1966ApJ...143..336M

BERYLLIUM IN F- AND G-TYPE DWARFS*

ANN E. MERCHANT
Lick Observatory, University of California, Mount Hamilton, California

Received May 24, 1965; revised August 20, 1965

ABSTRACT

The abundance of beryllium (relative to the Sun) has been determined in 10 F- and G-type stars from the λλ 3130, 3131 resonance lines of Be II, for comparison with the lithium abundances in these same stars. The position of the continuum has been carefully checked in an attempt to make the data not only internally consistent but also meaningful when compared with other stars and other elements. With the exception of two stars, θ Cyg and α CMi, the total spread in Be abundance is a factor of four as compared to a Li spread in these same stars of a factor of 30. The stars θ Cyg and α CMi have upper limits on Be of 25 times less than solar; the possible effect of the companions of these two stars on the light-element abundances is considered as a possible explanation of this phenomenon.

Four of the stars have appreciable amounts of Li^6; this is interpreted to mean that there has probably been little or no convective depletion of either Li or Be. The mean abundance ratio of Li/Be for these four stars is 0.6, with a variation about the mean of 50 per cent. This may represent a constant initial value of Li/Be; a fixed ratio would be expected if production of these light elements were the result of spallation.

I. INTRODUCTION

The abundances of the light elements and their relation to theories of nucleosynthesis have received much attention in recent years. Deuterium has not been positively identified in stars, so only upper limits on the abundances are available (Peimbert and Wallerstein 1965). Lithium has been observed most extensively: survey programs were carried out in G- and K-type stars by Bonsack (1959), in F and G dwarfs by Herbig (1965), in the Hyades by Wallerstein, Herbig, and Conti (1965), in T Tauri stars by Bonsack and Greenstein (1960). The abundance of beryllium has been determined in four A-type stars by Bonsack (1961) and in peculiar-A stars by Sargent, Searle, and Jugaku (Sargent 1964). Only for the Sun and meteorites does simultaneous abundance information exist for more than one of these light elements.

It was anticipated that study of the abundances of both Li and Be in the same stars might provide a basis for understanding the mechanism of production of these light elements. Simultaneous observations of both elements are possible, however, only in a small range of spectral type. The Be II resonance lines lie in the ultraviolet at λ 3131.06 and λ 3130.42, not far above the atmospheric cutoff. (The lines of Be I at λ 3321 are very weak in the Sun [Greenstein and Tandberg-Hanssen 1954] since they arise from levels of 2.71-eV excitation.) In stars of type A where the ultraviolet line spectrum is uncrowded and therefore the Be II lines readily observable, Li I λ 6707 is generally undetectable since Li is almost totally ionized. There is the additional handicap that there are very few bright, sharp-lined stars of type A. In stars later than the Sun, the ultraviolet is very crowded with metallic lines and the color temperature is unfavorably low, so that both detection and analysis of Be II is very difficult. Furthermore, due possibly to the deepening of the convection zone with decreasing surface temperature, few of the later G-type stars show appreciable Li abundances (Herbig 1965; Wilson 1963). Thus in principle, the optimum spectral domain for positive observations of both Li and Be is that of the sharp-lined F- and early G-type dwarfs.

II. OBSERVATIONS

Ten F- and early G-type stars were observed at 8 Å/mm with the 40-inch camera of the coudé spectrograph, 120-inch reflector, in the second order of a 600-groove/mm

* *Contributions from the Lick Observatory*, No. 192.

Babcock grating blazed near λ 3800. The heavy exposure needed to produce an acceptable photographic density near λ 3100 required the use of a Corning 9863 filter behind the spectrograph slit. This was necessary to suppress the overlapping first-order λ 6000 spectrum to which the Kodak IIa-O emulsion is very slightly, but objectionably, sensitive. In addition, a spectrogram of the daytime sky was obtained with the same equipment for comparison of the other stars with the Sun. Due to the steepness of the atmospheric extinction curve in the ultraviolet, it is difficult to get both the Be I and Be II regions properly exposed on the same spectrogram. But since the Be I lines were sought but not found in the first few stars observed, subsequent plates were deliberately over-exposed in this region to obtain photometric densities near λ 3130. All the stars observed were brighter than $m_v = 4.5$. Under average conditions the exposure time for a star of that magnitude, widened to 0.5 mm, is about 2 hours. Thus it would be difficult to extend appreciably this list of ten stars to fainter magnitudes.

Seven of these ten stars had also been observed at 4 Å/mm in the yellow-red with the 160-inch camera by Herbig (1965) as part of his Li program; for these seven stars the Li abundance and atmospheric parameters have been taken from his publication. The other three, θ Cyg, π^3 Ori, and α CMi, were newly observed in the red at 8, 4, and 2 Å/mm, respectively. The Li abundance and atmospheric parameters were determined by the same method used by Herbig, so consistency is insured. The resulting parameters of these three additional stars are listed in Table 1.

TABLE 1

ATMOSPHERIC PARAMETERS

Star	$\Delta\theta$	$[P_e]$	$[V_{Fe}]$	[Fe/H]
θ Cyg.....	−0.09	+0.11	+0.10	+0.04
α CMi....	− .07	− .16	+ .20	+ .03
π^3 Ori.....	−0.07	0.00	+0.04	+0.16

III. DETERMINATION OF THE BERYLLIUM ABUNDANCE

Direct-intensity microphotometer tracings were made covering the region from λ 3100 to λ 3160. By careful comparison with other known solar features, the Be II lines were identified on the sky tracing as well as on greatly enlarged prints of the original plates. The continuum was drawn through the high points with the assistance of the solar "windows" noted by Canavaggia and Chalonge (1946) in this wavelength region. The errors arising from the heavy blending and the difficulty of properly drawing the continuum represent the greatest uncertainty in the data. However, since the continuum was positioned as identically as possible for all the stars, including the Sun, the data should at least be internally consistent. The continuum position chosen and the resulting measurements of the equivalent widths of the Be II line are supported by two other facts. First, the value of the equivalent width of Be II λ 3131 on the plate of the sky, 71 mÅ, compares favorably with the value of 79 mÅ obtained by Greenstein and Tandberg-Hanssen. Second, the [Fe/H] ratio was determined independently from the ultraviolet spectrograms from six relatively unblended Fe I and Fe II lines, and Wrubel's (1949) theoretical curve of growth for $B^{(0)}/B^{(1)} = \frac{1}{3}$ and log a = 1.8. The analysis was similar to that for Be II as described below; the log η_0's were read from Wrubel's theoretical curve, the atmospheric parameters were taken from the results of the plates in the red spectral region, and the continuous opacity coefficients for λ 3130 were used. The result is listed in Table 2 for those stars for which there are photometric determinations of [Fe/H] by Strömgren and Perry (1966), through the empirical conversion procedure described by Strömgren (1963). Considering the many uncertainties, the agreement between photometric and spectroscopic values of [Fe/H] is satisfactory. Therefore, it is assumed that the continuum is properly drawn and that the data are not only internally consistent, but can be safely compared with other elements and other stars.

Tracings of this spectral region are shown in Figure 1 for all the stars. Reproductions of the original plates appear in Figure 2 for three of the stars. Due to the serious blending of Be II λ 3130.4 with lines of Ti I and Ti II at λ 3130.8, and OH and V II at λ 3130.3, only Be II λ 3131.06 was used for the analysis. However, the presence of λ 3130 furnishes a gross check on the reality of an identification of the line at λ 3131 with Be II in any star. From Figure 1 it is clear that the last seven stars and the Sun all have a detectable amount of Be II. The lines of π^3 Ori are rotationally broadened, but the

TABLE 2

ABUNDANCE DATA[a]

Star	Sp. Type	W_{Be} (mÅ)	[Be/H]	Be*	Li*	Li*/Be*	$Li^6/(Li^6+Li^7)$	$[Fe/H]_{phot}$	$[Fe/H]_{uv}$
θ Cyg	F4 V	< 18	<−1.3	< 0.35	<12	....	....	+0.16	+0.07
α CMi	F5 IV–V	< 12	<−1.5	< 0.21	< 4.4	....	....	+ .28	+ .17
π^3 Ori	F6 V	∼ 81:	−0.01:	6.7:	6.8:	1.0:	....	+ .19	+ .46:
10 Tau	F8 V	111	+0.62	29	15	0.50	0.35	....	....
χ Her	F9 V	99	−0.01	6.8	33	4.8	.03	− .44	− .42
β Com	G0 V	115	+0.41	17	16	0.91	.28	+ .14	+ .01
β CVn	G0 V	110	+0.34	15	< 3.5	≤0.24	....	− .12	− .06
λ Ser	G0 V	95	+0.18	10	< 4.4	≤0.43	....	....	....
ξ UMa A	G0 V	104	+0.50	22	17	0.79	.21	....	....
ι Per	G0 V	124	+0.64	30	10	0.34	0.24	+0.19	+0.32
Sun	G2 V	71	0.00	6.9	1.1	0.16	....	....	....

[a] Explanation: W_{Be} (mÅ) is the measured equivalent width of Be II λ 3131.06 in milliangstroms.

[Be/H] is the logarithm of the number of Be atoms per gram of stellar material, divided by the same quantity for the solar atmosphere.

Be* is the number of Be atoms in the star per 10^6 Si atoms in the Sun (i.e., 6.9 × antilog [Be/H]), on the assumption that the denominators of (Be/H)* and (Be/H) cancel.

Li* is the number of Li atoms in the star per 10^6 Si atoms in the Sun (i.e., 1.1 × antilog [Li/Ca]). It is assumed that the abundance of Ca per gram is the same in star and Sun. The solar data for both Li and Be have been taken from the most recent determinations (Mutschlechner 1963).

$Li^6/(Li^6 + Li^7)$ is the abundance ratio of Li^6 to $Li^6 + Li^7$, as determined from the isotope shift of Li I λ 6707.

[Fe/H] is the logarithm of the number of atoms of Fe per gram of stellar material divided by the same quantity for the Sun; the subscripts "phot." and "*uv*" indicate values obtained from Strömgren and Perry's photometry and from the ultraviolet lines of Fe I and Fe II, respectively.

blended line clearly includes a Be II contribution, otherwise the slope on the longward side of the blend would be steeper. Possibly θ Cyg has a small amount of Be II, but there is no evidence for it in α CMi, where even the badly blended line λ 3130 is also absent. Upper limits on the abundances are given in Table 2 for the last two stars.

The turbulent velocity (ξ) was derived from v(Fe), obtained from the red plates. Using this value, v(Be) was calculated from

$$v\,(\text{Be}) = \left(\frac{9.2995 \times 10^{10}}{\theta_{\text{exc}}} + \xi^2\right)^{1/2}. \tag{1}$$

For Be the thermal velocity component is dominant. Due to the high thermal velocity of Be and the difficulty of constructing a curve of growth from heavily blended ultraviolet lines, Wrubel's theoretical curve of growth for $B^{(0)}/B^{(1)} = \frac{1}{3}$ and $\log a = -1.8$ was used to read out $\log \eta_0$. The abundance relative to the Sun was determined from

$$\log \frac{N^*\,(\text{Be})}{N^{\odot}\,(\text{Be})} = \Delta \log \eta_0 + \Delta \log k_\lambda + \Delta \log v_{\text{Be}} + \log \frac{N_T}{N_1} + \Delta \log \frac{u_1(T)}{u_0(T)}, \tag{2}$$

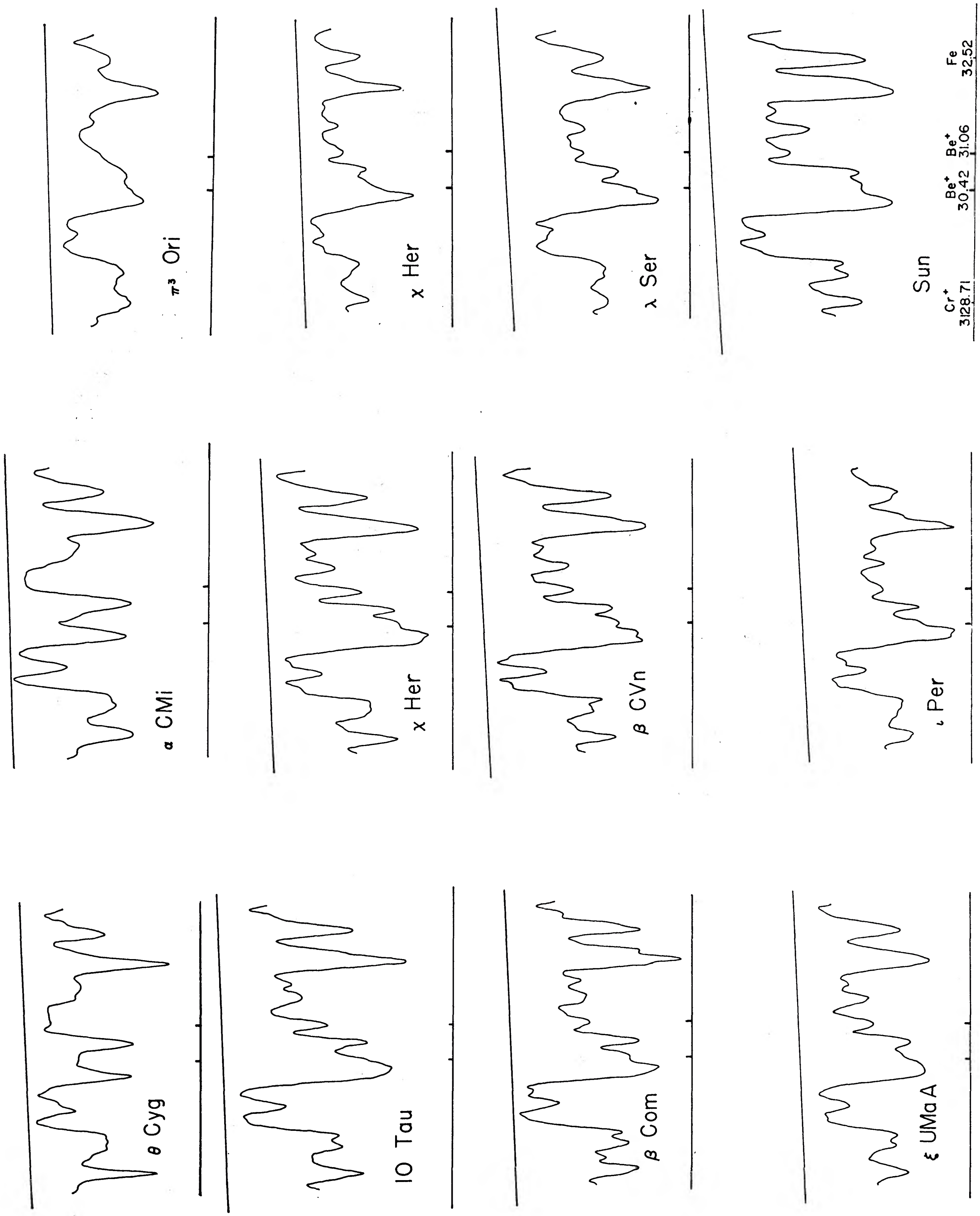

FIG. 1.—Microphotometer tracings showing the region of the Be II lines. The upper slanted line on the individual tracings represents the continuum; the lower line is clear plate. The two marks on the lower line give the location of the Be II lines as labeled on the tracing of the Sun. The second plate of χ Her is a weaker exposure as depicted in the tracings.

where $\Delta x = x^* - x_\odot$ (where x is any physical parameter), and k_λ is the continuous opacity coefficient, $u(T)$ is the partition function. Log k_λ was read for λ 3130, as a function of θ_{ion} and P_e, from tables given by Allen (1963) which include the contribution due to neutral hydrogen. The partition functions were taken from Claas (1951). Log $[N(\text{Be I}) + N(\text{Be II})]/N(\text{Be II})$ was found from the Saha equation. The final abundance data are collected in Table 2.

IV. DISCUSSION

The data in Table 2 show that, with the exception of θ Cyg and α CMi, the stars observed contain approximately the same amounts of atmospheric Be. The mean number of Be atoms per 10^6 Si atoms is 21. Whereas the Li abundance varies by a factor of 30 for the stars listed, the Be range is only a factor of 4. The reaction rate for Be (p,α) reactions is about 300 times less than that for Li^7 at a representative temperature near 4×10^6 ° K (Reeves 1965). Consequently, Be is much less sensitive to convective depletion than lithium. Therefore, the abundance of Be could reflect variations from star to star in the initial production of the very light elements. (Stars of spectral type earlier than K2 V will not deplete Be during pre–main-sequence contraction or during subsequent main-sequence evolution according to recent calculations [Bodenheimer 1966], but both theory and observation indicate that Li is depleted by convective mixing in stars of spectral type G and later [Herbig 1965; Bodenheimer 1965].) It is possible to interpret the present results as indicating a variation in the initial Be content by a factor as much as 4. However, even though reasonable adjustments of the continuum do not change the equivalent width by more than 10 per cent, the accidental error is larger, and a probable error of a factor of 3 will be assumed for an abundance determination from a single line. Therefore, the observed spread of a factor of 4 for Be could be only observational error.

The stars θ Cyg and α CMi are strikingly lacking in Be: their Be content is less than solar by a factor of at least 25. Neither star shows Li λ 6707; the upper limit Li abundances are rather high since both stars are hotter than the others, and the Li II/Li I ratio large. Furthermore, θ Cyg was observed at only 8 Å/mm in the red. Bonsack (1961) has shown that α CMa A also has no detectable Be, and he speculates on the possible effect of the white-dwarf companion on the surface abundances of α CMa A. The absence of both Li and Be in α CMi, which also has a white-dwarf companion, tends to strengthen that hypothesis. The star θ Cyg (type F4 V) has a companion 3″ distant (projected distance of about 40 a.u.). The absolute magnitude of the companion, if it is physically associated with θ Cyg, is +12, appropriate for either a white dwarf or a main-sequence red dwarf. Due to the faintness of the secondary and the small separation, it is not presently known which of these alternatives is correct. Therefore, it is unknown whether the low Be content of θ Cyg A can be linked with the same phenomenon in α CMa A and α CMi A through the possession of a white-dwarf companion.

The isotope Li^6 will be destroyed by convective mixing at lower temperatures than will Li^7; the reaction rate for the Li^6 (p,α) reaction is about 90 times greater than that for Li^7. (At $T = 10^6$ ° K the factor is close to 100; at 4×10^6 ° K it is about 83 according to Reeves.) It is possible that various amounts of the two isotopes could be destroyed by the convection mechanism with an observable amount of Li^6 still remaining on the surface. However, there is a greater probability that the stars which have retained appreciable quantities of Li^6 have suffered less convective destruction of Li than those stars which have destroyed all of their Li^6. Therefore, stars with appreciable Li^6 more nearly reflect the initial Li abundance than the others. There is an additional complication of subsequent production of both Li and Be by spallation reactions induced through surface magnetic activity. It is expected that such magnetic activity would be correlated with the presence of chromospheric activity. However, none of the stars observed here shows any emission in the core of the H- and K- lines of Ca II. The absence of chromo-

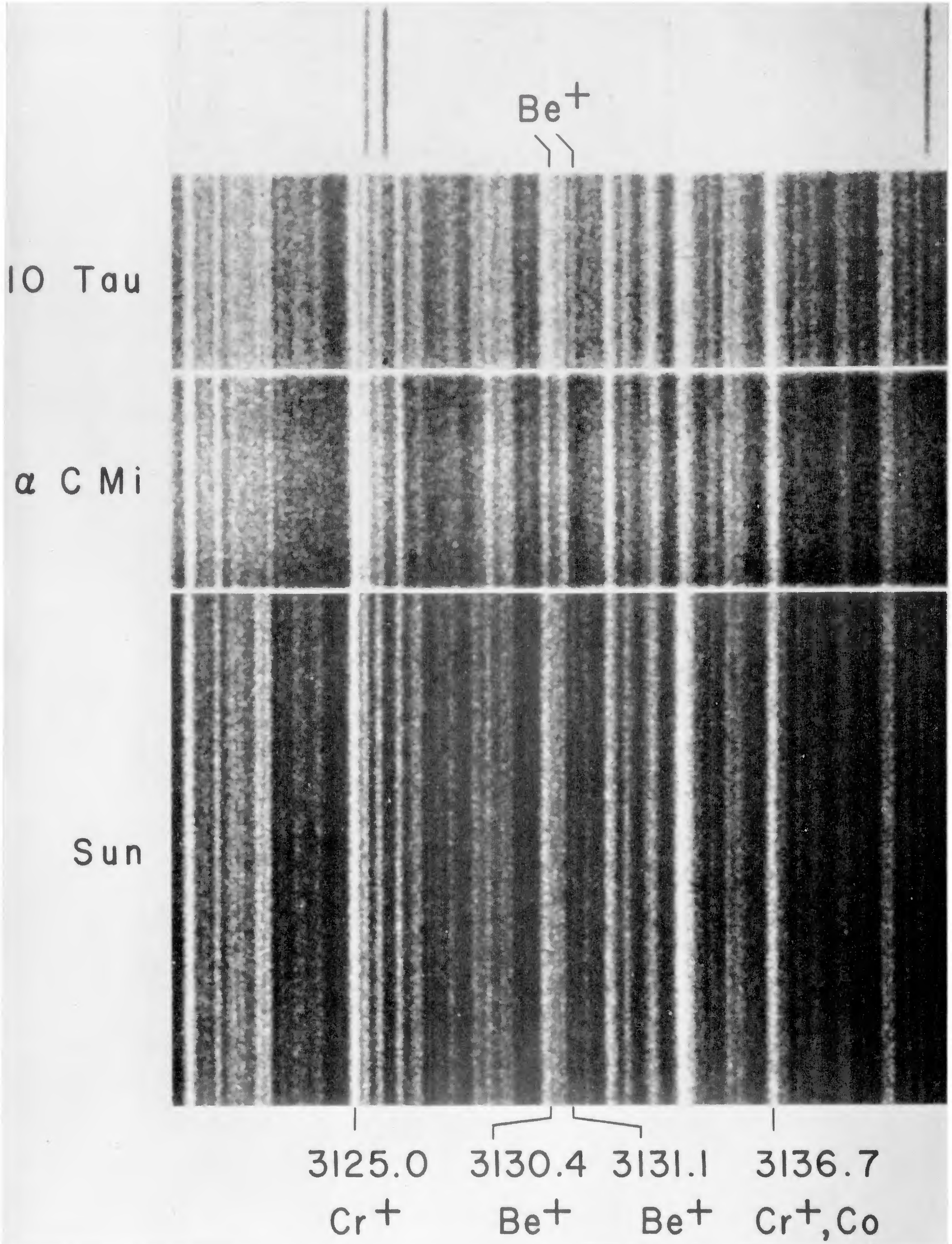

FIG. 2.—Ultraviolet spectra of the sky, α CMi, and 10 Tau. Be II lines are indicated in 10 Tau and the sky; note the absence of Be II in α CMi.

spheric activity inferred from the lack of Ca II emission would seem to imply that the conditions for producing Li and Be on the surfaces of these stars are unfavorable.

Laboratory data on the spallation-production ratio (Bernas, Epherre, Gradsztajn-Klapisch, and Yiou 1965) indicate that between 22 and 36 per cent of the total Li produced by proton bombardment of C^{12} and O^{16} is in the form of Li^6, the exact amount depending upon the initial proton energy and the target nucleus. Therefore, stars with "appreciable Li^6" will, for the present purpose, be taken as those having a Li^6 content of about 30 per cent. Table 2 also lists the $Li^6/(Li^6 + Li^7)$ ratio, adapted from Herbig (1964). The four stars 10 Tau, β Com, ξ UMa A, and ι Per are seen to have "appreciable Li^6" in this sense. The data for these four stars are summarized in Table 3. On the above argument, one assumes that the probability of appreciable pre–main-sequence or main-sequence convective depletion of either Li or Be in these four stars is small, and hence that they more nearly reflect the original abundances than the non-Li^6 stars. The mean abundance ratio of Li/Be in these four stars is 0.64 with a total variation about the mean of approximately 50 percent. This ratio, if regarded as representative for "subsequently unprocessed" stellar material, is in disagreement with the prediction of Fowler, Greenstein, and Hoyle (1962) for the spallation yield from the process they

TABLE 3

STARS WITH APPRECIABLE Li^6 CONTENT

Star	$Li^6/(Li^6+Li^7)$	Li*/Be*	Be*	Li*
10 Tau	0.35	0.50	29.0	14.5
β Com	.28	.91	17.5	16.0
ξ UMa A	.21	.79	22.0	17.5
ι Per	0.24	0.34	29.8	10.2
Mean	0.27	0.64	24.6	14.5

believe to have been operative in the early solar system. Their prediction, based partially on the observed terrestrial and meteoritic abundances and including the effects of thermal neutrons, is Li/Be = 2.8.

Herbig (1964) finds seven of his fifteen stars to have appreciable Li^6; these seven have a range in Li/Ca abundance of a factor of 3. The eight stars found here to have detectable Be (four of which are Herbig's Li^6 stars) show a spread in Be abundance of a factor of 4. This indicates comparable spreads in the Li and Be contents in stars which have been assumed to have suffered little or no convective destruction of Li or Be. In addition, the mean Li/Be value (from the ratio of the mean value of Li from Herbig's seven Li^6 stars to the mean value of Be from the eight Be stars observed here) is 0.71, in good agreement with the above value of 0.64 determined from the four stars in common to both studies.

The aforementioned four stars in which Li^6, Li^7, and Be abundances are now available show a range in Li and Be contents of about a factor of 2; this is comparable to the error expected of a single abundance determination in a given star. Therefore, a one-to-one correlation between Li and Be would not be expected from these data, even if it existed.

The high-velocity, metal-deficient star, χ Her, is a conspicuous exception to the hypothesis of a constant Li/Be ratio. It has essentially no Li^6, but 30 times more Li^7 than the Sun, while the Be abundance is identical to the solar value. In comparison to the mean abundances in Table 3, χ Her is overabundant in Li^7 by a factor of 3 and underabundant in Be by a factor of 3.5. It is difficult to imagine that spallation pro-

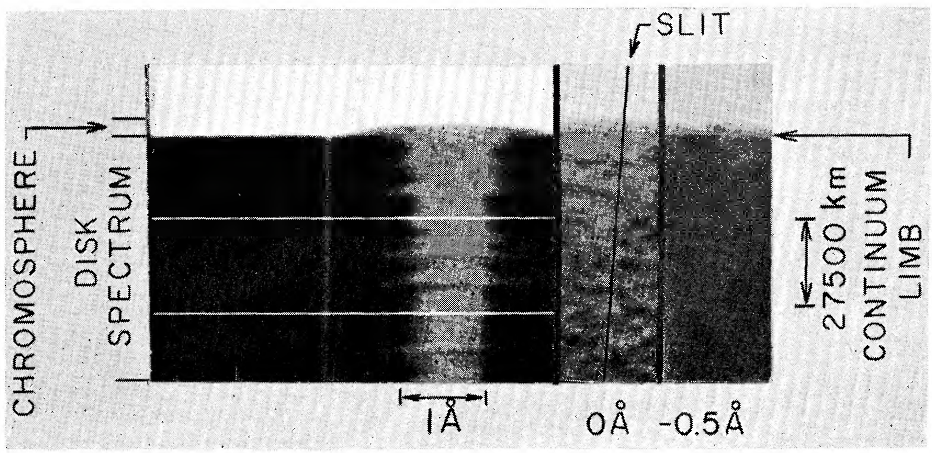

FIG. 1.—A sample of Hα-limb spectra made with a slit almost perpendicular to the solar limb and the companion Hα filtergrams to show the chromospheric fine structure falling on the slit. Note the chromospheric emission in the spectra and the double limb in the filtergrams. On the Hα-disk spectrum one can identify six bright arches that are readily associated with bright flocculi in the on-band filtergram.

duction is responsible for the excess of Li^7, because if spallation reactions produce constant ratios of these light elements, Li^6 and Be should be proportionally abundant. If more Li^6 had been produced initially and since destroyed by the convection mechanism, it would seem likely that some Li^7 would also have been burned. But more indicative is the Be abundance: if additional Be had been produced and subsequently destroyed by convective mixing to higher temperatures, the Li would have been depleted also. There exist three alternatives to explain the abundances in this star: (1) the excess of Li^7 was not produced by spallation (or the spallation output has been strongly modified by thermal neutrons); (2) the Li/Be ratio produced by spallation is *not* constant; or (3) the Be is destroyed by some other means than (p,α) reactions.

None of the other stars observed is inconsistent with the idea of a relatively uniform initial abundance ratio of Li/Be. Both the Li and Be content of π^3 Ori are poorly determined. The Be abundance is more uncertain than in the other stars since the lines are rotationally broadened ($v \sin i = 20$ km/sec); even though the Li content was obtained from two 4-Å/mm plates, the line is very weak and therefore the abundance uncertain. The stars β CVn, λ Ser, and the Sun have probably all reduced their initial supply of Li by convective depletion; the upper limits for the first two stars and the solar value of Li/Be at least are not in conflict with an initial ratio of about 0.6.

It is a pleasure to express my appreciation to Dr. G. H. Herbig for suggesting the problem and obtaining the coudé spectrograms. I am indebted to Dr. Herbig and Dr. Peter Bodenheimer for valuable discussions. A prepublication copy of the Strömgren-Perry photometric catalogue was supplied to me by Dr. Charles Perry. This investigation was supported by a grant from the National Science Foundation.

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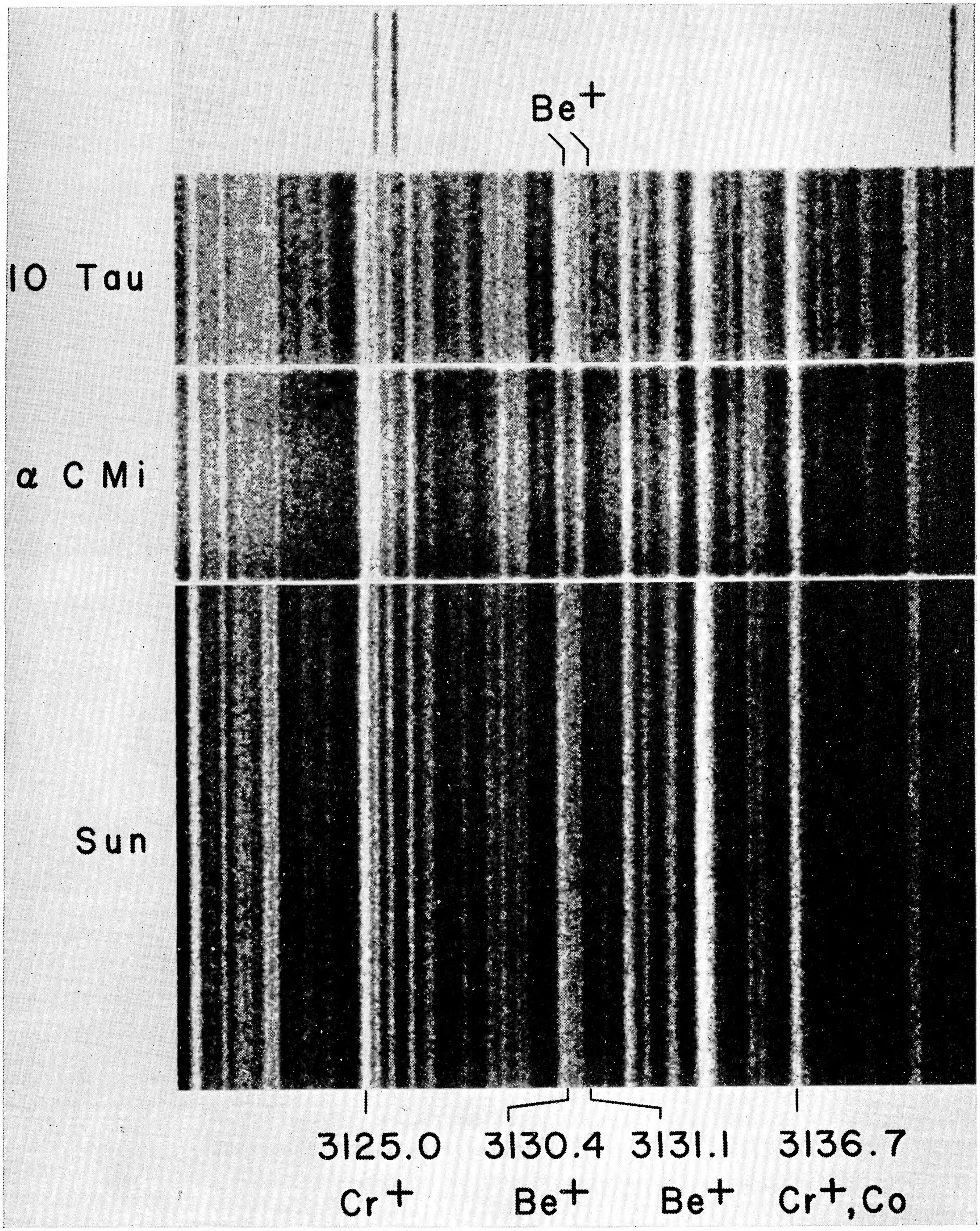

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