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THE CHEMICAL COMPOSITIONS OF 26 DISTANT LATE-TYPE SUPERGIANTS AND THE METALLICITY GRADIENT IN THE GALACTIC DISK

R. EARLE LUCK[1] AND HOWARD E. BOND[1]
Department of Physics and Astronomy, Louisiana State University
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ABSTRACT

From an analysis of high-dispersion Mount Wilson spectroscopic data, we have obtained atmospheric parameters and chemical abundances for 26 distant supergiants of spectral types G through M. Iron-to-hydrogen ratios with respect to the Sun, [Fe/H], can be determined from this material with an uncertainty of ± 0.2 dex.

It is found that supergiants more than about 0.5 kpc from the Sun in the direction of the galactic anticenter are significantly metal-deficient relative to those in the solar neighborhood. Combining our new analyses with those published earlier by Luck for 28 additional supergiants, we derive a radial metallicity gradient $d[\mathrm{Fe/H}]/dR = -0.24 \pm 0.04\ \mathrm{kpc}^{-1}$ for the region of the galactic disk between 7.7 and 10.2 kpc from the galactic center. This gradient is steeper than is found from older objects (such as field main-sequence stars, red giants, and open clusters) and suggests that the metallicity gradients in disk galaxies steepen significantly with age.

Subject headings: galaxies: Milky Way — galaxies: stellar content — stars: abundances — stars: late-type — stars: supergiants

I. INTRODUCTION

In the study of galactic structure, supergiants have long been recognized as objects of great importance. As they are extremely young and very luminous objects, they can be used to trace out the spiral structure of the Galaxy (Humphreys 1970). Their youth also makes them prime candidates for the study of the chemical composition at different locations in the Galaxy at the present epoch. When the homogeneity of age and kinematic properties are combined with the great intrinsic luminosity of these objects, it becomes immediately obvious that we have at our disposal an excellent probe into distant regions of the galactic disk. These stars should be useful in studies of chemical evolution and the determination of the galactic radial metal-abundance gradient.

The question of the current chemical composition of the Galaxy and, in particular, the composition of the local region about the Sun, has been a subject of controversy during the past several years. Pagel and Patchett (1975) investigated the mean abundance of stars as a function of age and concluded that the current generation of stars has a mean metal abundance 2 to 3 times that of the oldest disk stars. However, McClure and Tinsley (1976) point out that the Pagel and Patchett results could be adversely affected by small random errors in photometry, which could give rise to a spurious correlation between age and composition. But Luck (1977*a*, *b*; 1979) investigated a sample of 28 supergiants located generally within 0.5 kpc of the Sun and found that there is indeed a systematic enhancement of the Fe/H ratio in these stars with respect to the solar value. The mean overabundance found was a factor of 2, which is in agreement with the original finding of Pagel and Patchett. Therefore, since the supergiants are unquestionably young objects, it seems that the galactic disk has continued its evolution toward higher metallicities, at least in our neighborhood, since the formation of the Sun.

It has become apparent that the disks of external spiral galaxies show abundance gradients (see, e.g., Searle 1971; Jensen, Strom, and Strom 1976; Shields and Searle 1978). Such gradients have also been claimed in our Galaxy (Mayor 1976; Peimbert, Torres-Peimbert, and Rayo 1978; Janes 1979), but their size and behavior are still somewhat uncertain. A radial abundance gradient is expected on the basis of theoretical models of galactic chemical evolution (Larson 1976; Tinsley and Larson 1978), but the form of the gradient is dependent upon model parameters. The recent observational work of Janes (1979) suggests that the gradient may not be large inward of the Sun's position, but may be more pronounced toward the galactic anticenter.

A direct approach to the problem would be to select a group of stars of similar ages located at a large range of distances from the galactic center and to determine their chemical compositions through high-dispersion spectroscopic analysis. Late-type supergiants meet the criteria of homogeneity in age and observability over large distances and are thus seen to be a natural choice for the direct determination of the radial metallicity gradient at the present epoch.

The primary hindrances to the spectroscopic analy-

[1] Guest Investigators, Hale Observatories.

sis of late-type supergiants in the past have been (1) the necessity of observing them in the red spectral region, where line blending is less severe but where photographic plates have low sensitivity, and (2) the lack of adequate model stellar atmospheres. The first problem has now been overcome with the introduction of image tubes, Reticons, and similar detectors. The model-atmosphere problem has been greatly eased in recent years by the computation of realistically line-blanketed models (e.g., Gustafsson *et al.* 1975; Sneden, Johnson, and Krupp 1976; Kurucz 1979). The problems that remain in models of supergiant atmospheres concern the failures of the assumptions of LTE and plane-parallel geometry (Auman and Woodrow 1975; Watanabe and Kodaira 1978). The effects of these problems are not yet known with certainty, but it is though that they will be of great importance only in the coolest and lowest-gravity atmospheres ($T_{\rm eff} \lesssim 3500$ K, $\log g \lesssim 1.0$). We have therefore limited our analyses, insofar as possible, to supergiants of luminosity class Ib and spectra type earlier than M3.

In this paper we shall primarily be concerned with determination of the metallicity gradient in the direction of the galactic anticenter. The 26 stars to be analyzed are listed in Table 1, with some basic information. The objects were selected primarily from the catalogs of Humphreys (1970, 1978), with the aim of selecting objects lying 0.5–2 kpc from the Sun.

II. OBSERVATIONS AND REDUCTIONS

The analysis of the stars in Table 1 is based on spectroscopic observations we obtained as Guest Investigators at Mount Wilson Observatory during 1978–1979 using the 2.5 m Hooker reflector with the coudé photon-counting Varo-Reticon detector designed by Shectman (see Shectman and Hiltner 1976). Three observations of each star were acquired, each having a spectrum length of 175 Å, and centered at 6350, 6560, or 6710 Å. The spectral resolution in each case was 0.3 Å, and the formal signal-to-noise ratio at the central wavelength was in excess of 50. A typical integration time was 20 minutes. If a star was a known variable, all data were acquired in a short time relative to the known or suspected period as given in the *General Catalogue of Variable Stars*.

The Varo-Reticon data were reduced using a package of computer programs developed or modified by one of us (R. E. L.) and H. Delgado. The initial program performs sky subtraction, divides by a flat-field scan, adds buffers, co-adds channels, and performs various other auxiliary functions. After this preliminary processing is completed, the spectrum is smoothed by a fast-Fourier transform (originally developed by C. Webb at the University of Texas). From a plot of the smoothed data, the continuum is set by hand, and lines of known wavelength are chosen and marked. This information, along with the smoothed spectrum, is then fed to another program, which normalizes the spectrum to the desired continuum level, computes the wavelength dispersion relation, and finally determines line equivalent widths from the formula

$$W_\lambda = 1.06 l_d \Delta\lambda ,$$

where $\Delta\lambda$ is the full width at half-maximum, and l_d is the line depth. The line list used was that of Luck

TABLE 1

DATA FOR THE PROGRAM STARS

HR	HD	NAME	OTHER DESIG	SPECTRAL TYPE	V (MAG)	T_{EFF} (K)	LOG G (CGS)	V_T (KM/S)
800	16901	14 PER		G0 IB	5.60	5500	1.00	5.0
	33299			K1 IB	6.67	4500	0.70	3.5
	35601			M1.7 IAB	7.35	4000	0.70	4.0
1845	36389	119 TAU	CE TAU	M2.1 IAB	4.29	3700	0.70	2.0
	37387			K1 IB	7.57	4500	1.20	4.0
1939	37536		NO AUR	M1.8 IB	6.10	3800	0.70	4.0
	38247			G8 IAB	6.61	4750	1.70	5.5
	39949			G2 IB	7.22	5250	1.10	4.0
	42454			G2 IB	7.33	5250	1.10	4.0
	42474		WY GEM	M2.1 IB+B	7.29	3800	0.70	4.0
2190	42475		TV GEM	M0.6 IAB	6.58	4000	0.70	4.0
2197	42543	6 GEM	BU GEM	M1.0 IA	6.41	3800	0.00	4.5
	44391			K0 IB	7.74	4700	0.55	3.0
	45829			K0 IAB	6.63	4500	0.20	5.0
2453	47731	25 GEM		G5 IB	6.42	5000	1.00	4.0
	48640			K1 IB	7.20	4500	2.25	5.0
	49068			K0 IB	7.51	4500	0.75	3.0
2615	52005	41 GEM		K3 IB	5.69	4400	0.75	4.0
3026	63302			G8 IAB	6.70	4500	0.20	4.5
3459	74395			G2 IB	4.61	5250	1.30	4.0
	187238			K3 IAB-IB	7.70	4500	0.75	5.0
	187299			G5 IAB-IB	7.12	5000	2.10	5.0
7892	196725	θ DEL		K3 IB	5.72	4500	1.30	3.0
8321	207089	12 PEG		K0 IB	5.29	4500	1.90	3.5
8982	222574	104 AQR		G0 IB	4.80	5500	1.80	4.0
9103	225212	3 CET		K3 IB	5.16	4250	0.75	4.5

NOTES: SPECTRAL TYPES: G AND K STARS - HUMPHREYS 1970, 1978
M STARS - WHITE AND WING 1978
MAGNITUDES : HUMPHREYS 1970, 1978

(1979). For each star, between 175 and 250 equivalent widths were measured. The bulk of these measures precludes their publication, but they are available from the authors upon request.

In an effort to determine the accuracy of these equivalent-width measures, several tests have been made. First, there is some wavelength overlap between integrations for each star, and a comparison of equivalent widths from the different integrations shows agreement to within $\pm 20\%$. This is satisfactory since the ends of the scans suffer considerable vignetting and some defocusing. In several cases, two spectra of the same object were obtained at the same central wavelength. The comparison in these cases showed very good agreement, to within $\pm 10\%$. To test the external accuracy of the equivalent-width scale, integrations at 6250 Å were obtained for ϵ Peg and 9 Peg, both of which have previously been analyzed on photographic plates by one of us (Luck 1977*a*). Comparison of the Varo-Reticon equivalent widths to those measured in the earlier study (on 3.5 Å mm^{-1} plates with a resolution of 0.07 Å) is shown in Figure 1. The agreement is satisfactory, with a small systematic shift of 0.05 dex between the reduced equivalent widths in the sense that the Varo-Reticon data give larger equivalent widths. This shift is about what we expect, since lower-resolution spectra tend to give somewhat larger equivalent widths (see Cayrel and Cayrel 1963; Luck and Bond 1980). As this shift is quite small, it should cause little error in the comparison of abundances derived from the present material with the abundances derived in the earlier studies.

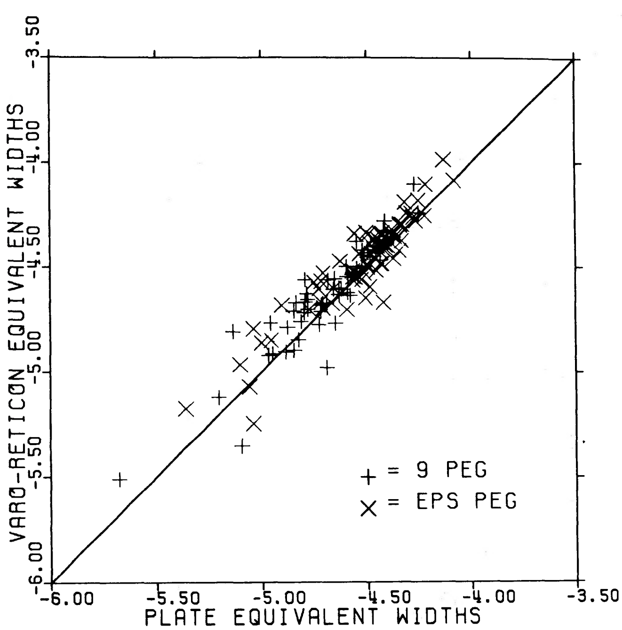

FIG. 1.—A comparison of equivalent widths measured from Varo-Reticon data and plate data. There is a small systematic shift of +0.05 dex between the reduced equivalent widths, which is as expected based on the respective resolutions of the source data. See text for further discussion.

III. METHOD OF ANALYSIS

For this study we have adopted the technique of fine analysis using equivalent-width data. In this method, equivalent widths are calculated for an assumed abundance by integration through a model atmosphere. The computed equivalent width is then compared with an observed equivalent width. If the agreement is not adequate, the abundance of the species in question is changed and the calculation repeated. This procedure is continued until a match is achieved. The underlying assumptions of such an analysis are the usual ones, specifically LTE, plane-parallel geometry, and hydrostatic equilibrium.

The calculations were carried out using a line-synthesis code originally developed by Sneden (1973) and subsequently modified by one of the authors (R. E. L.). Model atmospheres for the G and K stars were taken from the grid of Gustafsson *et al.* (1975), as supplemented by Gustafsson (1979) and new calculations performed at LSU using the MARCS code of Gustafsson *et al.* For the M stars, models from an unpublished grid of models by H. R. Johnson and his co-workers at Indiana University were used. These models were computed using methods discussed by Sneden, Johnson, and Krupp (1976).

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 the *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 differential with respect to the Sun. The use of model-atmosphere fine-analysis techniques removes the difficulties formerly encountered when dissimilar objects such as supergiants and dwarfs were compared.

The method of derivation of effective temperatures, gravities, microturbulent velocities, and abundances for the program stars used is that given by Luck (1979). Briefly, the effective temperature and microturbulent velocity are arrived at by taking an initial model with a series of microturbulent velocities and computing the abundance of Fe I from all lines with equivalent widths less than 250 mÅ. The proper velocity is the one that gives no dependence of abundance on equivalent width. With the microturbulent velocity determined, the dependence of abundance upon lower excitation potential is examined, and changes are made in the assumed effective temperature until there is no dependence on excitation. The abundance-versus-equivalent–width relation is then reexamined for possible trends, and the procedure is iterated as necessary until there are no trends in the individual Fe I abundances with either equivalent width or excitation potential.

Gravities were, in most cases, derived after obtaining the effective temperature and microturbulent velocity by forcing Fe I and Fe II to give the same abundance. In the case of the M stars this was not feasible, as no reliable Fe II lines were measured. For the M stars, therefore, we have had to resort to a theoretical determination of the gravity based on assumed luminosities. Examination of the K-line magnitudes for Ib objects (Wilson 1976) shows that these stars have remarkably homogeneous absolute V magnitudes, with a mean $M_v = -4.5$. We adopt this value for the absolute V magnitudes of all the M Ib stars. For the M Iab stars we adopt a mean absolute V magnitude of -5.8 (Lee 1970). To obtain bolometric absolute magnitudes we use the bolometric corrections of Johnson (1966) in combination with the derived effective temperatures. Converting these bolometric magnitudes to luminosities, and using the spectroscopically derived effective temperatures, we place these objects on the theoretical evolutionary tracks of Paczyński (1970) and obtain a mean mass of 10 $M_\odot$. This mass and luminosity then translate into a log g of 0.7 for Ib objects and 0.5 for Iab objects. Considering the uncertainties in the derivation, we simply adopted 0.7 dex as the gravity for all M-type Ib and Iab objects. It is known that evolutionary and spectroscopic gravities are in good agreement for Ib stars of earlier spectral types (Luck 1977*a*, 1979), so there should be no major problem involved in the use of these gravities. For the sole M Ia object (BU Gem), we have assumed an absolute V magnitude of -6.5 and proceeded as above, deriving a gravity of 0.0 dex. The derived parameters are given in Table 1 for all program stars.

Abundances for the program stars are given in Table 2. They have been derived by computing the abundance for each species at the model-atmosphere grid points which bracket the derived parameters and then interpolating, if necessary, to the proper effective temperature and gravity.

IV. RESULTS OF THE ABUNDANCE ANALYSIS

In this section we shall discuss the derived stellar parameters and chemical abundances, and the uncertainties associated with them.

a) *Parameters*

Effective temperatures for the program stars are given in Table 1. The possible error in these temperatures can be obtained from the uncertainty in the slope of the abundance-versus-excitation–potential relation. A typical value for this uncertainty is ± 0.05 in terms of $\theta = 5040/T$. At 5000 K this translates into a possible uncertainty in temperature of ± 250 K, while at 4000 K the uncertainty is ± 150 K. The effective temperatures given in Table 2 have a tendency to lie at the model grid points (temperature spacing in the Gustafsson grid is 250 K; in the Indiana M-star grid 200 K), which can be understood because the spacing of the grids in temperature is about equal to the temperature resolution of the data. Therefore, the effective temperatures can be assigned to the grid points without incurring any significant error. We will not attempt to derive from these temperatures an intrinsic color-temperature relation, as all of these objects are undoubtedly reddened to some extent. Unfortunately there is no way to deredden most of these objects without the assumption of a color-temperature relation. We will return to this problem in § V.

Demanding that the agreement between the abundances of Fe I and Fe II be better than ± 0.17 dex leads to a range of ± 0.3 dex in the value of log g. We feel that our neutral abundances are reliable at this level, and hence feel that the error in the gravities is on the order of ± 0.3 dex, except for the M stars where a figure of ± 0.5 dex is more likely. The uncertainty (except for the M stars) is derived from considering the sensitivity of the Fe II abundance to gravity and how much variation in log g could be allowed before the Fe I and Fe II abundances are not in adequate agreement (agreement meaning a difference of no more than 0.17 dex). Some confirmation of the gravities is found in the abundances of Ti I and Ti II given in Table 2, but the Ti II data are somewhat unreliable. The uncertainty in the M-star gravities is very difficult to estimate, as there is no quantitative check possible. The possible error must be as large as that for the directly determined gravities, and we feel that ± 0.5 dex is a realistic estimate.

The derived microturbulent velocities are estimated to have an internal accuracy of ± 0.5 km s^{-1}. This is due to the fact that the abundance-versus-equivalent–width relation is very sensitive to the assumed velocity, and a change in excess of 0.5 km s^{-1} from the derived value leads to large relative changes in the slope of that relation. The velocities derived in this study compare very well with those derived for other Ib stars by Luck (1979).

Three of the stars considered in this work have been analyzed previously. Bakos (1971) performed a curve-of-growth analysis of HD 45829 and 41 Gem, and van Paradijs (1973) analyzed 3 Cet using model-atmosphere curve-of-growth techniques. Bakos does not give effective temperatures or gravities for the stars in his analysis, so the results cannot be compared with the parameters derived here. Van Paradijs gives an effective temperature of 4100 K and a log g of 1.1 for 3 Cet, which are to be compared with the values of 4250 K and 0.75 derived here. Given the difference in technique, the agreement is adequate. Microturbulent velocities were derived in the earlier analyses, with the values being 9.4, 8.5, and 3.0 km s^{-1} for HD 45829, 41 Gem, and 3 Cet, respectively. Our values for these objects are 5.0, 4.0, and 4.5 km s^{-1}, respectively. The difference between the Bakos values and those derived here are particularly large and must result from gross differences in technique and selection of standard parameters such as the solar microturbulent velocity.

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TABLE 2

SUPERGIANT ABUNDANCES WITH RESPECT TO SOLAR VALUES

SPECIES	Z	LINES MAX	LINES MIN	14 PER	HD 33299	HD 35601	119 TAU	HD 37387	NO AUR	HD 38347	HD 39949	HD 42454	WY GEM	TV GEM	BU GEM	HD 44391
NA I	12	1	1			-0.44										
AL I	13	2	1	0.15							0.11					0.80
SI I	14	7	4	-0.04	0.17			0.25		0.25	0.03	0.28				0.47
CA I	20	11	2	0.21	-0.29	-0.34	0.29	0.09	-0.19	-0.07	-0.07	0.19	-0.60		-0.49	0.41
SC II	21	5	1	0.03	-0.07	-0.35	0.35	0.34	-0.41	0.03	-0.14	-0.32	-0.75	-0.14	-0.10	0.26
TI I	22	11	3	0.07	-0.24	-0.20	0.32	0.06	-0.44	0.24	-0.18	-0.04	-0.61	-0.37	-0.32	0.0
TI II		2	1		-0.07		0.02	0.52		0.52	-0.15	0.17			-0.22	0.01
V I	23	17	5	0.15	-0.38	-0.38	0.43	-0.05	-0.50	0.21	-0.31	-0.05	-0.65	-0.31	-0.37	0.01
CR I	24	6	2		-0.21	-0.52	0.59	-0.12	-0.45	-0.02	-0.11	-0.27	-0.64	-0.22	-0.49	-0.02
FE I	26	70	11	0.02	-0.09	-0.24	0.11	0.13	-0.15	0.03	-0.16	-0.06	-0.36	-0.36	-0.42	0.21
FE II		5	2	0.0	-0.09			0.13		0.06	-0.16	-0.04				0.21
CO I	27	6	2	0.12	0.08	-0.04	0.18	0.42	-0.23	0.39	-0.07	-0.07	-0.04		-0.02	0.44
NI I	28	16	5	-0.11	-0.04	-0.11	0.10	-0.01	-0.10	-0.06	-0.27	-0.17	-0.37	-0.33	-0.26	0.11
Y I	39	3	2	-0.12					-0.49		0.06	-0.26		-0.43	-0.57	
ZR I	40	4	1		0.13		-0.22		-0.40	0.11	0.12	0.46	-0.84	-0.96	-0.38	
LA II	57	3	1	0.19	0.34				0.14	0.89	0.03	0.11	0.07		-0.06	0.36
SM II	62	1	1		-0.11			0.10		0.13				-0.13	-0.13	
EU II	63	1	1	-0.12	0.24		0.27	0.46	0.13	0.64	-0.07	0.08				0.12

SPECIES	Z	LINES MAX	LINES MIN	HD 45829	25 GEM	HD 48640	HD 49068	41 GEM	HR 3026	HR 3459	HD 187238	HD 187299	THETA DEL	12 PEG	104 AQR	3 CET
NA I	12	1	1	0.16						0.24	0.10					
AL I	13	2	1	0.48		0.25				0.47				0.77	0.32	0.15
SI I	14	7	2	0.18	0.07	0.19	0.18	-0.04	0.06	-0.06	0.33	0.23	0.36	0.30	0.07	0.20
CA I	20	12	5	-0.33	-0.15	-0.38	-0.41	-0.13		-0.08	-0.08	0.37	0.11	-0.15	0.07	-0.40
SC II	21	5	2	-0.18	-0.28		-0.12	-0.38	-0.25	-0.58	0.27	0.33	0.19		-0.18	-0.37
TI I	22	12	4	-0.25	0.04	0.07	-0.25	0.06	0.31	-0.13	0.25	0.40	0.15	0.0	0.17	-0.41
TI II		2	1	0.0	-0.03		-0.23	0.0	0.59				0.76		0.04	
V I	23	19	10	-0.36	-0.04	-0.01	-0.51	-0.04	0.16	-0.03	0.06	0.43	0.12	0.02	0.18	-0.21
CR I	24	6	3	-0.22	-0.47	-0.03	-0.16	0.09	0.10	-0.11	0.17	0.45	0.12	0.17		-0.25
FE I	26	58	22	0.0	-0.16	-0.11	-0.24	-0.20	0.18	-0.11	0.19	0.17	0.21	0.06	0.05	-0.20
FE II		7	2	-0.02	-0.16	-0.19	-0.28	-0.23	0.16	-0.12	0.23	0.14	0.25	0.05	0.04	-0.21
CO I	27	7	2	0.10	0.21	0.44	0.34		0.44	-0.12	0.38	0.60	0.69	0.59	0.23	
NI I	28	18	10	-0.18	-0.20	-0.10	-0.08	-0.27	0.06	-0.13	0.19	0.29	0.10	0.09	-0.01	-0.17
Y I	39	3	1		-0.02	0.0	-0.47	0.21		-0.19	0.10	0.59	-0.09	-0.45		
ZR I	40	3	1			0.16	-0.53	-0.16			0.09	0.16			0.28	
LA II	57	3	1	0.41	0.11	0.59	-0.19	0.42	0.70	-0.04				0.78	-0.03	0.15
SM II	62	1	1	-0.43	-0.56	0.14	-0.19	-0.38	-0.10		0.17		0.09			-0.29
EU II	63	1	1	-0.05	0.08	0.59	0.09		0.28	0.07					0.08	

The difference between van Paradijs and this work is not so great but will result in abundance shifts, due to desaturation, between the two studies.

b) *Abundances*

Abundances for the program stars are given in Table 2. The uncertainty in these abundances arises from two sources: (1) line-to-line scatter, and (2) possible errors in the stellar parameters. The first source of error can be evaluated directly from the data in the case where the abundance is determined from an appreciable number of lines ($n > 5$). A typical standard deviation about the mean abundance for this case is ± 0.3 dex. For Fe I, which has numerous lines, this translates into an error in the mean of less than ± 0.1 dex in all stars, and as small as ± 0.04 dex in the most favorable case. For species whose abundance is determined from five or fewer lines, the errors are more difficult to ascertain. Examination of the abundances of these elements on a star-to-star basis (comparing only objects with similar [Fe/H] ratios) indicates that an uncertainty of ± 0.4 dex is not unrealistic.

The uncertainty in the derived parameters is approximately ± 150 to ± 250 K in T_{eff}, ± 0.3 in $\log g$, and ± 0.5 km s^{-1} in the microturbulent velocity. In Table 3 the sensitivity of abundances derived from Fe I and Fe II are given as a function of the line strength for a selection of parameter changes. These parameter changes are selected to be between model atmosphere grid points for effective temperature and gravity, and a change of 1.0 km s^{-1} has been used in the microturbulent-velocity parameter. As a result the sensitivities shown in Table 3 are extreme values but are very illustrative of the effects of changing parameters. The error to assign to an abundance due to parameter errors is not the direct Gaussian sum of the individual uncertainties such as shown in Table 3. This is because a change in one parameter will in general cause a shift in another, the net effect of which could be no change in abundance. On the basis of numerical experiment with such changes, we estimate that typical parameter errors should lead to an uncertainty of no more than ± 0.2 dex in the abundances. This figure takes into account the interaction of the parameters and is not a direct product of Table 3, which shows only the effect of unilateral changes.

We note at this point that all abundances in Table 2 have been computed from solar-abundance models. As can be seen, some of the stars are slightly metal-deficient relative to the Sun. The effect of using metal-poor ([M/H] $= -0.5$) models has been investigated and the effect found to be small (change in abundance < 0.1 dex), as can be seen from the values given in Table 3. The only stars for which metal-poor models perhaps should be used are some of the M stars; however, the Johnson grid has no metal-poor models. In any case, the net effect would be only a lowering of

TABLE 3

SENSITIVITY OF DERIVED ABUNDANCES TO PARAMETER CHANGES

PARAMETER CHANGE	FE I 50 MA	FE I 100 MA	FE I 200 MA	FE II 50 MA	FE II 100 MA	FE II 200 MA
TEMPERATURE CHANGE[1]						
5000 → 5250 K	+0.25	+0.25	+0.25	-0.10	-0.10	-0.10
4250 → 4500	+0.12	+0.12	+0.12	-0.33	-0.36	-0.41
3800 → 4000	-0.01	-0.03	-0.04	-0.31	-0.44	-0.44
GRAVITY CHANGE[2]						
0.75 → 1.50 DEX	+0.04	+0.00	+0.00	+0.34	+0.34	+0.34
0.75 → 1.50	+0.14	+0.14	+0.17	+0.46	+0.48	+0.53
0.5 → 1.0	+0.17	+0.19	+0.24	+0.38	+0.39	+0.42
MICROTURBULENCE CHANGE[3]						
4.0 → 5.0 KM/S	-0.02	-0.07	-0.22	-0.03	-0.10	-0.29
4.0 → 5.0	-0.02	-0.05	-0.23	-0.06	-0.14	-0.29
4.0 → 5.0	-0.03	-0.07	-0.25	-0.08	-0.13	-0.28
METALLICITY CHANGE[4]						
-0.5 → 0.0 DEX	+0.00	-0.03	-0.13	-0.15	-0.15	-0.15
-0.5 → 0.0	+0.11	+0.11	+0.11	+0.24	+0.26	+0.27

NOTE: THE TABLE GIVES THE CHANGES IN [FE/H] (DERIVED FROM FE I AND FE II LINES OF VARIOUS STRENGTHS AND LOWER EXCITATION POTENTIAL OF 3 EV) THAT RESULT FROM VARIOUS CHANGES IN THE MODEL-ATMOSPHERE PARAMETERS.

1) AT CONSTANT LOG G = 1.5 ; [M/H] = 0.0 ; V_T = 4.0 KM/S

2) AT 5000 K, 4250 K, AND 3800 K RESPECTIVELY ; V_T = 4.0 KM/S ; [M/H] = 0.0

3) AT 5000 K, 4250 K, AND 3800 K RESPECTIVELY ; LOG G = 1.5 ; [M/H] = 0.0

4) AT 5000K AND 4250 K RESPECTIVELY ; LOG G = 1.5 ; V_T = 4.0

the derived [Fe/H] ratio by at most 0.1 dex, which compared with the total uncertainties in the analysis is small.

Iron-to-hydrogen ratios have previously been derived for three of the objects under study. These are HD 45829, 41 Gem, and 3 Cet. Bakos (1971) derived [Fe/H] ratios of −0.16 and −0.29 for the first two objects, while van Paradijs (1973) derived +0.23 for the last star. Our values are 0.00, −0.20, and −0.20, respectively, for these objects. The first two determinations are in adequate agreement, but the difference for 3 Cet is rather large compared with the likely errors. As the two sets of stellar parameters are comparable, we conclude that a large part of the difference lies in the assumed stellar microturbulent velocities. This study has the larger value by 1.5 km s^{-1}, which would desaturate the lines and lead to a lower abundance, as is observed.

We conclude from the above discussion that the derived [Fe/H] ratios given in Table 2 are generally accurate to ±0.2 dex. In the G- and K-type supergiants, a large number of Fe I lines were used, so that the error in [Fe/H] is dominated by parameter errors. In some of the M-type supergiants, as few as 11 Fe I lines were used (because of much more severe line blending), but even in these cases the line-to-line standard deviation of about ±0.3 dex leads to an error in the mean of less than ±0.1 dex, so parameter errors again dominate.

Several comments are appropriate at this point concerning the derived abundances. First, the [Fe/H] ratios for the M supergiants are well determined from the analysis, even though they are derived by using a gravity obtained from theoretical arguments. This result comes about due to the behavior exhibited in Table 3 by Fe I in relation to possible changes in the stellar parameters. As can be seen, the [Fe/H] ratio for the M stars is relatively insensitive to temperature (assuming 3 eV represents the mean excitation potential of the lines analyzed, which is very nearly the case), and the expected uncertainty in the gravity leads to an uncertainty in the abundance of only ±0.2 dex. Thus we are fortunate in that the gravity is not vital to the derivation of our most important result, namely the [Fe/H] ratio. We noted also that the abundances derived using the Johnson models agree very well with those obtained using the Gustafsson models (mean difference <0.1 dex) when the same data are reduced with respect to both grids.

Another point of interest concerns the lack of any evidence for *s*-processing, or other anomalous element abundances, in any of these stars. We thus do not confirm Bakos's (1971) claim that supergiants show *s*-process enhancements. For a more thorough discussion of *s*-processing and the evolutionary status of late-type supergiants, see Luck (1977*a*, *b*; 1978).

V. THE GALACTIC METAL-ABUNDANCE GRADIENT

In the present work we have determined chemical compositions for 26 supergiants, most of which lie at distances of 0.5–2 kpc in the direction of the galactic anticenter. In earlier studies of 28 stars within 0.5 kpc of the Sun (Luck 1977*a*, *b*; 1979), it was found that the local supergiants have a nearly uniform [Fe/H] near +0.3. By contrast, the more distant supergiants have lower metallicities, lying in the interval $-0.4 \leq [\mathrm{Fe/H}] \leq +0.2$. Particularly striking are the results for three supergiants each in the anticenter associations Aur OB1 and Gem OB1; their mean values of [Fe/H] are −0.16 and −0.39, respectively.

In order to quantify this apparent metallicity gradient in the anticenter direction, we need to know the galactocentric distances for the 54 supergiants of this paper and Luck's earlier work. In several cases, the supergiants belong to OB associations, and for these we have adopted the mean distance moduli given by Humphreys (1978). For the Cepheid *l* Car we used the distance given by Fernie and Hube (1968).

For the other stars, we need both the interstellar absorption and the absolute magnitude in order to obtain the distance. For more than half the stars, absolute magnitudes determined from the K-line emission width are available from Wilson (1976) and were adopted. For the remainder of the stars we adopted $M_v = -5.8$ for luminosity class Iab, −4.5 for class Ib, and −2.1 for class II (see Blaauw 1963; Lee 1970; Keenan 1973; Wilson 1976). An alternative procedure for obtaining the absolute magnitudes for these 14 stars would have been to assume a mass and then calculate the luminosity from the derived spectrscopic temperature and gravity. However, we feel this offers no greater precision than the use of average absolute magnitudes for luminosity classes.

The visual absorption was obtained from the relation $A_v = 3.1E(B - V)$. The color excess was determined by using the derived effective temperature and gravity with the T_{eff}, $\log g$, [M/H], $B - V$ relation of Bell and Gustafsson (1978) to obtain the intrinsic color $(B - V)_0$, which when combined with the observed $B - V$ gives $E(B - V)$. To allow for metal-abundance dependence of the intrinsic colors we have interpolated or extrapolated as necessary using as base points the colors associated with $[\mathrm{M/H}] = -0.5$ and $[\mathrm{M/H}] = 0.0$ models. A few of the stars to which this procedure must be applied lie outside the temperature-gravity bounds of the Bell and Gustafsson calibration. For the stars hotter than the Bell and Gustafsson relation, we used the Buser and Kurucz (1978) calibration. In the case of the M stars, most of which are cooler than the Bell and Gustafsson calibration, we are fortunate in that they mostly lie in OB associations and we already know the distance. For the one M star not in an association, 119 Tau, we extrapolated the Bell and Gustafsson calibration to obtain $(B - V)_0$ and $E(B - V)$. Our distance for 119 Tau thus obtained agrees well with that given by Humphreys (1970). Table 4 presents the interstellar absorption A_v, distance r (denoted R_{SUN}), and galactocentric distance R (denoted R_{GC}) for all objects. R is the projected distance in the galactic plane, calculated assuming that

TABLE 4

Supergiant Parameters, Abundances, and Distances

STAR	L	B	SPECTRAL TYPE	V	B-V	TEFF	LOG G	[FE/H]	M_V	A_V*	DISTANCES (KPC) Z	R_{SUN}	R_{GC}	ASSOCIATION	NOTES
BETA AQR	48.0	-37.9	G0 IB	2.87	0.84	5475	1.30	0.16	-4.7	0.17	0.19	0.30	8.37		A 2
THETA DEL	58.0	-16.6	K3 IB	5.72	1.53	4500	1.30	0.21	-2.1	0.83	0.07	0.25	8.41		A *
104 AQR	59.4	-71.4	G0 IB	4.80	0.82	5500	1.80	0.05	-3.7	0.23	0.43	0.45	8.46		A *
HD 187238	59.5	1.4	K3 IAB-B	7.70		4500	0.75	0.20			0.05	2.00	7.73	VUL OB1:	C *
ALPHA AQR	59.9	-42.1	G2 IB	2.93	0.97	5300	1.40	0.26	-5.3	0.31	0.26	0.38	8.39		A 2
HD 187299	61.5	-0.3	G5 IAB-B	7.12	1.60	5000	2.10	0.15	-6.2	1.77	0.01	2.00	7.73	VUL OB1	C *
EPS PEG	65.6	-31.4	K2 IB	2.39	1.52	4400	1.00	0.25	-4.1	0.53	0.08	0.16	8.48		A 1
9 PEG	72.0	-26.5	G5 IB	4.31	1.18	4925	1.45	0.04	-3.8	0.53	0.15	0.33	8.44		A 1
12 PEG	76.7	-22.8	K0 IB	5.29	1.38	4500	1.90	0.05	-5.0	0.60	0.34	0.87	8.38		A *
BETA DRA	79.6	33.3	G2 IB	2.78	1.00	5375	1.35	0.30	-5.2	0.48	0.17	0.32	8.49		A 2
31 CYG	82.7	6.8	K4 II+B	3.80	1.28	4175	1.50	0.29	-2.1	0.70	0.01	0.11	8.52		D 1
XI CYG	85.9	-2.1	K5 IB	3.70	1.65	4100	1.75	0.39	-2.0	0.70	0.00	0.10	8.52		A 1
3 CET	87.0	-70.1	K3 IB	5.16		4250	0.75	-0.20	-4.5	0.50	0.64	0.68	8.53		E *
56 PEG	95.1	-31.7	K0 IB	4.77	1.35	4500	1.75	-0.02	-1.6	0.49	0.08	0.15	8.54		A 1
ZETA CEP	103.0	1.6	K1 IB	3.35	1.55	4425	1.00	0.33	-4.7	0.65	0.01	0.30	8.60		A 1
HR 8726	104.6	-9.0	K5 IB	4.94	1.77	4000	0.75	0.04	-4.4	0.57	0.09	0.57	8.69		A 2
PSI AND	111.3	-15.0	G5 IB	4.96	1.18	5000	1.50	0.27	-4.2	0.55	0.14	0.53	8.73		A 1
ETA PER	139.1	-3.2	K3 IB	3.79	1.69	4300	1.00	0.20	-4.4	0.91	0.02	0.29	8.75		A 1
14 PER	142.9	-14.5	G0 IB	5.60	0.90	5500	1.00	0.01	-4.5	0.44	0.21	0.86	9.20		A *
MU PER	153.9	-1.8	G0 IB	4.15	0.95	5450	1.40	0.21	-4.6	0.47	0.01	0.45	8.94		A 1
ZETA AUR	165.0	0.4	K5 II+B	3.75	1.60	4025	1.35	0.28	-2.0	0.33	0.00	0.12	8.65		A 2
HD 33299	174.2	-5.3	K1 IB	6.67	1.58	4500	0.70	-0.09	-5.1	1.20	0.12	1.30	9.84	AUR OB1	C *
NO AUR	176.9	0.7	M2 IAB	6.10	2.12	3800	0.70	-0.15	-5.9	1.48	0.02	1.30	9.84	AUR OB1	C *
HD 35601	177.0	-2.9	M1 IB	7.35	2.20	4000	0.70	-0.24	-5.0	1.76	0.07	1.30	9.84	AUR OB1	C *
HD 42454	182.4	5.3	G2 IB	7.33	1.32	5250	1.10	-0.05	-4.5	1.45	0.11	1.19	9.71		B *
HD 39949	182.7	1.4	G2 IB	7.22	1.08	5250	1.10	-0.16	-4.5	0.77	0.04	1.55	10.07		B *
HD 37387	184.0	-4.2	K1 IB	7.57	1.81	4500	1.20	0.13	-4.5	1.69	0.09	1.19	9.71		B *
HD 44391	184.8	6.7	K0 IB	7.74	1.40	4700	0.55	0.21	-4.5	0.56	0.25	2.17	10.67		B *
119 TAU	187.1	-8.1	M2 IB	4.29	2.05	3700	0.70	0.11	-4.8	0.92	0.06	0.43	8.95		A *
WY GEM	187.9	2.3	M2 IAB+B	7.29	2.30	3800	0.70	-0.36			0.06	1.53	10.00	GEM OB1	C *
BU GEM	188.2	2.2	M1 IA	6.41	2.25	3800	0.0	-0.40	-6.5	1.98	0.06	1.53	10.00	GEM OB1	C *
HD 38247	188.7	-5.4	G8 IAB	6.61	1.62	4750	1.70	0.05	-4.5	1.66	0.07	0.78	9.29		B *

TABLE 4—*Continued*

STAR	L	B	SPECTRAL TYPE	V	B-V	TEFF	LOG G	[FE/H]	M_V	A_V *	DISTANCES (KPC) Z	R_{SUN}	R_{GC}	ASSOCIATION	NOTES	
TV GEM	189.1	1.6	M1 IAB	6.58	2.30	4000	0.70	-0.40	-6.5	2.16	0.04	1.53	10.00	GEM OB1	C	*
25 GEM	186.5	10.4	G5 IB	6.42	1.09	5000	1.00	-0.16	-3.9	0.41	0.17	0.96	9.46		A	*
EPS GEM	189.5	9.6	G8 IB	2.98	1.40	4600	0.85	0.07	-4.5	0.50	0.04	0.25	8.77		A	1
HD 48640	190.1	9.7	K1 IB	7.20		4500	2.25	-0.15	-4.5	1.20	0.21	1.26	9.75		F	*
41 GEM	199.5	9.2	K3 IB	5.69	1.66	4400	0.75	-0.20	-3.1	0.95	0.06	0.37	8.87		A	*
HD 45829	203.5	-1.1	K0 IAB	6.63	1.58	4500	0.20	0.00	-5.8	1.25	0.03	1.72	10.13		B	*
HD 49068	231.1	-10.5	K0 IB	7.51	1.04	4500	0.75	-0.25	-4.5	0.63	0.34	1.89	9.80		G	*
HR 3459	233.3	21.0	G2 IB	4.61	0.84	5250	1.30	-0.11	-4.1	0.01	0.20	0.55	8.84		A	*
HD 63302	233.6	4.7	G8 IAB	6.70	1.78	4500	0.20	0.18	-5.8	1.25	0.15	1.78	9.68		B	*
OMI 1 CMA	235.0	-10.2	K3 IAB	3.92	1.71	4175	0.75	0.36	-6.6	1.05	0.13	0.75	8.98	COLL 121	C	1
145 CMA	236.5	-5.2	K3 IB	4.78	1.70	4350	1.20	0.28	-4.5	1.07	0.04	0.44	8.78		B	1
DEL CMA	238.4	-8.3	F8 IA	1.84	0.67	6250	1.00	0.52	-7.9	0.36	0.11	0.75	8.98	COLL 121	C	3
XI PUP	241.5	0.6	G3 IB	3.35	1.25	4975	0.90	0.30	-4.7	0.63	0.00	0.31	8.68		A	1
1 PUP	243.9	-2.3	K3 IB	4.59	1.63	4325	1.30	0.07	-4.5	0.91	0.02	0.43	8.73		B	1
CANOPUS	261.2	-25.3	F0 IB	3.70	0.15	7500	1.85	0.35	-4.5	0.13	0.03	0.07	8.49		B	3
LAM VEL	265.9	2.8	K5 IB	2.21	1.65	4250	1.40	0.23	-3.8	0.85	0.01	0.11	8.54		A	3
L CAR	283.2	-7.0	G2 IB			5100	1.50	0.30			0.03	0.27	8.47		H	3
HR 4050	285.5	-3.8	K5 IB	3.35	1.55	4500	1.60	0.54	-4.5	0.85	0.07	0.57	8.42		B	3
HR 4337	290.0	1.3	G0 IA-0	3.91	1.24	5750	0.40	0.32	-9.2	1.65	0.04	1.96	8.07	CAR OB2	C	3
DEL TRA	323.4	-9.2	G5 IB	3.84	1.10	5000	1.50	0.10	-4.5	0.38	0.06	0.39	8.22		B	3
BETA ARA	335.4	-11.0	K3 IB	2.84	1.56	4600	1.30	0.50	-4.5	0.98	0.04	0.19	8.36		B	3
IOTA 1 SCO	350.6	-6.1	F2 IA	2.98	0.51	7000	1.25	0.27	-7.2	0.93	0.08	0.71	7.83		B	3

NOTES TO TABLE 4

1. Distances: Z = absolute value of distance from galactic plane; R_{SUN} = line of sight distance; R_{GC} = galactocentric distance.

2. (A) Absolute magnitude from Wilson 1976. Intrinsic color from Bell and Gustafsson (1978) if $T_{eff} < 6000$ K. Intrinsic color from Buser and Kurucz (1978) if $T_{eff} > 6000$ K. Color for 119 Tau extrapolated from Bell and Gustafsson calibration. (B) Assumed absolute magnitude. Colors obtained as in A. (C) Absolute magnitude and visual absorption from Humphreys 1978. (D) 31 Cyg is a binary—A_v taken from ξ Cyg—absolute magnitude from Wilson 1976. (E) 3 Cet: $B - V$ not available—A_v taken from 56 Peg—assumed absolute magnitude. (F) HD 48640: $B - V$ not available—A_v taken from HD 33299—assumed absolute magnitude. (G) HD 49068: $B - V$ too blue for derived temperature—A_v taken from HD 45829—assumed absolute magnitude. (H) *l* Car is a Cepheid—distance taken from Fernie and Hube 1968.

3. (1) Parameters and abundances from Luck 1977*a*. (2) Parameters and abundances from Luck 1977*b*. (3) Parameters and abundances from Luck 1979. (*) Parameters and abundances from this paper.

4. References for spectral types, magnitudes, and colors can be found in abundance reference. Colors for stars analyzed in this paper from Humphreys 1978.

the Sun lies 8.5 kpc from the center (Gunn, Knapp, and Tremaine 1979). The choice of the solar distance has little effect on the gradient calculation as it mainly provides a zero point.

It is apparent that the distances derived in this fashion are rather uncertain. For example, an error of ~ 1 mag in $m_v - M_v - A_v$, which is entirely possible in view of the "quantization" of the adopted absolute magnitudes for some of the stars, leads to a $\sim 50\%$ error in the distance. Fortunately, we have a large sample of stars, so that the effects of random errors in the distances are expected to be minimal.

Figure 2 plots the [Fe/H] values for supergiants against galactocentric distance. In order to limit our sample strictly to the youngest disk objects, we omitted nine stars from Table 4 that appear to have distances from the galactic plane $|Z| = r \sin |b| \geq 200$ pc. The figure shows a pronounced tendency for [Fe/H] to decrease with distance. A linear fit yields a gradient $d[\mathrm{Fe/H}]/dR = -0.24 \pm 0.04\ \mathrm{kpc}^{-1}$.

The derived slope depends almost entirely upon the lower metallicities of the distant stars analyzed in this paper (triangles in Fig. 2) relative to the solar-neighborhood supergiants analyzed earlier on the basis of different observational material. Although great care was taken to place all abundance determinations on the same scale, the possibility of a systematic shift between these studies must be considered. Fortunately, a few of the objects analyzed in this paper lie between $R = 7.7$ and 8.5 kpc, and it can be seen that the triangles alone in Figure 2 define nearly as steep a gradient as the entire sample, $d[\mathrm{Fe/H}]/dR = -0.17 \pm 0.05\ \mathrm{kpc}^{-1}$. If we further confine our attention to the three OB associations represented in our new sample, which have the most accurate distances, we again obtain a rather steep gradient, $d[\mathrm{Fe/H}]/dR = -0.21 \pm 0.04\ \mathrm{kpc}^{-1}$.

We therefore conclude that an iron gradient of $d[\mathrm{Fe/H}]/dR \approx -0.2\ \mathrm{kpc}^{-1}$ exists in the young supergiants and, by inference, the interstellar gas, in the galactic disk near the Sun. A similar gradient in the nitrogen abundance in H II regions has been reported by Peimbert *et al.* (1978), along with a somewhat less steep oxygen gradient. Although somewhat shallower N and O gradients have been obtained from H II regions by Hawley (1978), it seems clear that the N, O, and Fe contents of the interstellar gas and the youngest stars all decrease significantly with distance from the galactic center.

The formation and chemical evolution of galactic disks have been modeled by Tinsley and Larson (1978). They show that a metallicity gradient quite generally arises among the older disk stars, because the star-formation, supernova, and nucleosynthesis rates are lower in the outer parts of the disk. The metallicity gradient of the interstellar gas at the present epoch, however, depends more sensitively upon details of the models. If metal-poor gas continues to fall into the disk, the gradients will remain shallow and the overall metal content will increase, at best, slowly. On the other hand, if infall is not important, then both the metallicity and its gradient in the gas and young stars are expected to increase with time. Tinsley and Larson also point out that the gradient could be further enhanced if there are relatively fewer massive stars, and therefore lower nucleosynthesis yields, at larger radii, or if there are radially inward gas flows in the disk.

There is indeed some observational evidence that the abundance gradient is shallower for older stars than the slope of $\sim -0.2\ \mathrm{kpc}^{-1}$ that we find for young stars. Janes (1979) finds $d[\mathrm{Fe/H}]/dR = -0.05\ \mathrm{kpc}^{-1}$ for field G and K giants and open clusters; he also summarizes a number of other papers that generally find similar values. This apparent difference in the gradients between old disk stars and young stars and gas, if substantiated, will provide an important new constraint on models for the evolution of the Galaxy.

Future work in this area should include abundance determinations in the more distant supergiants that can be reached at high spectral resolution. Of particular interest would be the galactic-center direction, where there is some hint in our Figure 2 that the gradient may be flattening out. This would be in agreement with both the observational work of Janes and the predictions of the Tinsley-Larson models. It would also be of interest to press as far as possible in the anticenter direction; in particular, the Perseus double cluster contains a number of M supergiants for which abundance determinations are possible. Finally,

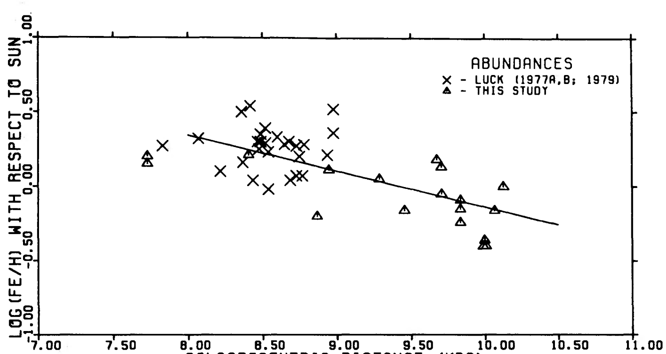

FIG. 2.—[Fe/H] versus galactocentric distance for 45 supergiants. The indicated gradient has a slope of $-0.24\ \mathrm{kpc}^{-1}$. See text for discussion.

it would be interesting to study the CNO abundances in supergiants in order to make a direct comparison with the H II region abundances. Work on several of these projects is underway.

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HOWARD E. BOND and R. EARLE LUCK: Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803