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THE CHEMICAL COMPOSITIONS OF NINE SOUTHERN SUPERGIANT STARS[1]

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ABSTRACT

A fine analysis of nine southern supergiants of spectral types F through K, including the bright Cepheid variable *l* Car, is presented. The average metal-to-hydrogen ratio is found to be twice the solar value. No essential differences are found between the nonvariable stars and the Cepheid variable.

In an initial attempt to determine the spatial distribution of abundances within the local region of the Sun ($r \lesssim 0.5$ kpc), the abundances of this study are combined with abundances from previous studies. The data are consistent with a homogeneous distribution of metallicity in supergiants within 0.5 kpc of the Sun.

Subject headings: stars: abundances — stars: late-type — stars: supergiants

I. INTRODUCTION

In the study of galactic structure, supergiants are of great importance. Humphreys (1970) showed in detail how these objects trace out the spiral arms within 5 kpc of the Sun. Due to their great intrinsic brightnesses, these objects can be observed at large distances—even through moderate to large amounts of extinction. This allows supergiants to be used as tracers not only of galactic structure but also of galactic chemical composition. As these objects are very young [total lifetime $\lesssim 5(10^7)$ years], their compositions reflect the current composition of the interstellar medium. Therefore the determination of supergiant abundances is of great importance in terms of galactic chemical evolution.

There is evidence that our Galaxy shows abundance gradients with distance from the galactic center (Peimbert, Torres-Peimbert, and Rayo 1978; Hawley 1978). External disk galaxies also show such gradients (Jensen, Strom, and Strom 1976; Shields and Searle 1978). These gradients are generally traced out in the light elements ($Z < 10$) by use of photometric CN indices or H II regions. Within our Galaxy, abundance gradients based on analysis of individual stars are lacking, primarily because ordinary stars that lie at sufficient distance over which to establish a baseline for measurement are too faint for adequate observation and/or are affected by an unknown amount of reddening. Supergiants, however, are so luminous that they provide an excellent means of studying such gradients within the Galaxy through direct spectroscopic analysis which gives abundances independent of the reddening. The principal drawback to the use of supergiants in such a determination is that the abundance gradient so determined will be for iron and similar heavy elements, whereas the gradients obtained from H II regions for our Galaxy and other external galaxies will be for light elements, most commonly He, C, N, and O. This is due to the fact that the spectroscopic data necessary for determining light-element abundances in supergiants are difficult to obtain (see Luck 1978 for a discussion), and essentially impossible for apparent magnitudes fainter than five. Thus we are restricted to the heavier elements in obtaining supergiant abundances, with the possible exception of lithium in cool stars, where a crude analysis should be possible. However, the information gained from an analysis of lithium does not have a direct relation to the question of galactic abundance gradients but more properly bears on the question of the evolution of individual stellar objects. Nevertheless, the determination of supergiant abundances through spectroscopic analysis should provide essential information on the galactic abundance gradient.

Pagel and Patchett (1975) investigated the mean metal abundance of stars as a function of age and concluded that stars being formed at the present time have metal abundances 2 to 3 times that of the oldest disk stars. However, McClure and Tinsley (1976) showed that the Pagel and Patchett result could be adversely affected by random errors in photometry, and as a result could give spurious answers for the present chemical composition of the Galaxy. A probe of the present composition of the Galaxy is afforded by supergiants. The writer (Luck 1977*a*, *b*) determined the abundances of 19 northern G and K Ib supergiants with the result that all of these objects have abundance enhancements with respect to solar values on the order of a factor of 2, which supports the Pagel and Patchett finding. As the sample analyzed by the writer included no objects between galactic longitudes 270° and 360°, it would be desirable to analyze stars in that region in order to obtain a more complete sample of stars within the local region ($r \lesssim 0.5$ kpc).

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The primary drawback to spectroscopic determinations of supergiant abundances has been the lack of adequate model atmospheres. This situation has been rectified to a large extent by the inclusion in the models of line blanketing due to atomic and molecular species in a reasonable fashion (Gustafsson *et al.* 1975; Sneden, Johnson, and Krupp 1976; Relyea and Kurucz 1978). The remaining difficulty concerns the failure of the assumption of plane-parallel geometry (Watanabe and Kodaira 1978). This problem affects low-gravity models ($\log g < 1.5$) and becomes most severe at gravities appropriate to Ia stars, $\log g \lesssim 1.0$. As most of the stars analyzed here are Ib stars ($\log g > 1.0$), this difficulty should not be fatal.

In this paper an analysis of nine supergiants is presented. These objects were selected to complete the sample of Luck (1977*a*, *b*) between galactic longitudes 270° and 360° to a distance of approximately 0.5 kpc. This group of stars will provide a sample of the local region to within the prescribed radius and will yield the current abundance level of the local region. Further, these stars will, in future work, provide the basis of comparison for supergiants which lie at greater distances, particularly in the direction of the galactic center and anticenter. One Cepheid variable has been included in the group to determine whether there are any gross differences between variable and nonvariable supergiants. The stars to be analyzed, along with some basic data, are given in Table 1.

II. OBSERVATIONAL DATA AND REDUCTION TECHNIQUES

This study is based on spectrograms obtained with the 1.5 m reflector of Cerro Tololo Inter-American Observatory. All spectrograms were taken on unbaked IIa-F plates centered at 6000 Å with a dispersion at the central wavelength of 9 Å mm^{-1}. Each spectrum was trailed to a width of 0.6 mm and has a usable spectral range of 5700–6850 Å or 5400–6850 Å, as noted in Table 2, which gives details of the individual spectrograms. For all objects but *l* Car two spectra were obtained. The phase of *l* Car at the time of observation was 0.16 past maximum.

The plates were traced by H. E. Bond on the PDS microdensitometer at Kitt Peak National Observatory. Intensity calibrations were obtained at wavelengths of 5850 Å and 6400 Å, using spot-sensitometer plates taken at the time of the stellar exposure and developed with the spectrograms.

Continuum levels were found by superposing plots of each pair of spectra of an object and taking common high points to define the continua. Equivalent widths were then determined by use of the Gaussian approximation in a computer code that locates given wavelengths and then determines the half-width (FWHM) relative to the assigned continuum. The assumption of a Gaussian line profile is based on the results of Luck (1977*b*, 1978). It was found in those studies, based on detailed analysis of high-resolution data, that observed supergiant line profiles are fitted very well by Gaussians. The equivalent widths are then determined from the formula $W_\lambda = 1.06(\Delta\lambda)D$, where D is the line depth and $\Delta\lambda$ is the full line width at half-maximum. The line list used for this study is that used by Luck (1977*a*, *b*), supplemented by lines found in the G2 Ib supergiant β Dra but not present in the Luck line list. The list contains some 1200 lines; thus the amount of data precludes their publication, even though for any individual object perhaps only 800 or fewer lines were

TABLE 1

BASIC DATA FOR PROGRAM STARS

HR	Name	Spectral Type	m_V	M_V	$\log L/L_\odot$	B−V	R−I	Photometry Source
2326	Canopus	F0Ib	−0.75	----	----	0.15	0.20	1
6615	ι^1 Sco	F2Ia	2.98	----	----	0.51	----	3
2693	δ CMa	F8Ia	1.84	−7.4	4.81	0.67	0.33	1
4337	----	G0Ia-0	3.91	(−9.0)	(5.49)	1.24	0.60	2
6030	δ TrA	G5Ib	3.84	−3.9	3.49	1.10	----	3
6461	β Ara	K3Ib	2.84	+0.6	2.05	1.56	----	3
3634	λ Vel	K5Ib	2.21	−2.8	3.21	1.65	0.94	1
4050	----	K5Ib	3.35	−3.7	3.29	1.55	0.78	2,3
3884	ℓ Car	cG2	3.40	−5.9	4.23	----	----	3

Notes - Spectral types from Bright Star Catalog (Hoffleit 1964); Absolute magnitudes from Warner (1969) except for δ CMa (Parsons and Bouw 1971), HR 4337-assumed value based on average luminosities (Keenan 1973), and ℓ Car (Fernie and Hube 1968); Luminosities computed using the bolometric corrections of Johnson (1966); Photometry sources: 1) Johnson et al (1966), 2) Mendoza V. (1967), 3) Bright Star Catalog (Hoffleit 1964). ℓ Car magnitude is maximum light.

TABLE 2

PLATE DATA

Object	Plate	Coverage (A)	Exposure Time	Date
Canopus	1059b	5300-6850	15^m	3/21/78
	1059c	5300-6850	14^m	3/21/78
ι^1 Sco	1054b	5300-6850	1^h00^m	3/19/78
	1061a	5300-6850	0^h55^m	3/22/78
δ CMa	1052c	5300-6850	0^h39^m	3/19/78
	1060a	5300-6850	0^h54^m	3/22/78
HR 4337	1051a	5700-6850	1^h44^m	3/18/78
	1053c	5700-6850	$2^h\ 6^m$	3/19/78
δ TrA	1051b	5700-6850	$2^h\ 5^m$	3/18/78
	1053d	5700-6850	1^h28^m	3/18/78
β Ara	1051c	5300-6850	0^h47^m	3/18/78
	1054a	5300-6850	0^h29^m	3/19/78
λ Vel	1052d	5300-6850	0^h23^m	3/19/78
	1053b	5300-6850	0^h33^m	3/19/78
HR 4050	1053a	5300-6850	$1^h\ 7^m$	3/19/78
	1060a	5300-6850	1^h17^m	3/22/78
ℓ Car	1060c	5700-6850	1^h15^m	3/22/78

actually measured. For use in the analysis, the average of two measures of each line was required (except in the case of *l* Car). The mean internal random error, i.e., plate-to-plate difference, is on the order of $\lesssim 10\%$ when averaged over all lines. The systematic accuracy of the equivalent widths is difficult to determine, as no other equivalent widths in the appropriate wavelength range have been published or measured for the stars of this study. Comparison of equivalent widths determined by this method for several supergiants analyzed by Luck (1977*a*) with equivalent widths determined by van Paradijs (1973*b*) shows a slight shift of +0.05 dex without regard to strength. The equivalent-width data are available on request from the author.

III. METHOD OF ANALYSIS

The method of analysis to be used in this study is the technique of fine analysis using equivalent-width data. In this method, equivalent widths are calculated by integration through a model atmosphere and are then compared with an observed equivalent width. The calculation is repeated, changing the abundance of the species in question, until a match is achieved. The underlying assumptions of such an analysis are the usual ones, specifically local thermodynamic equilibrium (LTE), plane-parallel geometry, and hydrostatic equilibrium.

The line-synthesis code of Sneden (1973), as modified by the author, was used to carry out the necessary calculations. Model atmospheres from the grid of Gustafsson *et al.* (1975), as supplemented by Gustafsson (1978) (henceforth designated as Gustafsson models), were used for stars with effective temperatures lower than 6250 K. For stars with effective temperatures greater than 5500 K, the models described by Relyea and Kurucz (1978) (henceforth designated as Kurucz models) were used. In the overlap region, 5500–6250 K, models from both grids were utilized.

Oscillator strengths for the lines used in this study were derived from an inverted solar analysis. Solar equivalent widths were taken from Moore, Minnaert, and Houtgast (1966). A depth-independent microturbulent velocity of 1.0 km s^{-1} (Smith, Testerman, and Evans 1976) was used in conjunction with the Holweger solar model (Holweger 1967; Holweger and Müller 1974). The abundances of Ross and Aller (1976) were adopted for the derivation of *gf*-values, except for Na through Ca, for which the abundances of Lambert and Luck (1978) were used. The use of these solar oscillator strengths makes this study in essence a differential one with respect to the Sun. The use of model-atmosphere techniques removes the difficulties usually encountered when dissimilar objects such as supergiants and dwarfs are compared.

Several of the species under analysis are affected by hyperfine structure. In a differential curve-of-growth analysis, the usual method allowing for such effects is to use additional microturbulence for the affected species (van Paradijs 1973*a*). The desired effect is to desaturate the lines to the same degree that the line splitting due to hyperfine structure would. However, this procedure is not always successful (Luck 1977*a*), and the exact value of additional microturbulence necessary is difficult to obtain, as often there are no laboratory data available. As a result of these difficulties we have decided to neglect the problem of hyperfine structure, both in the derivation of solar *gf*-values and in the computation of supergiant abundances. If a significant effect is introduced into the abundances by the neglect of hyperfine structure, it should make itself obvious by causing anomalous abundances in the species most affected.

Effective temperatures, gravities, and microturbulent velocities for the program stars were derived solely from an analysis of Fe I and Fe II lines. This procedure is necessitated by the fact that no other species has sufficient numbers of lines to derive these parameters. Photometry was not used as a primary indicator of effective temperature due to unknown reddening and difficulties in calibrating the temperature-color relations (Luck 1977*a*). A discussion of the implied temperature-color relation will be given in § IV.

Microturbulent velocities were derived by requiring that there be no dependence of abundance on equivalent width in the domain of interest (W_λ < 175 mÅ) for Fe I. Models bracketing the anticipated parameters for each star were selected and the microturbulence iterated until a best value was obtained. Using this value of microturbulence, the effective temperature was derived by demanding that there be no dependence of abundance on excitation potential. At each of the appropriate model grid points, the slope of the relation between excitation potential and abundance was derived, and the proper effective temperature then obtained by interpolating to the temperature where the slope would be zero. This interpolation should cause no problem in the effective temperatures, as the primary grid used (Gustafsson models) has a temperature spacing of only 250 K. Finally, the gravity was obtained, using the previously determined effective temperature and microturbulence, by forcing the Fe II lines to give the same abundance as Fe I. The microturbulence was then rederived at the nearest grid point, and in all cases found to be not significantly different from its original value. The derived parameters are given in Table 3.

TABLE 3

PARAMETERS FOR SUPERGIANTS

Star	$T_{\rm eff}$	$\log g_{\rm SP}$	$\log g_{\rm EV}$	ξ_T (km s^{-1})
Canopus......	7500	1.85	...	2.7
ι^1 Sco.........	7000	1.25	...	5.0
δ CMa........	6250	1.00	1.0	4.5
HR 4337......	5750	0.40	0.4	7.0
δ TrA.........	5000	1.50	1.6	4.2
β Ara.........	4600	1.30	2.5	4.2
λ Vel.........	4250	1.40	1.5	4.8
HR 4050......	4500	1.60	1.6	4.5
l Car.........	5100	1.50	1.1	7.0

Abundances for all other species were derived at each grid point bracketing the derived effective temperature and gravity, and the actual abundances were then obtained by interpolating to the proper parameters. To be included in the analysis, a line had to have an equivalent width less than 250 mÅ, which considerably reduced the number of lines that could be utilized. This equivalent-width limit is adopted because at large equivalent widths the line opacity approaches unity at very shallow continuum optical depths, yielding an inadequate representation of the line-formation process. The number of weak lines per species varies greatly, ultimately depending on the available number of lines. In the case of Fe I, at least 35% of all lines utilized had an equivalent width less than 100 mÅ. Other species represented by only one or two lines in the observed spectral range had any line accepted which fell below the maximum equivalent-width limit. The division between weak lines and those affected by saturation occurs at a fairly large equivalent width (125–150 mÅ), due to the large microturbulent velocities derived for these stars. Therefore errors in the microturbulent velocity of less than 1.0 km s^{-1} (the estimated accuracy of the velocities) should have only small effects on the abundances, particularly for species such as Fe I. The derived abundances are given in Table 4.

In the stars of spectral type G0 and later, an attempt was made to determine the lithium abundance. As shown by Luck (1977*b*), the lithium feature at 6707.8 Å is actually a blend of neutral lines of Fe, V, and Li, as well as CN and TiO in later-type objects. This situation necessitates the adoption of a spectrum-synthesis technique. As the resolution and signal-to-noise ratio of the present data do not warrant an elaborate analysis, the approach taken was to determine the equivalent width of the total blend and attribute it solely to the three atomic species. The *gf*-value for the Fe I line at 6707.441 Å was taken from Müller, Peytremann, and de la Reza (1975), while the *gf*-value for V I 6708.10 was taken from Corliss and Bozman (1962). The oscillator strength for the lithium doublet was taken from Wiese, Smith, and Glennon (1966). The model grid point nearest the actual parameters was used for the synthesis. With the use of previously determined iron and vanadium abundances, the observed equivalent width was matched, using the lithium abundance as the free parameter. After matching the feature, the actual lithium equivalent width can be determined and the LTE abundance derived. However, Luck (1977*b*) showed that the lithium doublet is affected by non–LTE processes and gave correction factors for LTE abundances as a function of stellar parameters and lithium equivalent width. These factors were used to derive the final non–LTE abundances, which are given in Table 5 along with the equivalent-width data.

IV. RESULTS AND DISCUSSION

The derived parameters and abundances for the program stars are presented, with a discussion of the directly related uncertainties and the relation between this and other studies. An extensive discussion of errors introduced by failure of underlying assumptions and limitations of models has been previously given by Luck (1977*a*), and therefore will not be repeated in detail.

a) *Parameters for Supergiants*

Effective temperatures for the program stars are given in Table 3. From the uncertainty in the slope of the abundance versus excitation potential relation of Fe I (typical value: ± 0.04 in terms of $\theta = 5040/T$), which we found to be zero, the internal error of the effective temperatures is estimated to be ± 200 K. In the region 5500 K $\lesssim T_{\text{eff}} \lesssim$ 6250 K, the effective temperature was derived from both Gustafsson and Kurucz models. In both cases, HR 4337 and δ CMa, the derived temperatures were the same to within 100 degrees. For maximum consistency, the temperature derived with respect to the Gustafsson models is given when possible in Table 3.

In Figure 1 the derived temperatures from this study (excluding *l* Car) and Luck (1977*b*) are shown plotted against observed $B - V$ and $R - I$. As both sets of temperatures have been derived with respect to the same set of models (except for $T_{\text{eff}} > 6250$ K), there should be no difficulties encountered in combining the two sets of data. Figure 1 indicates a tight relation between the derived temperatures of the Ib stars and color. As all objects are reddened to some extent, this tight correlation implies that all have similar reddening. This is consistent with the distance moduli, which place most objects at comparable distances. Parsons and Bell (1975) have derived reddening [$E(B - V)$] values for several of these stars, with values ranging from 0.03 mag (δ CMa) to 0.34 mag (α Aqr). Adopting an average $E(B - V)$ of 0.25, and using 0.75 as the ratio of $E(R - I)$ to $E(B - V)$ (Johnson 1968), the relation given by the solid lines in Figure 1 is implied as the empirical relation between intrinsic color and temperature. Also plotted is the Johnson (1966) calibration. It can be seen that below an effective temperature of 5000 K the agreement between the Johnson's and our temperature scales is fair, but above 5000 K there is a systematic discrepancy.

Between 5000 and 5500 K the Johnson calibration is approximately 300 K hotter than the implied empirical calibration. If the theoretical $B - V$ calibration of Buser and Kurucz (1978) were extrapolated back to 5000 K in a linear fashion, it would be in modest agreement with our derived relation. It can also be noted that between 5500 and 7500 K the theoretical Buser and Kurucz relation is approximately 250 K cooler than the Johnson relation. In this regime (5500 to 7500 K) the empirical relation is weakest, as the stars analyzed are mostly Ia stars and thus cannot be expected to conform to the Ib relation; therefore little can be said concerning the relative calibration differences.

Bell and Gustafsson (1978) have provided a $B - V$ color-temperature relation for the models of the Gustafsson *et al.* (1975) grid. In the lower panel of Figure 1 this relation is shown for solar abundance

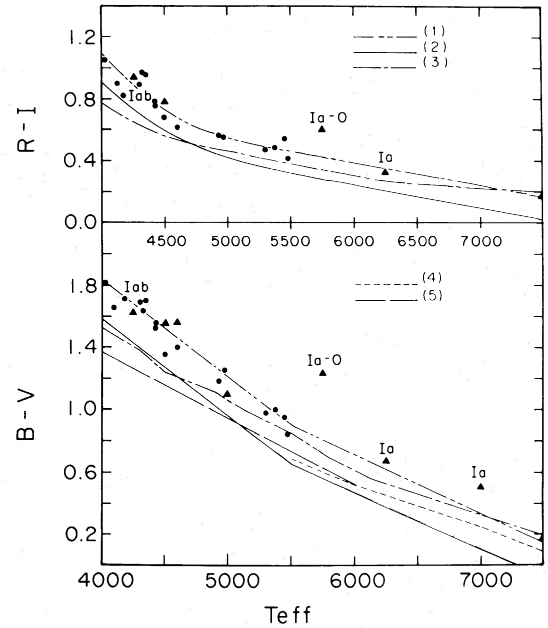

FIG. 1.—The derived effective temperatures plotted against observed $B - V$ and $R - I$. Note the tight relation between the derived temperatures and colors. *Filled circles*, stars from Luck (1977*b*); *filled triangles*, stars from this study. (1) "Best" eye fit to color versus derived effective temperature; (2) dereddened relation between derived effective temperatures and color; (3) Johnson (1966) color-temperature relation; (4) Buser and Kurucz (1978) color-temperature relation [($B - V$) only]; (5) Bell and Gustafsson (1978) color-temperature relation [($B - V$) only]. See text for discussion.

models with a gravity of 1.5 dex. In the effective temperature regime of 5000 to 5500 K, the theoretical relation is in fair agreement with the empirical dereddened relation. Below 5000 K the theoretical relation is approximately 0.15 mag bluer than the observed relation as well as the Johnson calibration. This discrepancy could be removed by invoking a larger average reddening, or by questioning the accuracy of the model fluxes as compared with actual supergiants. Inaccurate model fluxes could result from slight mismatches in filter functions, or inappropriate abundances in the models with respect to observed supergiant abundances. These problems should be studied further in detail. Also of importance are further analyses of bright F Ib stars to better determine the empirical color-temperature relation.

The surface gravities of the program stars are given in Table 3. They were derived by forcing the abundance of Fe II to equal that of Fe I. The correctness of the derived gravities is vouched for by the agreement of the abundances of neutral and ionized species of different elements as shown in Table 4. On this basis, the maximum error estimated is on the order of ± 0.3 dex in $\log g$. Further confirmation of the derived gravities is found by comparing the spectroscopic and evolutionary gravities (the latter derived using the absolute visual magnitudes of Table 1, the bolometric corrections of Johnson 1966, and the evolutionary tracks of Paczyński 1970), which are found to be in good agreement (Table 3) except in the case of β Ara. In the case of β Ara, the agreement between the abundance of neutral and that of ionized species is good for all elements, and the derived gravity is consistent with the assigned luminosity class, which would imply that the absolute magnitude derived by Warner (1969) is in error. The result that spectroscopic and evolutionary gravities have similar values for nonvariable supergiants is in agreement with previous analyses of Ib stars (van Paradijs 1973*b*; Luck 1977*a*).

Schmidt, Rosendhal, and Jewsbury (1974), in a comparison of Cepheids and nonvariable Ib stars, found that Cepheids show significantly lower gravities than Ib stars. However, *l* Car in this study does not show such behavior. This result is in agreement with similar findings of Parsons and Bell (1975) concerning Cepheids and nonvariable stars. The most probable reason for the discrepancy between Schmidt *et al.* and subsequent findings is erroneous gravities derived by Schmidt *et al.* for the nonvariable supergiants.

Microturbulent velocities for the program stars are also given in Table 3. The uncertainty in these velocities is estimated to be $\pm 1.0\ \mathrm{km\ s^{-1}}$ on the basis of the sensitivity of the abundance versus equivalent-width relation to the value of the microturbulent velocity. For the nonvariable Ib stars later than G0 a mean value of $4.4\ \mathrm{km\ s^{-1}}$ is obtained, which is in direct contrast to the mean value of $2.3\ \mathrm{km\ s^{-1}}$ obtained from Luck (1977*b*) for a similar group of Ib stars. The difference in microturbulent velocities is most probably due to the difference in the adopted solar microturbulent velocity, $1.0\ \mathrm{km\ s^{-1}}$ in this study, versus $0.5\ \mathrm{km\ s^{-1}}$ for the earlier work. The ratio of the assumed solar microturbulences is equal to the ratio of the derived supergiant microturbulent velocities. The microturbulent value obtained for the Cepheid *l* Car is in excellent agreement with that found by Rodgers and Bell (1968), $6\text{–}8\ \mathrm{km\ s^{-1}}$ (averaged over phase). For δ CMa, Bell and Rodgers (1965) obtained a microturbulent velocity of $12\ \mathrm{km\ s^{-1}}$, which is highly discordant with the present result of $4.5\ \mathrm{km\ s^{-1}}$. The Przybylski and Burnicki (1974) microturbulent value for Canopus is discordant with the one derived here by a similar amount. The most probable explanation for these discrepancies lies in differences in the method of analysis and the assumed standard microturbulent velocity.

b) *Abundances*

The abundances of the program stars are presented in Table 4 along with the mean abundance level averaged over all elements per star relative to the Sun, and the mean abundance of each element. It can be seen that there is a general overabundance with respect to solar values of a factor of 2 to 3. The mean abundances given in Table 4 are the means computed over the individual logarithmic abundances in the usual manner. The internal scatter (line-to-line difference) for each species has a rms value of ± 0.2 to ± 0.4 dex. The error associated with the mean value is then dependent on the number of lines used in the determination. The maximum and minimum number of lines utilized for a species are also given in Table 4, and the error in the mean is thus seen to range from 0.05 dex (a typical value for Fe I) to 0.3 dex. For species with three or fewer lines, a more accurate estimate of the possible error can be obtained by examining the star-to-star variation. On the average, for rare earths, light metals, and lanthanides, the abundance most likely has an error of ± 0.4 dex associated with it. For the iron-peak elements the associated error is much smaller (~ 0.15 dex).

The stars analyzed range from 4250 to 7500 K in effective temperature and from 0.4 to 1.85 in $\log g$. Over this entire range all abundances are consistent with a general overabundance of a factor of 2 to 3. This result argues against any systematic effects in the abundances due to temperature or gravity.

The error associated with an abundance due to possible inaccuracies in individual stellar parameters are 0.1 dex per 100 degree change in effective temperature for neutral species. The corresponding figure for $\log g$ is 0.2 dex change in ionized abundances for each change of 0.3 dex in gravity. Neutral abundances are generally not affected by gravity changes, and similarly, ionized abundances are not sensitive to temperature effects. This situation breaks down in the regime where the ionization balance is changing from predominantly neutral to ionized. In this case the neutral abundance is sensitive to gravity and the ionized abundance to temperature, but the degree of sensitivity depends on the particular circumstances and no general statements can be made. If this circumstance does apply, the effects have been taken into account, particularly in Fe I and Fe II, the species from which the effective temperature and gravity are derived.

The abundances of HR 4337 and δ CMa were determined with respect to both the Gustafsson and the Kurucz models. The parameters used for the analyses were identical for δ CMa and different by 75 K in T_{eff} and 0.1 in $\log g$ for HR 4337. In both cases a larger abundance was obtained from the Gustafsson models, with the differences ranging from 0.05 to 0.30 dex depending on the species. In particular, for Fe the difference is 0.10 dex for δ CMa and 0.02 dex for HR 4337. These differences can be thought of as representing the uncertainties in the abundances due to possible inadequacies in the models. The agreement between the two model grids may be bettered when account is made of molecular opacities in the Kurucz models.

Previous analyses of the stars in this group for abundances involve Canopus (Przybylski and Burnicki 1974), δ CMa (Bell and Rodgers 1965), and HR 4050 (Hyland and Mould 1974). Comparison of the derived [Fe/H] ratios for all objects indicates that this study is uniformly higher by approximately 0.4 dex, as all previous work yielded essentially solar abundances. For the hotter stars the differences are most likely due to the coarser techniques and models used in the earlier analyses. For HR 4050 the difference can be attributed to effective temperatures; Hyland and Mould used the Johnson calibration and the observed colors to derive

TABLE 4

Supergiant Abundances with respect to Solar Values

Species	Z	Lines max	Lines min	Canopus	ι^1 Sco	δ CMa	HR 4337	δ TrA	β Ara	λ Vel	HR 4050	ℓ Car	Solar A/H	Mean [A/H]	σ	Mean [A/Fe]
NA I	11	3	1	0.58	0.55	1.20	1.01	0.22			0.87	0.31	6.32	0.68	0.36	0.33
MG I	12	1	1			0.34							7.62	0.34		0.0
AL I	13	2	1	0.77			0.68	0.48		0.56		0.45	6.49	0.59	0.14	0.24
SI I	14	16	5	0.72	0.52	0.58	0.59	0.24	0.67	1.12	0.68	0.37	7.63	0.61	0.25	0.26
CA I	20	15	3	0.53	-0.01	0.42	0.25	0.07	1.15	0.79	0.76	0.26	6.34	0.47	0.38	0.12
SC I	21	3	1			1.16	1.11	0.47	0.30	-0.34	0.25	0.84	3.04	0.54	0.54	0.19
SC II		10	1	0.54	0.15			0.29	-0.02	-0.25	0.29					
TI I	22	24	3			0.73	0.83	0.42	0.34	0.42	0.56	0.38	5.05	0.53	0.19	0.18
TI II		2	1	0.52				0.47	0.43	0.49	0.48	0.39				
V I	23	24	3			0.75	0.51	0.01	0.30	-0.01	0.35	0.17	4.02	0.30	0.27	-0.05
V II		2	1			0.76	0.40	0.20	0.40							
CR I	24	8	6	0.19				0.30	0.53	0.24	0.80	0.92	5.71	0.50	0.31	0.15
CR II		6	2	0.40	0.74				0.64							
MN I	25	5	1	0.60	0.64	0.03		-0.28	0.36	0.37			5.42	0.29	0.35	-0.06
FE I	26	113	53	0.35	0.27	0.52	0.32	0.10	0.50	0.23	0.54	0.30	7.50	0.35	0.15	0.0
FE II		12	3	0.35	0.27	0.52	0.32	0.10	0.50	0.23	0.54	0.30				
CO I	27	9	1					0.48	0.37	0.31	0.66	0.50	4.90	0.46	0.13	0.12
NI I	28	20	5	0.55	0.74	0.32	0.23	0.16	0.34	0.23	0.31	0.24	6.28	0.35	0.18	0.0
SR I	38	1	1			2.65	2.20	0.66	1.77		1.08	0.75	2.90	1.52	0.82	1.17
Y I	39	3	1					0.20	0.18		0.13	0.26	2.10	0.19	0.05	-0.16
Y II		2	1	0.56	0.83	0.76		0.0								
ZR I	40	7	1					0.04	-0.01	-0.61	-0.16	-0.08	2.75	-0.16	0.26	-0.51
BA II	56	3	1	0.61	0.51								2.09	0.56	0.07	0.21
LA II	57	6	1		0.84	0.85	0.60	0.18	0.78	0.74	0.80	0.93	1.13	0.71	0.24	0.37
CE II	58	2	1			0.35	0.18		0.29	0.38	1.07	0.75	1.55	0.50	0.34	0.16
ND II	60	6	1		0.31	0.38	0.38	-0.03	0.38	0.74	1.14	1.14	1.23	0.55	0.42	0.21
SM II	62	1	1			-0.16			0.57	0.25	0.37	0.09	0.72	0.22	0.28	-0.12
EU II	63	2	1	0.70	0.40	0.20	0.50	0.20	0.70	0.60	0.70	0.40	0.70	0.49	0.20	0.14
MEAN				0.56	0.50	0.53	0.55	0.19	0.46	0.35	0.58	0.46		0.43		0.08
σ				0.15	0.27	0.37	0.29	0.20	0.27	0.42	0.34	0.33		0.20		0.20

the temperature, while in this work the Fe I spectrum was used. The difference in derived temperature is $\sim$450 degrees, this study having the higher temperature. The effect on the Fe abundances is 0.1 dex per 100 degrees, indicating an increase of 0.5 dex in abundance over the Hyland and Mould value in accord with the derived result.

A comparison of the abundances of the nonvariable supergiants with those of *l* Car shows no differences, either in magnitude or distribution. This result is in accord with the finding of Schmidt *et al.* concerning the relative abundances of nonvariable supergiants and Cepheids. On the basis of expected evolutionary changes (Iben 1967, 1975), this result is as expected, as any differential evolutionary changes between nonvariable supergiants and Cepheids would most probably affect the abundances of carbon, nitrogen, and oxygen, not the abundances of the iron-peak elements.

The derived mean abundances are plotted in Figure 2 as [*A*/Fe] versus atomic number (*A* the abundance of any particular species and [*A*/Fe] from Table 4). There is little to distinguish the data except for the general overabundance with respect to solar values of all species. The most striking feature of the plot is the great overabundance of Sr ($Z = 38$). However, as Y and Zr ($Z = 39$ and 40, respectively) show no enhancement, this overabundance cannot be due to *s*-processing, but must be an artifact of some other process, not necessarily related to abundance. The most likely explanation is that the great line strengths of Sr I are due to a non–LTE process enhancing the population of the lower level of the observed transition. This explanation is reasonable, considering that such processes are known to affect subordinate lines of Na I (Kelch 1975) which are analogous to the Sr I line used in this analysis.

Considering the scatter in the abundances there is little evidence that the general metal abundance level is significantly higher than that of Fe, particularly as Fe has the most well-determined abundance. There is no evidence of *s*-processing or any other anomaly in the abundances. Inspection of the abundances also shows no effects that could be attributable to hyperfine structure (even-odd effects in the lanthanide abundances, anomalous V, Mn, or Co abundances); therefore it can be concluded that use of solar *gf*-values makes allowance for these effects to at least a first approximation.

Significant overionization effects in electron-donor metals have been predicted in cool, late-type giants (Auman and Woodrow 1975). Such effects have been claimed in Na I and Ca I on an observational basis by Kelch (1975) and Ramsey (1977). However, van Paradijs (1973*c*) searched for non–LTE effects in the Fe I spectra of late-type supergiants and found no evidence for such processes. The effects predicted by Auman and Woodrow are not expected to cause significant problems in the calculation of models of stars with parameters of G and K Ib stars. This is because the primary electron donors are predominantly ionized in a LTE calculation (Ca and Na), or show negligible departures from LTE (Al and Mg). Therefore, the overall metal abundance level will not be affected by departures from LTE in the electron-donor metals; but the abundances of the donor metals computed from neutral lines may be affected. To obtain an estimate of the possible overionization of Na and Ca, we follow the treatment of Auman and Woodrow and estimate that

$$\frac{(N_2/N_1)_{\text{non-LTE}}}{(N_2/N_1)_{\text{LTE}}} = \frac{J_\nu(\bar{\tau})}{B_\nu(\bar{\tau})},$$

where ν is the limiting frequency of the photoionization continuum of the first excited state of either Na I or Ca I, $\bar{\tau}$ is the mean depth of formation for the observed lines, B is the Planck function, J is the continuum source function for pure scattering, N_2 is the number of ionized atoms, and N_1 is the number of neutral atoms of the particular elements. These source functions have been determined for a model from the Gustafsson grid with an effective temperature of 4000 K and a gravity

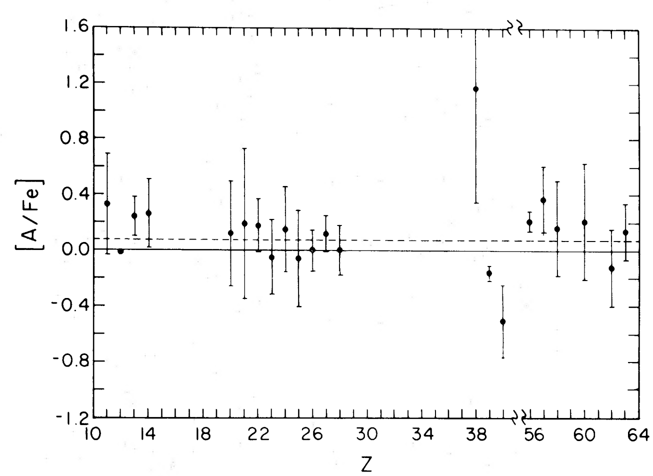

FIG. 2.—The derived mean abundances relative to Fe versus atomic number. *Dashed line*, mean abundance level averaged over all species except Sr. The error bars shown represent 1 standard deviation about the individual mean abundance. See text for discussion.

of 1.5 dex. The ratio ranges between 1.3 and 3 over the line-forming region. However, this ratio is overestimated due to the lack of ultraviolet opacities in the calculations, and therefore a correction must be applied. This correction factor is difficult to estimate but must have a minimum value of 1.4, based on the work of Cohen (1978). Therefore we can assume that the maximum overionization is of the order of a factor of 2 for Na or Ca. Such a result would not disturb the general level of overabundance derived for all elements. A large problem in the work of Auman and Woodrow is the lack of atomic and molecular line blanketing in their models. Such a major deficiency will have a strong effect on any derived result. We urge theoreticians to remedy this deficiency and further the calculations to include such species as Sc and Ti.

Lithium abundances for the cooler stars are given in Table 5 with respect to the solar value ($\log \epsilon_{\rm Li} = 1.0$ with respect to $\log \epsilon_{\rm H} = 12.0$; Müller *et al.*). The generally accepted interstellar abundance is [Li/H] = 2.0 (Boesgaard 1976), which implies that these stars have all undergone lithium depletion and dilution during their evolution. Theoretical predictions for a 5 $M_\odot$ star (Iben 1966) predict a dilution of approximately a factor of 60 from the initial abundance, which is in rough accord with the derived abundances. The derived abundances are in good agreement with those derived for other Ib stars by Luck (1977*b*). Any errors in the derived abundances are directly attributable to the difficulty of obtaining the actual strength of the lithium feature. Numerical experiments in fitting the observed equivalent width indicate that an error of $\pm 50\%$ is not unrealistic. Therefore the error in the derived abundances is at least ± 0.2 dex and may range as high as ± 0.4 dex if some important contributor to the blend has been overlooked or handled improperly. For this reason, the lithium equivalent width of λ Vel and the derived abundance are particularly uncertain. However, it is obvious that evolutionary effects have altered the lithium content of these stars and that the end result is in rough accord with what would be expected on the basis of the predictions of stellar evolution calculations.

TABLE 5

LITHIUM ABUNDANCES

	W_λ			
STAR	Observed Blend	Li I 6707 Å	$[\mathrm{Li/H}]_{\rm LTE}$	$[\mathrm{Li/H}]_{\text{non-LTE}}$[a]
HR 4337......	47	30	+1.09	+1.29[b]
δ TrA........	57	24	+0.11	+0.26
l Car.........	75	41	+0.48	+0.63
β Ara.........	123	31	−0.37	−0.14
HR 4050......	289	165	+0.35	+0.65
λ Vel.........	109	8	−0.65	−0.25

[a] Non-LTE corrections taken from Luck 1977*b*.

[b] Non-LTE correction extrapolated from Luck 1977*b*.

V. CONCLUSIONS

The predominant feature of the derived abundances for these stars is their overabundance with respect to solar values. As Fe has the most well-determined abundance, it can be considered the primary abundance level indicator. The mean [Fe/H] ratio for these objects is +0.35 dex with a standard deviation of 0.15. For the objects studied by Luck (1977*a*, *b*), the mean [Fe/H] ratio is +0.22 dex (± 0.12). Considering the differences in the analysis techniques (this is a differential fine analysis, while the previous work was a differential model-atmosphere–curve-of-growth technique; Cayrel and Cayrel 1963), and the standard deviations of the mean abundances, both analyses are consistent with a [Fe/H] ratio of 0.3 dex. The remaining abundances (except for Sr I) in all studies are consistent with a general overabundance level on third order. Therefore, as a class, supergiants are metal-rich with respect to the Sun.

No evidence of *s*-processing has been detected in any supergiant thus far studied. This result implies that these stars have not reached a stage of thermal pulsing, as at that point the surface abundances of the *s*-process elements should be enhanced (Iben 1975). The low lithium abundances derived indicate that normal stellar evolution has affected these objects, giving lithium dilution in the expected amounts. During the course of evolution, the abundances of C, N, and O, and the $^{12}C/^{13}C$ ratio, will also be affected; however, it is not possible to obtain any information on such changes in these objects, as the necessary observational data are lacking. Therefore, on the basis of the derived lithium abundances and the lack of evidence for enhanced abundances of *s*-process elements, we conclude that these objects have undergone normal stellar evolution through the first giant branch. As the processes which take place during this evolution affect only the light-element ($Z < 10$) abundances, the derived surface abundances must reflect the original composition of these stars for all elements except lithium.

The galactic distribution of these objects defines a well-sampled region of the Galaxy centered on the Sun with a radius of approximately 0.5 kpc. As all derived abundances for these stars are consistent with an overabundance of +0.3 dex with respect to the solar value, it can be concluded that the local region ($r \lesssim 0.5$ kpc) has been enriched in heavy metals by a factor of 2 since the time of formation of the Sun. Additional information on current abundance levels and confirmation of these results could be obtained from H II regions, early F stars near the ZAMS, young clusters, and B-type stars. However, analyses of H II regions and B-type stars do not yield heavy-metal abundances, but the abundances of light elements. Heavy-metal abundances are difficult to obtain from young F stars and open clusters due to observational difficulties, i.e., the stars are in general too faint to obtain the necessary data for a detailed analysis. Therefore, for heavy metals we are forced to rely on supergiant stars to give the abundance level of the local region.

There are two objects, HR 4337 and ι^1 Sco, both Ia stars, which are at a greater distance than 0.5 kpc.

Their derived [Fe/H] ratios are consistent with the remaining abundances. However, these two objects do not constitute a proper sample, and also, their abundances are among the most uncertain due to possible inadequacies in the models (primarily due to the assumption of plane-parallel geometry). Therefore, no statement can be made about large-scale abundance gradients on the basis of the present data. The primary conclusion which can be drawn from the present data is that the local region about the Sun has a present metal abundance which is twice solar and has a uniform distribution. This result supports the contention of Pagel and Patchett (1975) that the Galaxy has continued large-scale chemical evolution since the time of formation of the Sun.

Obviously necessary to the study of galactic chemical evolution is the need to further the studies of supergiant abundances, particularly at greater distances in the directions of the galactic center and anticenter. This work is in progress.

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