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IRON ABUNDANCES IN G AND K GIANTS FROM NEAR-INFRARED SPECTRA

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ABSTRACT

High-resolution near-infrared spectra of μ Leonis, α Arietis, ϵ Virginis, and δ Tauri, published equivalent widths for α Bootis and the Sun, and a grid of flux-constant model atmospheres have been used to derive iron-to-hydrogen ratios. The results for the super-metal-rich prototype μ Leo ([Fe/H] = 0.48) are in better agreement with photometric determinations of iron abundances than with previous spectroscopic analyses. Systematic errors associated with line blending should be less serious than at the shorter wavelengths used for the previous spectroscopic work.

Subject headings: infrared: spectra — stars: abundances — stars: atmospheres — stars: late-type

I. INTRODUCTION

The possible existence of "super-metal-rich"[1] G and K giants has been a major point of controversy since the work on scanner abundances by Spinrad and Taylor (1969). Analyses of narrow-band photometric indices intended to be sensitive to Fe I line strengths have led to the conclusion that SMR stars do exist (Williams 1971; Gustafsson, Kjaergaard, and Andersen 1974). However, curve-of-growth analyses of μ Leo, the prototype of the apparently SMR stars, have not confirmed a significant overabundance of iron (Strom, Strom, and Carbon 1971; Blanc-Vaziaga, Cayrel, and Cayrel 1973; Oinas 1974). Peterson (1976) has concluded that μ Leo is not metal-rich, but is instead boundary-cooled, owing to strong blocking by CN lines. In her view an overabundance of nitrogen by a factor of 2 is responsible, via CN blocking and boundary cooling, for all of the spectral peculiarities which have drawn attention to stars like μ Leo. Deming (1978) disagrees with Peterson's conclusions; in his view, if μ Leo is boundary-cooled it is because μ Leo is metal-rich.

In this paper we present the results of a differential curve-of-growth analysis of μ Leo, α Ari (an apparently typical field K giant, having nearly the same effective temperature and surface gravity as μ Leo), δ Tau (a Hyades cluster giant), ϵ Vir, and α Boo (Arcturus). The resulting iron-to-hydrogen ratios for the giants are linked to that of the Sun by a comparison of ϵ Vir and the Sun.

The analysis is based on high-resolution spectra near 7800 and 8700 Å, whereas previous curve-of-growth analyses involving μ Leo have been based on spectra at shorter wavelengths.

[1] SMR: having a metallicity significantly greater than that of Hyades cluster members.

II. OBSERVATIONS

The echelle grating spectrograph, the Reticon 1024 element silicon-diode array (Vogt, Tull, and Kelton 1978), and the 2.7 m telescope of the McDonald Observatory were used to obtain high-resolution (0.12 Å), low-noise spectra of μ Leo, α Ari, ϵ Vir, and δ Tau in the wavelength ranges 7700–7870 and 8680–8780 Å. These spectral regions were chosen to be relatively free of telluric absorption and to avoid the strongest parts of the $\Delta v = +1$ and $+2$ sequences of the red band system of CN. However, it is not possible to avoid CN entirely, especially in μ Leo. To ensure that atomic lines seriously blended with CN would not be used in the analysis, a model atmosphere was used to generate a synthetic spectrum of $^{12}C^{14}N$, taking into account lines of the (2, 0)–(6, 4), (3, 0)–(8, 5), and (7, 3)–(9, 5) bands (Davis and Phillips 1963; Swensson *et al.* 1970; Brault 1976). The electronic oscillator strength was adjusted to achieve the best fit between the synthetic spectrum and the spectrum of μ Leo. $^{13}C^{14}N$ lines are not important in these spectral ranges. The $^{12}C/^{13}C$ ratio is about 20 in μ Leo, α Ari, ϵ Vir, and δ Tau (Tomkin and Lambert 1974; Tomkin, Lambert, and Luck 1975; Tomkin, Luck, and Lambert 1976). In α Boo the $^{12}C/^{13}C$ ratio is only about 7 (Day, Lambert, and Sneden 1973; Upson 1973; Krupp 1973; Griffin 1974), but the CN bands are relatively weak. Synthetic CN spectra with an assumed 3 km s^{-1} Gaussian macroturbulence distribution matched the observed μ Leo spectra quite well.

Equivalent widths of 15 Fe I lines and three Fe II lines were measured. Two of the Fe II lines, at 5991 and 6369 Å, were measured from observations made specifically for this purpose. For α Boo and the Sun the equivalent widths were taken from Mäckle *et al.* (1975*a*) and Moore, Minnaert, and Houtgast (1966). Equivalent widths (log W/λ) and excitation potentials

TABLE 1

EQUIVALENT WIDTHS OF Fe I AND Fe II LINES

λ (Å)	χ (eV)	log W/λ μ Leo	α Ari	ε Vir	δ Tau	α Boo	Sun
		Fe I					
7719.04..........	5.03	5.10	5.27	5.20	5.17	5.36	5.46
23.21..........	2.28	4.83	4.94	4.99	4.95	4.92	...
33.74..........	5.06	5.34	5.56	5.52	5.47	5.64	...
72.68..........	5.07	5.65	6.04	6.05	6.01	...	...
80.57..........	4.47	4.68	4.78	4.77	4.73	4.78	...
98.86..........	3.02	5.78	6.16	...	...	...	...
7802.51..........	5.08	5.22	5.45	5.39	5.39	5.61	5.81
07.91..........	4.99	4.90	5.00	4.97	4.97	5.06	...
20.81..........	4.29	5.30	5.66	5.66	5.60	5.99	6.19
32.21..........	4.43	4.65	4.77	4.73	4.73	4.77	...
44.56..........	4.83	5.25	5.48	5.43	5.45	5.64	5.85
8699.46..........	4.95	4.86	5.05	4.96	5.00	5.05	...
8700.31..........	4.95	5.60	5.93	...	...	...	...
55.75..........	5.35	5.48	5.77	5.62	5.75	...	6.16
63.98..........	4.65	4.76	4.88	4.85	4.83	4.91	...
		Fe II					
5991.38..........	3.15	5.16	5.25	5.03	5.07	...	5.32
6369.46..........	2.89	5.27	5.39	5.16	5.21	...	5.55
7711.73..........	3.90	5.18	5.31	...	5.10	...	5.21

The Fe II lines at 5991 and 7711 Å are blended with weak CN lines [(7, 2)Q_1(35) and and (7, 4)P_1(15), respectively]. Corrected equivalent widths are listed. The corrected values, obtained by subtracting the expected equivalent widths of the CN lines from the observed equivalent widths of the blends, are only approximate.

(χ) are listed in Table 1. The eight weakest Fe I lines in μ Leo and α Ari are shown in Figures 1 and 2. Near some of these lines the signal-to-noise ratio is noticeably better for α Ari than for μ Leo. In order to avoid systematic errors in equivalent widths, the local continuum was carefully set with reference to the smooth curve, which is the filtered power spectrum of the data.

Thirty lines of elements other than Fe were also measured, but not fully analyzed. Preliminary analysis indicates that these elements vary at least approximately in lockstep with iron; a detailed analysis will be necessary to decide whether small departures from lockstep actually occur.

Two interesting conclusions can be drawn simply from inspection of the spectra or the data in Table 1.

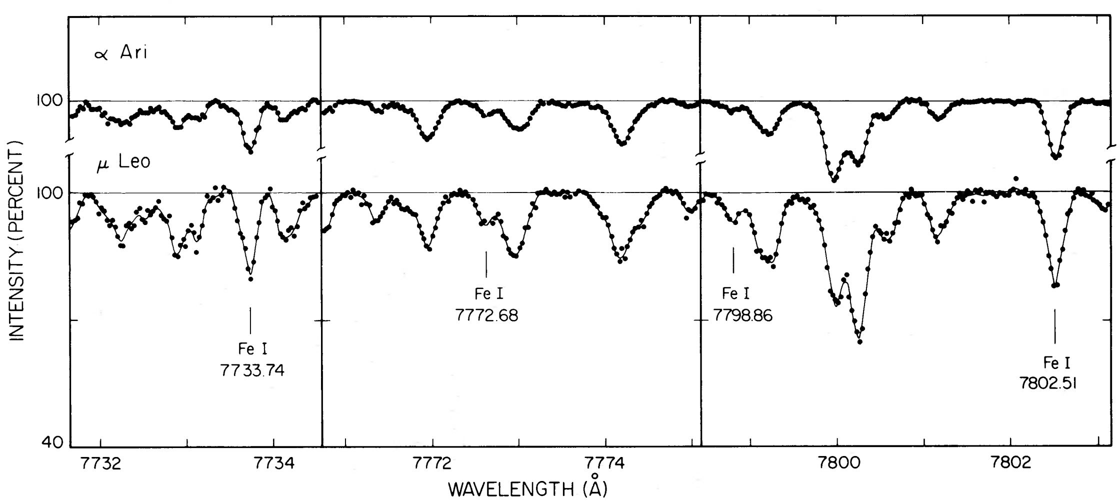

FIG. 1.—Four weak Fe I lines in the spectra of α Ari and μ Leo. The greater strengths of the Fe I lines in μ Leo are evident. Most of the other lines are due to CN. The intensity scales for the α Ari and μ Leo spectra are equal.

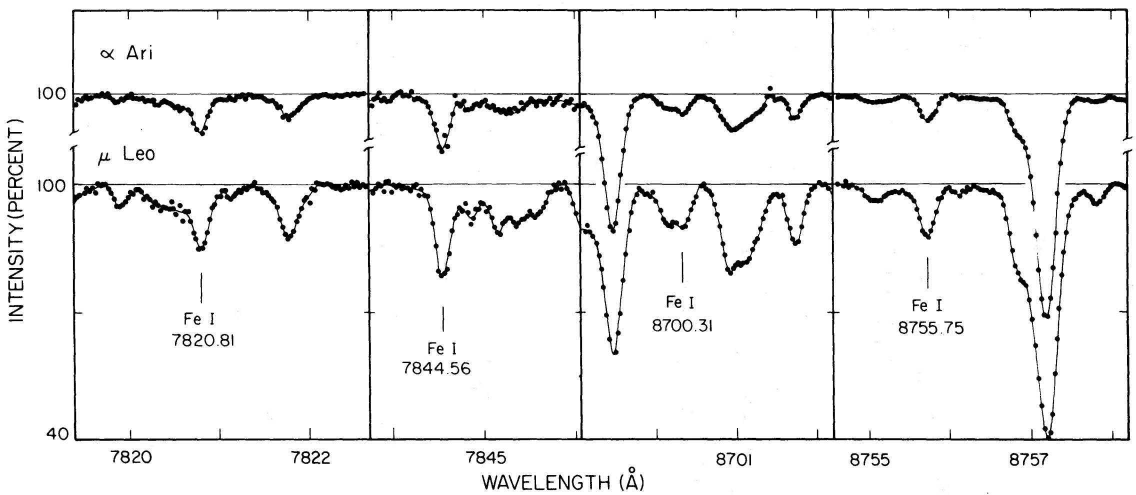

FIG. 2.—Like Fig. 1

The effective temperatures and surface gravities of μ Leo and α Ari are similar, but Fe I lines, including weak ones of high-excitation potential, are obviously stronger in μ Leo than in α Ari. Therefore μ Leo must be metal-rich with respect to α Ari. The temperatures and gravities of ϵ Vir and δ Tau are also similar, and the spectra of these two stars are practically identical. Their metallicities must be nearly equal.

III. ANALYSIS

The adopted values of effective temperature and surface gravity are shown in Table 2. For μ Leo, ϵ Vir, δ Tau, and α Boo, these are the values used by Lambert and Ries (1977); for α Ari, the values used by Tomkin, Lambert, and Luck (1975). The adopted temperatures run about 100 K hotter than values obtained from $R - I$ photometry (Johnson 1966), but the temperature differences are nearly the same. The microturbulent velocities v_t, derived from CN lines by the same authors, are also shown in Table 2.

The analysis was based on a grid of flux-constant, metal-deficient, and solar-abundance models for red giants (Gustafsson *et al.* 1975; Bell *et al.* 1976), supplemented by metal-rich models ([Fe/H] = 0.5) computed by Dr. Drake Deming, using the program of Gustafsson *et al.* Fe I curves of growth for a series of microturbulent velocities and excitation potentials were computed for each model. The lines used in the analysis were sufficiently weak that it was possible to use a single value of the damping parameter for each model ($a = 0.005$ for the giants and 0.05 for the Sun).

For the Sun the model given by Holweger and Muller was adopted (see Lambert 1978 for a discussion of the relative merits of solar models). In the analysis a small correction was applied for the fact that the solar equivalent widths given by Moore, Minnaert, and Houtgast (1966) refer to the intensity at the center of the disk rather than the flux.

For each model atmosphere, computed curves of growth were used to determine the excitation-temperature parameter, $\theta_{\rm exc} = 5040/T_{\rm exc}$. A value of $\theta_{\rm exc}$ was assigned to each star by assuming that $\Delta\theta_{\rm exc}$(star-model) = $\Delta\theta_{\rm eff}$(star-model), where the model was as similar as possible to the star in effective temperature and gravity. The Doppler broadening velocity, $v_{\rm D}$, was then obtained from

$$v_{\rm D}^2 = 2kT_{\rm exc}/m + v_t^2 \, .$$

The values of $\theta_{\rm exc}$ and $v_{\rm D}$ are given in Table 2.

Differential curves of growth were constructed for the following star pairs: μ Leo and α Ari (Fig. 3), α Boo and α Ari, μ Leo and ϵ Vir, δ Tau and ϵ Vir, and the Sun and ϵ Vir. In principle, Fe I Doppler broadening velocities in each comparison star could have been determined by plotting $\log W/\lambda$ against $\log gf - \theta_{\rm exc}\chi$, and the difference in Doppler broadening velocities

TABLE 2

STELLAR PARAMETERS

Star	$T_{\rm eff}$ (K)	$\log g$ (cm s^{-2})	V_t (km s^{-1})	$\theta_{\rm exc}$	$V_{\rm D}$
μ Leo..........	4540	2.35	1.3	1.22	1.75
α Ari...........	4440	2.5	1.1	1.25	1.60
ϵ Vir...........	5000	3.0	1.3	1.13	1.78
δ Tau..........	4940	2.7	1.6	1.15	2.00
α Boo..........	4250	1.7	2.4	1.31	2.65
Sun............	5780	4.44	1.0	0.95	1.66

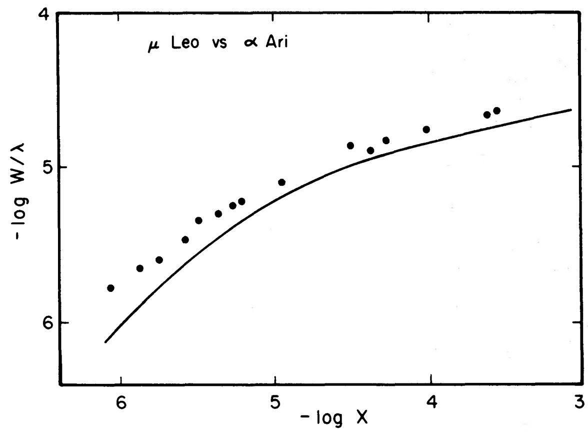

FIG. 3.—A normalized differential Fe I curve of growth for μ Leo with respect to α Ari, reduced to $\chi = 0.0$ eV. The shape of the curve of growth is from a model atmosphere having $T_{\rm eff} = 4500$ K, $\log g = 2.25$, [Fe/H] = 0.0, and $V_t = 2$ km s^{-1}.

for each star pair could have been found from vertical curve-of-growth shifts, but the number of lines and the accuracy of the available oscillator strengths are not really sufficient for these purposes. Instead, the following procedure was adopted. For each pair the analysis was carried out twice, assuming $v_t = 1$ and 2 km s^{-1} in the comparison star (either α Ari or ϵ Vir). Except in the comparison of α Boo and α Ari, the vertical curve-of-growth shift was taken to be zero. The differences between the values of $v_{\rm D}$ given in Table 2 for μ Leo, α Ari, ϵ Vir, δ Tau, and the Sun are not thought to be significant, and the fitting of the differential curves of growth did not require vertical shifts. We would, however, expect a significant vertical shift when α Boo is compared with α Ari. In this case the Fe I differential curve of growth was best fitted with a vertical shift of +0.1. For a given star pair, the horizontal curve-of-growth shift for each weak line ($\log W/\lambda \leq -5.20$ in both stars) was determined, and the mean was taken. The number of lines used ranged from five (the Sun compared with ϵ Vir) to eight (μ Leo compared with α Ari). For μ Leo, the number of weak lines used is greater than in any of the previous analyses. The empirical curve-of-growth shifts were compared with the computed shifts for the model atmospheres, and the iron-to-hydrogen ratios, [Fe/H], were determined by interpolation. Finally, the mean of the results obtained by assuming $v_t = 1$ and 2 km s^{-1} in the comparison star was taken. The values of [Fe/H] for the giants relative to the Sun are given in the first column of Table 3.

The results are based only on weak lines, and are not very sensitive to the assumptions about the Doppler broadening velocities. The sensitivity to errors in temperature and gravity is also weak. For μ Leo and α Ari, for example, a 100 K change in the adopted temperature difference would produce a change of 0.03 in the abundance difference, and a change of 0.3 in the adopted difference in $\log g$ would cause a change of 0.06 in the abundance difference. The weak sensitivity to temperature is due to the relatively high excitation potentials of the lines used. Errors due to interpolation in the grid of computed curve-of-growth shifts should be negligible. Therefore, unless systematic errors in the assumed temperatures and gravities, such as might be caused by an important source of unidentified opacity, occur, the major sources of error should be the uncertainties in the equivalent widths and the empirical curve-of-growth shifts. We regard the abundance differences among the giants to be determined to within ± 0.15 dex. The results relative to the Sun may be less accurate because the equivalent widths for the Sun are from a different source and the temperature and gravity are so much higher than in the giants.

TABLE 3

COMPARISON WITH PREVIOUS PHOTOMETRIC RESULTS

Star	[Fe/H] This Paper	Williams (1971)	Gustafsson, Kjaergaard, and Andersen (1974)
μ Leo......	+0.48	+0.46	+0.45
α Ari.......	−0.08	−0.23	...
ϵ Vir.......	+0.17	+0.06	+0.05
δ Tau......	+0.15	+0.22	+0.16
α Boo......	−0.49	−0.77	−0.51

It is important to note that in giants as cool as μ Leo and α Ari the equivalent widths of unsaturated Fe I lines are not directly proportional to iron abundance. This is because the fraction of iron which is neutral in the line-forming layers is not negligible, compared with unity. The horizontal curve-of-growth shift for μ Leo relative to α Ari must be multiplied by 1.4 to obtain the abundance difference.

In principle, the iron abundances could be derived from Fe II lines, but there are difficulties in practice. There are only a few lines, they are partially saturated, and some are blended with CN. Also, the Fe II line strengths are much more sensitive to temperature and gravity than are the Fe I lines. Nevertheless, the analyses of μ Leo relative to α Ari and δ Tau relative to ϵ Vir were carried out for the few Fe II lines available. It was found that the abundances derived by Fe II and Fe I could be made to agree by applying small changes to the adopted temperatures or gravities. For the μ Leo–α Ari comparison, the result for [Fe/H] would differ by less than ± 0.1 from the value given in Table 3, the sign of the difference depending on whether temperature or gravity was changed. For the δ Tau–ϵ Vir comparison, the difference would be less than ± 0.05.

IV. COMPARISON WITH PREVIOUS RESULTS

In Table 3 our results for the giants are compared with those obtained by Williams (1971) and Gustafsson *et al.* (1974) by model atmosphere calibration of narrow-band photometric indices. The agreement is good. From photometry of strong lines Spinrad and

Taylor (1969) estimated the metallicity difference between μ Leo and δ Tau to be 0.4 dex; our result is 0.33.

Previous spectroscopic investigations tended to show smaller abundance differences between μ Leo and the other giants. Oinas (1974) found the difference in [Fe/H] between μ Leo and α Ari to be 0.2, whereas our result is 0.56. Strom, Strom, and Carbon (1971) found a difference of 0.1 between μ Leo and δ Tau; our result is 0.33. Blanc-Vaziaga, Cayrel, and Cayrel (1973) found the difference between μ Leo and ϵ Vir to be -0.1, compared with our result of 0.31. Our results are not consistent with Peterson's (1976) conclusion that only molecular and low-excitation atomic lines are unusually strong in μ Leo, and that only nitrogen is overabundant. Most of the lines used in our analysis have $\chi \approx 5$ eV.

The abundance differences among the giants are independent of our comparison of ϵ Vir and the Sun. Cayrel and Cayrel (1963), and Cayrel, Cayrel, and Foy (1977) have found [Fe/H] = 0.00 for ϵ Vir. Their analysis was based on many lines from the visible part of the spectrum. Random errors should be small, but it is possible that systematic errors associated with line blending occur when data from short wavelengths are used.

V. DISCUSSION

The values of effective temperature and surface gravity used in our analysis are not controversial (except possibly for α Boo). Part of the analysis was repeated after replacing the flux-constant models by models scaled on the temperature distribution of the Harvard-Smithsonian Reference Atmosphere for the Sun (Gingerich *et al.* 1971), with very similar results. It seems likely, therefore, that the differences between our results and those of previous spectroscopic work are due to differences in the data rather than differences in the details of analysis.

One possibility is that an unidentified continuous opacity (Oinas 1974) affected the earlier work. If the opacity increases toward short wavelengths, relative to the H^- opacity, effective temperatures would be underestimated. This would affect the present results less than the earlier work because the lines we used are relatively insensitive to temperature. Also, direct weakening of spectral lines by the increased opacity would be more important at short wavelengths. Therefore, if the unidentified opacity depends on metal abundance, it might be possible to explain why abundance differences between μ Leo and other giants appear smaller when derived from data at short wavelengths. However, this would not explain the differences between the photometric and spectroscopic results, both based on short wavelengths.

A second possibility, which we consider more likely, is that overlapping of atomic and molecular lines in crowded spectral regions, combined with instrumental profile effects, causes systematic errors in continuum placement. This would tend to mask abundance differences derived spectroscopically, but not photometrically. The possible importance of this effect is being investigated by means of synthetic spectrum calculations and will be discussed in a separate paper.

Narrow-band photometry has shown that μ Leo has stronger bands of CN (Deming 1978 and references therein) and C_2 (Branch and Bell 1975) than most other stars of similar temperature and gravity. Lambert and Ries (1977) have used high-resolution data to derive abundances of carbon, nitrogen, and oxygen in 11 G and K giants, including μ Leo. In all of the stars the relative abundances of C, N, and O show evidence of processing through the CNO cycle, but the total number of CNO nuclei should not be changed by this. The results of Lambert and Ries for μ Leo may be expressed as $[(C + N + O)/H] = 0.10$. However, Lambert and Ries assumed [Fe/H] = 0.00. If a positive value of [Fe/H] had been assumed, the result for $[(C + N + O)/H]$ would have been higher also (although the relative abundances of C, N, and O would hardly have been affected). A detailed reanalysis of the C, N, and O abundances, using a metal-rich model atmosphere for μ Leo, would be of interest. At present, our results and those of Lambert and Ries seem consistent with a uniform initial enhancement of heavy elements in μ Leo, with subsequent processing by the CNO cycle.

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