THE ASTROPHYSICAL JOURNAL, 167:511–519, 1971 August 1

THE LITHIUM CONTENT OF CAPELLA

ANN MERCHANT BOESGAARD
Institute for Astronomy and Department of Physics and Astronomy,
University of Hawaii, Honolulu
Received 1971 March 1

ABSTRACT

The lithium content of the two components of the spectroscopic binary α Aur is determined from seven spectrograms of 2 Å mm^{-1} dispersion widened to 2 mm. A Li I line of 22 mÅ was detected in the G star in addition to the Li I line previously found in the F star by Wallerstein. An abundance analysis gives the result that the Li content of the F star is 15 times greater than in the G star. It is concluded that the G star need not have evolved to or past the red-giant tip, as was previously thought on the basis of Wallerstein's lower-dispersion work. Measurements made to determine the Li isotope ratio indicate that there is little or no ^{6}Li in either star, but the probable errors are fairly large due to the weakness of the Li line in the G star and the rotational broadening of the lines in the F star.

I. INTRODUCTION

A difference in the lithium content of the two giant-star components of the spectroscopic binary Capella (α Aur) has been reported by Wallerstein (1964, 1966) who found that the F8–G0 giant has at least 60 times more Li than the G5 giant. This difference has been interpreted by Iben (1965) to be caused by a greater depth of convective mixing and consequent dilution of Li in the G star. Wallerstein's (1966) analysis is based on four coudé spectrograms of 8 Å mm^{-1} dispersion. Two spectrograms were taken at a phase when there was maximum velocity displacement of the F-star lines to the red, the other two with maximum displacement to the blue. He found no evidence for a Li line in the G star but identified a strong line (200 mÅ) in the F star.

The observational confirmations of stellar evolutionary models are few and therefore of considerable interest. A more thorough investigation of the lithium properties of this binary has been undertaken here. For this study seven spectrograms were taken throughout the cycle at 2 Å mm^{-1} dispersion, all widened to 2 mm. A weak Li line has been found in the G star on all the spectrograms. A complete redetermination of the Li content in both components has been done. In addition measurements were made to determine the Li isotope ratio ^{6}Li/^{7}Li.

II. OBSERVATIONAL MATERIAL

Seven coudé spectrograms of 2 Å mm^{-1} dispersion were obtained with the 160-inch coudé camera of the 120-inch reflector by Dr. George H. Herbig between 1964 October and 1966 February. The plates cover the wavelength range from 5900 to 6900 on 103a-F emulsion and are all widened to 2 mm. The blending of lines formed in the two stars is greatly reduced by the high dispersion used. Because of that and the unusually large width of the spectra, the equivalent widths can be determined with high accuracy.

Capella has a 104-day period. A reproduction of the velocity curve of Struve and Kilby (1953) is shown in Figure 1, where crosses indicate the phase at which each of the seven spectrograms was taken. The three plates EC-3750, 4144, and 4171 correspond to maximum difference in radial velocity of the two stars, about 50 km sec^{-1}, or a line separation of about 1 Å. The plates, phases, and predicted velocities are given in Table 1.

Each plate was photometrically calibrated by an internal calibration device during the stellar exposure. Direct-intensity microphotometer tracings were made using a

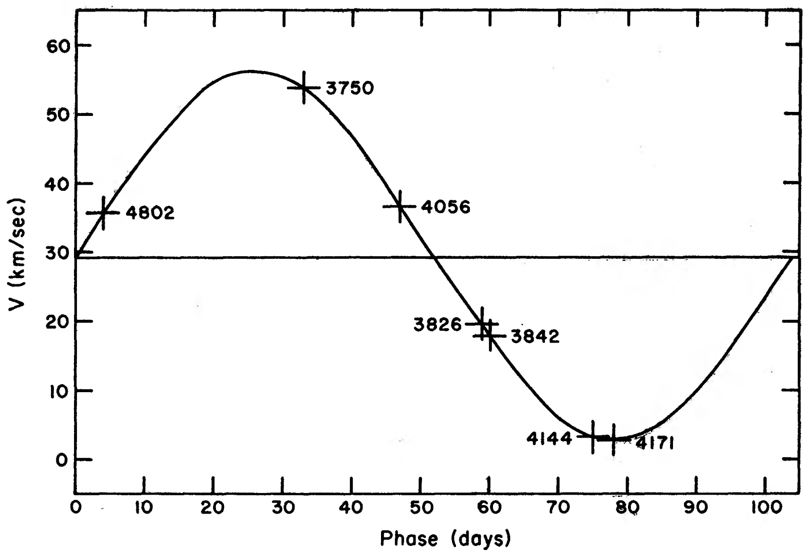

FIG. 1.—Velocity curve for the G component of Capella. Plus signs indicate the phases at which the plates were taken. Numbers opposite the pluses are plate numbers.

TABLE 1

VELOCITIES FOR THE COMPONENTS OF α AURIGAE

Plate	Phase (days)	Velocity (km sec^{-1}) G	F	G−F
4802	4	35	24	+11
3750	33	54	5	+49
4056	47	38	21	+17
3826	59	19	40	−21
3842	60	17	42	−25
4144	75	5	56	−51
4171	78	4	57	−53

computer-controlled digital microphotometer system developed by Bonsack (1970). Reproductions of the Li region of these tracings for EC-3750 and EC-4171 are shown in Figure 2. The broad feature is primarily due to Li in the F star, although the two plates at opposite phase allow an assessment to be made of the size of the blending features. The line at λ6707.45, which is present and unidentified in the Sun, is also found in the G star. In addition, a weak but definite Li line at λ6707.8 can be seen in the spectrum of the G star.

In order to determine the atmospheric parameters and the Li/Ca abundance ratio, equivalent widths were measured for forty-eight Fe I lines, nine Fe II lines, thirteen Ca I lines, and one Li I line in the G star. The lines in the F star are rotationally broadened and difficult to measure; equivalent widths were found for only six Ca I lines and one Li I line. The measured equivalent widths must be corrected for the effect of the composite continuous spectrum. Wright (1954) has determined the percentage that each component of Capella contributes to the total light as a function of wavelength. The G star contributes 55 percent between λ5900 and λ6100 and 60 percent from λ6100 to λ6750. Thus the equivalent widths in the shorter-wavelength region were multiplied by

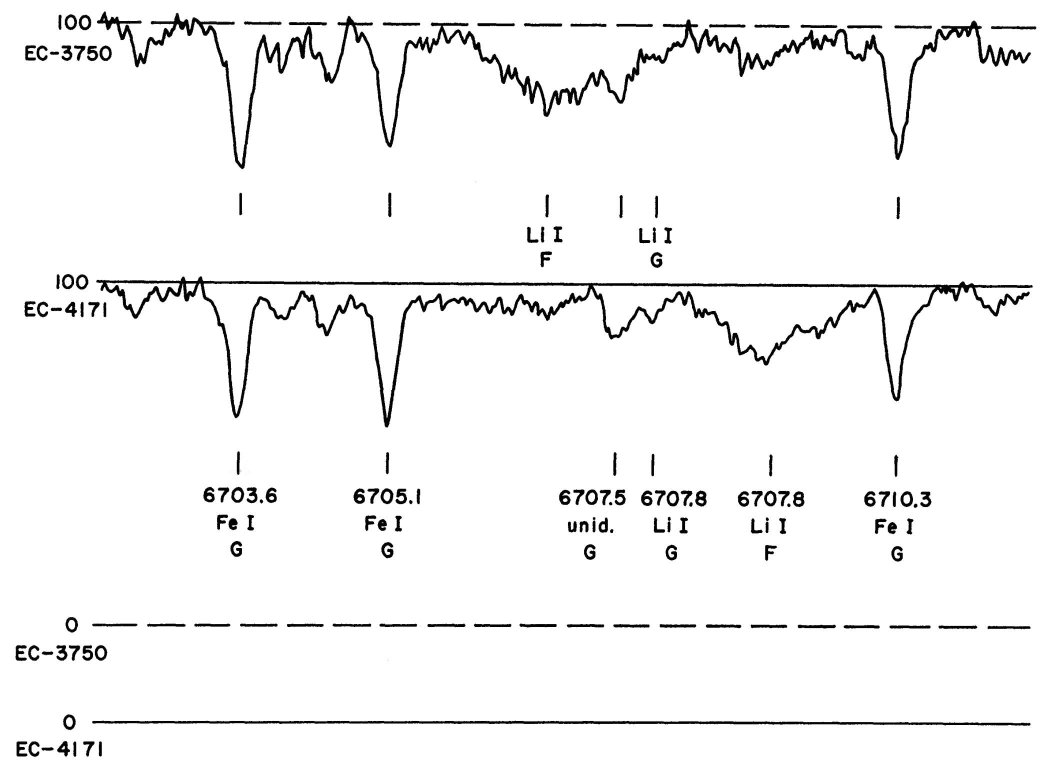

FIG. 2.—Reproductions of portions of intensity tracings of the Li region for the two plates EC-3750 and EC-4171. These two plates represent maximum velocity differences, in opposite directions, for the two stars. The lines in the G star are aligned. The Li I line in the F star is displaced to the blue in EC-3740 and to the red in EC-4171. The Li I line in the G star can be seen on both plates adjacent to the unidentified line found in the Sun at λ6707.45.

1.81 to find the appropriate value for the G star alone, while the multiplication factor was 1.67 for the longer-wavelength regions. Similarly, the equivalent widths of the F star were multiplied by 2.22 or 2.50.

The equivalent widths found from the three plates taken at maximum velocity difference agree very well. A sample is shown in Figure 3*a*, where equivalent widths of the Fe I lines in EC-4144 are plotted against those in EC-4171. However, for the other four plates the separation of the lines arising from the two stars is not as great, and (for the strong lines) the F-star lines are strong enough to produce blending, a condition which causes the resultant equivalent widths to be spuriously strong. Figure 3*b* shows a sample of this effect for EC-3842; whereas the weak lines fall along a 45° slope, the stronger ones deviate in the expected way. The direction and size of the effect are identical for EC-3826 and EC-3842—plates taken at the same phase. The two plates EC-4802 and EC-4056 are also very similar; the velocity differences between the two stars are very close. A straight line was drawn by eye through the strong lines which deviated from the 45° line. Each equivalent width was then reduced by the difference in mÅ between the two straight lines at that equivalent width. Figure 3*c* shows the corrected equivalent widths for EC-3842 plotted against the equivalent widths of EC-4144.

As a check to ascertain whether this correction procedure was reasonable, the data reduction was carried out for the average of the three plates which were not so corrected (EC-3750, 4144, and 4171), as well as for the average of all seven plates. Table 2 lists the final values for the equivalent widths averaged over the three plates and all seven plates for all the lines measured in both stars.

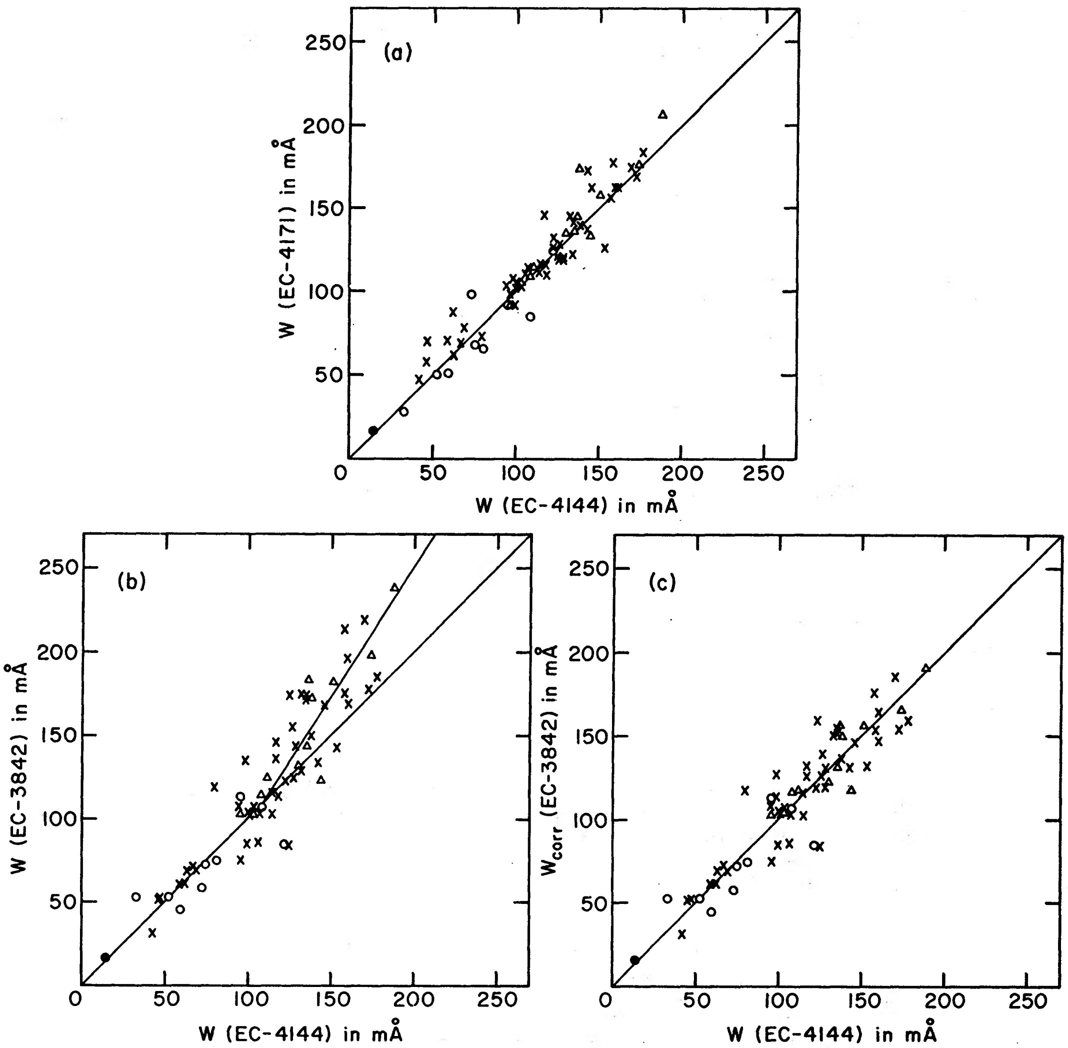

FIG. 3.—Comparison of equivalent widths for the G star from different plates. *Crosses*, Fe I lines; *circles*, Fe II lines; *triangles*, Ca I lines; *filled circle*, the Li I line. Panel (*a*) shows the close agreement in the measurements for the two plates taken at almost identical phases and minimum blending from the F-star lines. Panel (*b*) plots the equivalent widths in EC-3842, taken at a phase where there is more blending from the F star, against the equivalent widths from the minimum-blending plate, EC-4144. The 45° line shows where the points should fall; the strong lines are anomalously strong due to blending and fall along the upper line. Panel (*c*) shows the equivalent widths in EC-3842 corrected for this blending, as discussed in the text, plotted against the values for EC-4144.

III. ABUNDANCE DETERMINATION

The technique of analysis to determine [Li/Ca], the logarithmic ratio of Li/Ca relative to the solar ratio, for the G star was identical with that used by Herbig (1965) for his 4 Å mm^{-1} data and described by him in that paper. The atmospheric parameters θ_{exc}, the excitation temperature; θ_{ion}, the ionization temperature; log P_e, the electron pressure; and v, the velocity, were found from the curves of growth for Fe I and Fe II. These parameters and the [Fe/H] ratio are given in Table 3 for both the average of the three previously mentioned spectrograms and the average of all seven. The solar values used by Herbig are given for comparison. Figure 4 shows the Fe I curve of growth with equivalent widths averaged from all seven spectrograms. The [Li/Ca] ratio was then found

TABLE 2—EQUIVALENT WIDTHS

λ(Å)	$-\log W/\lambda$ G Star Average 3 Plates	$-\log W/\lambda$ G Star Average 7 Plates	λ(Å)	$-\log W/\lambda$ G Star Average 3 Plates	$-\log W/\lambda$ G Star Average 7 Plates
	Fe I			Fe I	
5956.7.....	4.67	4.68	6355.0.....	4.68	4.66
5983.7.....	4.68	4.71	6358.7.....	4.67	4.66
5984.8.....	4.61	4.64	6380.7.....	4.89	4.84
5987.1.....	4.75	4.74	6393.6.....	4.61	4.59
6024.1.....	4.64	4.64	6411.7.....	4.67	4.67
6027.1.....	4.75	4.75	6420.0.....	4.73	4.75
6056.0.....	4.78	4.77	6421.4.....	4.51	4.59
6062.9.....	4.79	4.81	6430.9.....	4.60	4.60
6065.5.....	4.55	4.55	6469.2.....	4.80	4.81
6137.7.....	...	4.48	6499.0.....	4.75	4.75
6151.6.....	4.78	4.80	6546.2.....	4.64	4.64
6157.7.....	4.80	4.77	6569.2.....	4.80	4.78
6173.3.....	4.71	4.72	6574.2.....	4.75	4.79
6200.3.....	4.72	4.72	6593.9.....	4.58	4.68
6213.4.....	4.70	4.70	6625.0.....	4.92	4.92
6219.3.....	4.64	4.66	6627.6.....	4.97	5.04
6232.7.....	4.75	4.74	6678.0.....	4.58	4.61
6246.3.....	4.55	4.59	6703.6.....	4.97	4.95
6252.6.....	4.51	4.55	6705.1.....	4.97	4.93
6254.3.....	4.53	4.56	6710.3.....	5.01	5.01
6265.1.....	4.62	4.67	6725.4.....	5.19	5.19
6335.3.....	4.70	4.66	6726.7.....	5.02	4.98
6336.8.....	4.66	4.67	6733.2.....	5.15	5.12
6344.2.....	4.73	4.72	6750.2.....	4.71	4.73

λ(Å)	$-\log W/\lambda$ G Star Average 3 Plates	$-\log W/\lambda$ G Star Average 7 Plates	$-\log W/\lambda$ F Star Average 3 Plates	$-\log W/\lambda$ F Star Average 7 Plates
		Fe II		
5991.4.....	4.92	4.90	...	...
6084.1.....	5.04	5.06	...	...
6149.2.....	4.96	4.94	...	...
6238.4.....	4.85	4.85	...	...
6247.6.....	4.75	4.80	...	...
6369.5.....	5.22	5.17	...	...
6416.9.....	5.12	5.04	...	...
6432.7.....	4.98	4.92	...	...
6456.4.....	4.84	4.78	...	...
		Ca I		
6122.2.....	4.51	4.50	4.47	4.50
6162.2.....	...	4.45	...	...
6166.4.....	4.80	4.78	4.74	4.85
6169.1.....	4.70	4.68	...	...
6169.6.....	4.64	4.63	...	...
6439.1.....	4.56	4.56	4.54	4.58
6449.8.....	4.65	4.65	...	...
6455.6.....	4.78	4.77	...	...
6471.7.....	4.70	4.69	4.64	4.66
6493.8.....	4.62	4.62	...	...
6499.6.....	4.71	4.72	4.67	4.77
6572.8.....	4.80	4.79	...	...
6717.7.....	4.64	4.63	4.68	4.72
		Li I		
6707.8.....	5.48	5.48	4.58	4.58

TABLE 3

ATMOSPHERIC PARAMETERS FOR THE G STAR

Criterion	θ_{exc}	θ_{ion}	log P_e (dynes cm^{-2})	v(Fe) (km sec^{-1})	[Fe/H]
Average for EC-3750, 4144, and 4171	1.13	0.98	0.56	3.5	+0.28
Average for all 7 plates	1.13	0.98	0.52	3.5	+0.26
Sun	1.04	0.89	1.30	2.8	0.00

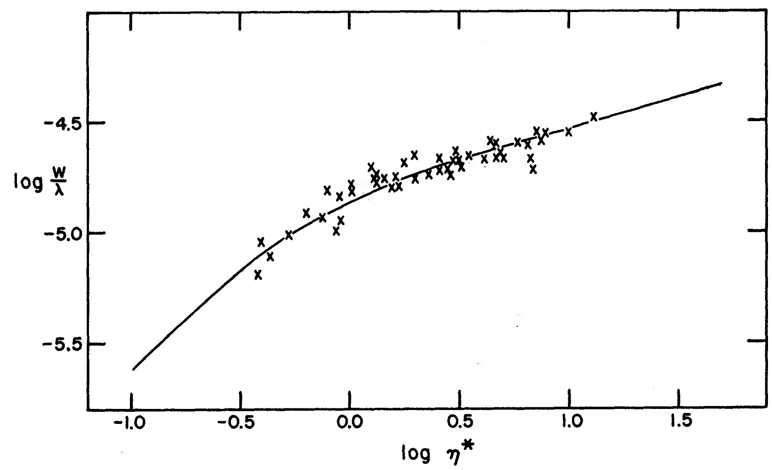

FIG. 4.—Final curve of growth for Fe I for the G star. Equivalent widths are the values averaged from all seven plates. Smooth curve is the shifted Goldberg-Pierce solar curve of growth.

through both the case I and case II methods of treating the Li doublet described by Herbig. (In case I the doublet lines are blended intrinsically in the stellar atmosphere whereas in case II the lines are separate but blended by low resolution, rotation, macroturbulence, etc.) The equation is

$$[\mathrm{Li/Ca}] = \log \eta^*(\mathrm{Li\,I}) - \log \eta_\odot(\mathrm{Li\,I}) - [\langle \log \eta^*(\mathrm{Ca\,I}) + \epsilon(\mathrm{Ca\,I})\Delta\theta - \log \eta_\odot(\mathrm{Ca\,I})\rangle]$$

$$+ \log \frac{k^*(\mathrm{Li\,I})}{k^*(\mathrm{Ca\,I})} + \log \frac{v^*(\mathrm{Li})}{v^*(\mathrm{Ca})} + \log \frac{u^*(\mathrm{Li\,II})}{u^*(\mathrm{Ca\,II})} - [I(\mathrm{Li\,I}) - I(\mathrm{Ca\,I})]\Delta\theta_{\mathrm{ion}} + \mathrm{constant}\,. \quad (1)$$

Here all the symbols have their usual meanings, and the partition functions u and the continuous absorption coefficients k are found in a manner similar to that described by Herbig with the exception that the value of λ6400 was taken to represent the mean wavelength for the Fe and Ca lines. The constant refers to the ratios of the k's, v's, and u's for the Sun and has a value of -0.03 for case I and $+0.15$ for case II, the difference arising from the different treatment of v(Li) in the two cases. For a line as weak as that measured in the G stars, the two cases will give the same results.

The analysis of the [Li/Ca] abundance for the F star followed Herbig's (1965) technique for his 16 Å mm^{-1} data. The value of $\Delta\theta(\theta_{\mathrm{star}} - \theta_{\mathrm{Sun}})$ was set equal to 0.00 as found by Wallerstein (1966). As mentioned by Wallerstein (1964), the microturbulent velocity for the F star could not be found since the lines are broadened by rotation of 10–12 km sec^{-1} and few lines could be measured. The velocity parameter found for the G star was therefore used to correct for the velocity difference between the Li atoms and the Ca atoms. The six Ca lines were used to determine the Ca I curve of growth with the Goldberg-Pierce solar curve, adjusted for the velocity parameter of the G star, drawn through the points. This curve was then entered with the equivalent width of the Li line for case I and case II, and the abundance ratio was found from equation (1) with the logarithmic ratios for v(0.29 for case I, 0.114 for case II), k(0.007), and u(0.33) the same as for the G star. (The value for u is virtually temperature independent for $\theta >$ 0.90; the ratio for k results from the reference wavelength λ6700 versus λ6400, and is very small.)

The final [Li/Ca] results for both case I and case II, for the three-spectrogram average and the seven-spectrogram average, for both stars are given in Table 4. For the G star there is no difference between the three- versus seven-spectrogram results or between cases I and II. The value of [Li/Ca] for the G star is +0.20. The abundances in the F star show a small discrepancy between the results from the three versus seven spectrograms. Since the lines are difficult to measure, the average of all seven plates gives better accuracy. (The F-star lines were not corrected for the blending as the G-star lines were.) There is a small difference between the case I and case II results—to be expected since the line is near the flat portion of the curve of growth. The Li doublet is certainly broadened extrinsically by stellar rotation (case II), but may already have been blended intrinsically (case I). The adopted [Li/Ca] value for the F star is +1.4, which corresponds to about 15 times more Li in the F star than the G star, as opposed to the value of 60 times found by Wallerstein (1966).

For a direct comparison with Wallerstein's abundances it is necessary that our two sets of results refer to the same solar Li abundance. The Greenstein-Richardson (1951) solar value was used in the present work, while Wallerstein used the Goldberg-Müller-Aller (1960) value. On the Greenstein-Richardson scale, Wallerstein's results for [Li/Ca] are +2.2 for the F star and $\leq +0.4$ for the G star. The definite value of +0.2 found in this study for the G star is consistent with Wallerstein's upper limit of $\leq +0.4$. This lower Li content results from the definite identification of a Li line, from the high dispersion used, and the detailed analysis done. The difference in the two results for the F star, +2.2 versus +1.4, is partially due to the smaller observed equivalent width in the F star. Also, Wallerstein does not specify if or how he has corrected his Li equivalent width for the velocity difference between Li and Ca; nor does he specify if he used the case I or case II treatment of the Li doublet. The difference in the abundances found could easily result from these factors, since Wallerstein's Li equivalent width falls on the flat portion of the Ca curve of growth whereas the case II doublet lines are on the linear portion.

IV. THE APPARENT LITHIUM ISOTOPE RATIO

An attempt was made to determine the apparent isotope ratio ^{6}Li/^{7}Li through measurement of the center of gravity of the Li line relative to the other lines as described by Herbig (1964). (The wavelength of a Li line formed from pure ^{7}Li is 6707.811 Å and from pure ^{6}Li is 6707.969 Å, a difference of 0.158 Å.) The three spectrograms with the maximum radial-velocity difference (EC-3750, 4144, and 4171) were measured. The

TABLE 4

LITHIUM ABUNDANCE IN BOTH STARS FOR CASE I AND CASE II

Criterion	G Star		F Star	
	$[Li/Ca]_I$	$[Li/Ca]_{II}$	$[Li/Ca]_I$	$[Li/Ca]_{II}$
Average for EC-3750, 4144, and 4171	0.19	0.20	1.36	1.27
Average for all 7 plates	0.20	0.20	1.46	1.38

radial velocities were found by measuring twenty-eight lines in the G star and ten lines in the F star on the long-wavelength half of the plate between $\lambda\lambda$6400 and 6800. The lines in the G star are very sharp and easy to measure at 2 Å mm^{-1}; the radial velocity of the star was determined with a probable error per line of ± 0.46 km sec^{-1} on all three plates. However, the Li line in the G star is very weak and blended, as can be seen in Figure 2, and consequently very difficult to measure. The lines in the F star are very broad, and there the probable error per line is ± 4.00 km sec^{-1}. The Li line in the F star is strong, but it too is very broad and blended.

Table 5 gives the measured radial velocity, the wavelength of the Li line as corrected for the radial velocity of the star, and the probable error per line, for both stars, for all three plates, and the average value for the three plates. The probable error associated with the average for the wavelength of the Li line is merely the average probable error divided by $\sqrt{3}$, since three plates were measured. The formal value for ^{6}Li/(^{6}Li + ^{7}Li) for the G star is 6 ± 4 percent. However, due to the weakness of the Li line, it is the most difficult line to measure; the probable error of ± 0.015 Å, associated with the deviations of the Li-wavelength values for the three plates, is a more realistic estimate of the error. This extends the probable error in the ^{6}Li content to ± 9 percent. There is little, if any, ^{6}Li in the G star. The F star shows no ^{6}Li, but on the basis of the probable error a ^{6}Li content of up to 26 percent could result. The probable error for the Li wavelength covers approximately the full range of values for ^{6}Li content found in stars, i.e., 0–35 percent (cf. Herbig 1964; Conti 1969; Feast 1970). Therefore, no meaningful conclusions can be drawn about the isotope ratio in the F star from the measurements. Conti (1969) has found that the hotter main-sequence stars have almost no ^{6}Li; the result for the G star is consistent with Conti's work since the mass of the G star is 3.0 $M_\odot$ (Wright 1954). It also implies that the F star should be expected to have no ^{6}Li (as found here), since it has a mass of 2.9 $M_\odot$ (Wright 1954).

On the basis of the measurements and discussion it is concluded that there is little or no ^{6}Li (less than 10 percent) in either star at present and probably little or no ^{6}Li during their main-sequence phases. Since ^{6}Li can be diluted more than ^{7}Li (Iben 1965), a star with pure ^{7}Li will undergo less total dilution. However, the lack of ^{6}Li and consequent smaller dilution is not confronted as a difficulty in the present analysis, since the difference in the Li content of the two stars found is only a factor of 15.

V. CONCLUSIONS

There is a measurable but weak Li line in the G star detected on all seven spectrograms which results in [Li/Ca] = +0.2. The G star seems to contain almost pure ^{7}Li. The Li abundance found for the F star from the broad, strong Li feature in that star is [Li/Ca] = +1.4. The important comparison is the Li abundance in the two components of Capella; the F star has about 15 times more Li than the G star. This value is smaller

TABLE 5

MEASUREMENTS FOR LITHIUM ISOTOPE RATIOS

	G Star			F Star		
Plate	V (km sec^{-1})	λ(Li) (Å)	p.e. (Å)	V (km sec^{-1})	λ(Li) (Å)	p.e. (Å)
3750	52.99	6707.824	±0.010	4.24	6707.813	±0.068
4144	4.10	6707.796	±0.011	57.14	6707.779	±0.118
4171	3.71	6707.839	±0.010	58.72	6707.815	±0.083
Average	...	6707.820	±0.006	...	6707.802	±0.050

than Wallerstein's ratio of 60 times. The difference between the two ratios is due partly to the higher dispersion, width, and number of the spectrograms used in this study and partly to the difference in analysis of the data for the F star as discussed near the end of § III. According to the summary of Herbig and Wolff (1966), main-sequence stars with the *highest* Li/Ca ratios have values of [Li/Ca] $\approx +1.8$. This new result for the F star is consistent with this limit.

From a theoretical study of a 3 $M_{\odot}$ star, Iben (1965) finds that the Li content of a giant will remain constant and equal to its main-sequence value until the convective envelope starts to grow. Iben asserts that the F star has not evolved to a point where post–main-sequence convection has affected the surface Li content. Surface mass loss could deplete the total Li while not affecting the observable number of Li atoms per gram. In order to explain Wallerstein's observed difference between the two stars, Iben concluded that the G star had been to the red-giant tip and was moving to the left in the H-R diagram. However, if the G star's Li content is only 15 times less than the F star's, it need not have evolved to and beyond the red-giant tip. According to Iben, there are two stages during which changes take place in the surface content of Li, ^{12}C, and ^{14}N. The first stage begins near the lowest-luminosity point on the evolutionary track and ends halfway to the red-giant tip. Then ^{14}N α-burning in the core results in the star's becoming slightly fainter again. The second stage begins when the star has again reached a point about halfway to the red-giant tip and ends at the red-giant tip. At the end of the first stage a star with pure ^{7}Li will have diluted its surface Li by a factor of 48. It is suggested that the G star is in this first phase of Li dilution. Boesgaard (1970) shows a plot of the Li content of F5–M4 giants as a function of temperature. The points define a band showing a monotonic decrease in Li abundance with temperature. The width of the band is attributed to a spread of masses and evolutionary stages at each temperature. Even this new value of [Li/Ca] $= +0.2$ for the G star puts it near the top of this band, which tends to reinforce the conclusion of a lower evolutionary age for this star. Thus it is concluded that the G star is not in such an advanced evolutionary stage as previously thought.

I am very grateful to Dr. George H. Herbig for lending me his beautiful spectrograms of α Aur. It is a pleasure to express my appreciation to Mr. Neal M. Shimanuki, a participant in the National Science Foundation Secondary Science Training Program, for his very capable and diligent assistance in the data reduction for the abundance determination. I also thank Mr. Frank M. Young for the care and skill he applied in the microphotometry of the spectrograms with the computer-controlled digital microphotometer system.

REFERENCES

Boesgaard, A. M. 1970, *Ap. Letters*, **5**, 145.
Bonsack, W. K. 1970, *A.A.S.*, **2**, 298.
Conti, P. S. 1969, *Ap. J.* (*Letters*), **155**, L167.
Feast, M. W. 1970, *M.N.R.A.S.*, **148**, 489.
Goldberg, L., Müller, E., and Aller, L. 1960, *Ap. J. Suppl.*, **5**, 1.
Greenstein, J. L., and Richardson, R. S. 1951, *Ap. J.*, **113**, 536.
Herbig, G. H. 1964, *Ap. J.*, **140**, 702.
———. 1965, *ibid.*, **141**, 588.
Herbig, G. H., and Wolff, R. J. 1966, *Ann. d'ap.*, **29**, 593.
Iben, I. 1965, *Ap. J.*, **142**, 1447.
Struve, O., and Kilby, R. F. 1953, *Ap. J.*, **117**, 272.
Wallerstein, G. 1964, *Nature*, **204**, 367.
———. 1966, *Ap. J.*, **143**, 823.
Wright, K. O. 1954, *Pub. Dom. Ap. Obs.*, **10**, 1.