the remainder of the nebula from which the star condensed. Extremely strong extrastellar sodium D lines are present in the spectrum of T Tau; these exhibit a radial velocity of -120 km/sec (Joy 1945). This high velocity and the nearness of the star (~ 100 pc) indicate that these lines originate in a circumstellar rather than an interstellar cloud. There is no trace of non-stellar Li I, which suggests that lithium may be less abundant in the nebula than in the stellar atmosphere. The equivalent widths of the circumstellar lines were measured on the tracing of Pd 4233 as 1.06 Å (D_2) and 0.83 Å (D_1); the strength of any displaced Li I doublet was estimated as less than 0.06 Å. To interpret these measurements, it was assumed that the extra-

stellar absorption arose in a single cloud near T Tau, and Strömgren's (1948) curve of growth for interstellar lines (damping constant $a = 0.001$) was extended to the greater equivalent widths needed here. This damping constant is appropriate to natural damping at a kinetic temperature of 10^4 ° K. The doublet ratio suggests a temperature of 34000°, but this may be too high if the doublet ratio is reduced by the blending of D₁ with the stellar D lines. The ionization temperature, which has little effect on the result, was assumed equal to the effective temperature of a G5V star. For kinetic temperatures between 10^2 and 3.4×10^4 ° K an abundance ratio $Li/Na < 10^{-4}$ results, assuming a value of Strömgren's (1948) correction to the ionization equation for non-equilibrium conditions equal to that computed by Spitzer (1949) for the general interstellar medium. It seems likely that the T Tauri nebula is closer to thermodynamic equilibrium than average interstellar matter; if the relative ionization is that of thermodynamic equilibrium, $Li/Na < 10^{-5}$.

The limit 10^{-4} obtained for the T Tauri nebula is three orders of magnitude smaller than that obtained by Spitzer (1949) for the general interstellar medium, largely because Spitzer compared his limiting Li density with the mean observed for sodium over all interstellar space. The value obtained here is close to the upper limit derived by Spitzer and Field (1955) for the ratio of interstellar beryllium to sodium. Since Be and Li are probably made in the same processes, their initial abundances should be similar.

The ratio of lithium to metals is of the order of 10^2 times the solar value in the atmosphere of T Tau, and the solar ratio of Li to Na is of the order of 10^{-5} (Greenstein 1956); thus the Li/Na ratio in the T Tau atmosphere is 10^{-3} —ten times the upper limit in the surrounding nebula. The difference would be eliminated if the D lines arose in a number of clouds of different radial velocity and thus were unsaturated, but the doublet ratio of 1.3 cannot be enough in error to allow this possibility. If ten times more Li than Na were trapped in grains in the nebula the difference could be removed, but since the dissociation potentials, vapor pressures, etc., of typical compounds of Li and Na differ very little, this seems highly unlikely.

Thus there appears to be at least ten times more lithium in the atmosphere of T Tau per gram than in the surrounding nebula—a striking reversal of the case in the solar system. We conclude that if the star condensed out of the nebular material, it must have made some lithium. This result tends to support the hypothesis advanced in the last two paragraphs of Section V but leaves obscure the cause of the high terrestrial Li abundance.

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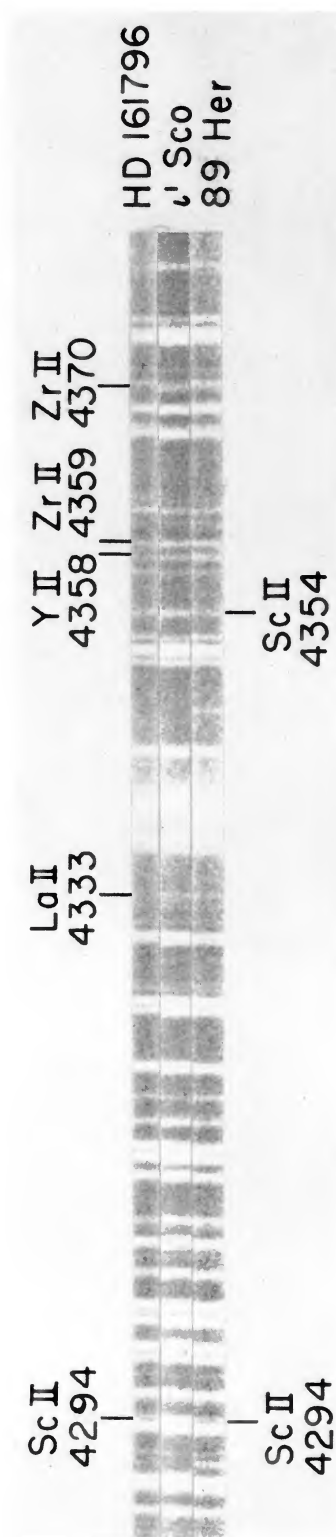


FIG. 1.—Portions of the spectra of the two high-latitude supergiants HD 161796 (*above*), F3 Ia, and 89 Herculis (*below*), F2 Ia, flanking the spectrum of the low-latitude supergiant ι Scorpii, F2 Ia. Note the relative weakness of the marked lines in the top and bottom spectra.