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THE CARBON-TO-IRON RATIO OF METAL-RICH DWARFS: AN ANALYSIS OF 14 HERCULIS

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ABSTRACT

Using high-resolution spectra and line-blanketed model atmospheres, we have carried out abundance analyses of the strong-lined K dwarf 14 Her and the normal K dwarf 70 Oph A. We confirm previous studies of high-resolution spectra of 14 Her which have shown it to be metal-rich; we find an overall enhancement of a factor of 2.5 compared to both the Sun and 70 Oph A. Relative abundances of all even-*Z* elements with respect to iron are found to be equal to the solar values in both stars. The uncertainties in the determination of carbon abundance, both in this and previous studies, are examined. When account is taken of these uncertainties, carbon-to-iron ratios determined for unevolved stars show little if any deviation from the solar value.

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

I. INTRODUCTION

The star 14 Herculis (HD 145675) is noteworthy as a K dwarf with extremely strong lines for its temperature and spectral type (Spinrad and Taylor 1969; Taylor 1970). According to Greenstein and Oinas (1968), CN and C_2 are especially enhanced, to an extent which indicates an overabundance of carbon. If this is so, it has important implications for several astrophysical problems, including the nature and operation of mechanisms of nucleosynthesis which preferentially produce carbon (e.g., Audouze, Lequeux, and Vigroux 1975); the calculation of theoretical models of stellar interiors (Simoda and Iben 1970; Iben 1974; Mengel *et al.* 1978) in which carbon is an important opacity source; and the origin and occurrence of the carbon-rich stars (Wallerstein 1973) and of planetary nebulae (Torres-Peimbert and Peimbert 1977; Shields 1978).

On the other hand, it is entirely possible that the strength of the CN and C_2 features arises from a general overabundance of metals in 14 Her. High-dispersion abundance analyses by Oinas (1974), Perrin, Cayrel de Strobel, and Cayrel (1975), and Hearnshaw (1976) all have shown that the metal abundance is a factor of 2 greater than the solar value. Where metals are enhanced to such a degree, it should be possible to directly test the prediction of overabundances of neutron-rich species in a metal-rich environment, a prediction which emerges from explicit calculations of explosive nucleosynthesis (Pardo, Couch, and Arnett 1974) and for which indirect evidence is found in the spectra of strong-lined elliptical galaxies (Peterson 1976; Faber 1977).

With this double motivation, we have obtained echelle-Kron spectra at 70 mÅ resolution of 14 Her and the standard K dwarf 70 Oph A (HD 165431). Our model-atmosphere analysis shows 14 Her to be metal-rich by a factor just over 2 with respect to both the Sun and 70 Oph A. All even-*Z* elements from carbon through the iron peak are increased by the same amount. Our observations are described in § II, the method of analysis is summarized in § III, and overall results are presented in § IV.

Subsequent discussion concerns the uncertainties in carbon-to-iron ratios in this and other metal-rich dwarfs. C I features were used in this determination; the uncertainties here are discussed and compared in § V to those of previous studies, which have used molecular features. We attempt to demonstrate in § VI that previous investigations point to a weak dependence, if any, of [C/Fe] on [Fe/H] among unevolved disk stars, which is also suggested by our determinations.

II. OBSERVATIONS

Spectra of 1.8 Å mm^{-1} dispersion were obtained on the 1.5 m (60 inch) telescope of the Smithsonian Astrophysical Observatory at Mount Hopkins, Arizona. The Cassegrain echelle spectrograph (Chaffee 1974; Chaffee and Schroeder 1976) and the Kron electrographic camera (Kron, Ables, and Hewitt 1969) were used in 1975 on the nights of May 19 and 20 to obtain one plate each of 14 Her and 70 Oph A. With an entrance slit of 0″.45, corresponding to a spectral resolution of 70 mÅ, exposure times were 205 minutes for 14 Her ($V = 6.5$) and 30 minutes for 70 Oph A ($V = 4.0$), under seeing conditions of 2″. The spectral region covered in one exposure extended from 4800 to 5600 Å; the coverage was incomplete toward each end.

Equivalent widths were measured at the Lockheed Solar Observatory following the procedure described by Peterson and Title (1975); values are listed in the Appendix. An estimate of the error in equivalent

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width was obtained from a similar plate of the standard G8 giant ϵ Vir, for which a 15 minute exposure was obtained May 19 with the same instrumental settings. Comparison of equivalent widths in the region 5185–5430 Å with those of Cayrel and Cayrel (1963) showed a measurement uncertainty of ±6 mÅ, corresponding to an uncertainty of about ±0.12 dex in the abundance deduced from a single line of 20–80 mÅ strength. This estimate is somewhat larger than is indicated by the scatter of the abundances of individual Fe I lines about the mean for each star. The standard deviation of an individual abundance was ±0.07 dex for both 70 Oph A and 14 Her. We take ±0.10 dex as a reasonable value.

III. METHOD OF ANALYSIS

Elemental abundances were derived using WIDTH5, which calculates an abundance for each observed equivalent width, given the relevant line data and a model atmosphere. For each star, the equivalent widths were run through three solar abundance models, with ($T_{\rm eff}$, $\log g$) = (5000 K, 4.5), (5500 K, 4.5), and (5500 K, 4.0); these were computed by Kurucz (1978) using ATLAS5 (Kurucz 1970). Stellar microturbulent velocity, temperature, surface gravity, and abundances were derived in succession as described below. The greater-than-solar abundance found for 14 Her made it necessary to compute an additional model (5500 K, 4.5, $3X$ solar metal abundance).

Solar abundances were derived for the same set of lines as in the stars. The solar equivalent widths of Moore, Minnaert, and Houtgast (1966) were run through WIDTH5 with the standard solar model of Gingerich *et al.* (1971). The *gf*-values were generally taken from the literature, except those for C I, Fe I, Co I, and Fe II, for which solar *gf*-values were derived by demanding that a particular abundance result from the solar equivalent width calculation. In all cases, damping constants 10 times classical were used. The solar microturbulent velocity was taken to be 0.5 km s^{-1}, as found by Foy (1972); calculations were also run at 1.0 km s^{-1}.

To avoid the numerous difficulties associated with abundance computations of saturated lines (e.g., Foy 1972; Peterson 1978), only those lines weaker than 85 mÅ were used to derive stellar temperatures, gravities, and abundances. In consequence, the values derived for these parameters are virtually free of error due to uncertainty in the shape of the curve of growth. An increase in solar microturbulent velocity to 1.0 km s^{-1} decreases the solar abundance of neutral species by 0.02 dex and of ionized species by 0.10 dex. An increase of stellar microturbulent velocity by 0.5 km s^{-1} increases 14 Her abundances by 0.08 dex and 70 Oph A abundances by 0.05 dex. Using van der Waals damping constants (Aller 1963) changes abundances by less than 0.02 dex, as does increasing these by 0.7 dex (Peterson 1978), because the lines are quite weak.

Stronger lines were incorporated in the determination of stellar microturbulent velocity. Both strong and weak lines of Fe I, all with excitation potential near 4 eV, were used. We demanded that no correlation with line strength be present in the abundances deduced from each line. The result was 1.44 ± 0.15 km s^{-1} for 70 Oph A and 1.62 ± 0.12 km s^{-1} for 14 Her. For both stars, v_t = 1.5 km s^{-1} was adopted. We note good agreement with an extensive investigation of microturbulent velocity in F and G dwarfs by Furenlid and Condal (1976), who found an increase of 1.0 km s^{-1} in the microturbulent velocity deduced from flux spectra of these stars over the value inferred from the solar intensity spectrum at the center of the disk. (See also Hearnshaw 1976.) Use of damping constants increased by 0.7 dex above the Unsöld approximation (Aller 1963) has negligible effect, because all lines are weaker than 100 mÅ.

Gravity was derived by demanding agreement between the abundances deduced from neutral and ionized lines of chromium. To within the ±0.05 dex uncertainty in the relative abundance of Cr I and Cr II, a gravity value of $\log g = 4.5 \pm 0.2$ was implied for both 70 Oph A and 14 Her. This value is in agreement with their parallaxes and is typical of K dwarfs. However, had we not calculated a model which included the 0.4 dex overabundance of heavy elements derived for 14 Her (§ IV), we would have found for this star an anomalously large surface gravity, $\log g = 5.0$, because the metals are the dominant electron contributors in these stars.

Iron was excluded from the surface gravity determination, because in both stars there is a disagreement of about 0.25 dex between abundances derived for Fe I and Fe II at $\log g = 4.5$, despite the good agreement between the Cr I and Cr II abundances. The choice of solar microturbulent velocity contributes at most 0.1 dex to this discrepancy. We feel that the primary factor has to do with the depth of formation of Fe II lines. While chromium is completely ionized throughout the photospheres of both stars, iron is not. Rather, Fe II is the dominant state only for optical depths near unity, with Fe I equal to Fe II at optical depths above about one-fifth. In consequence, Fe II lines are formed at extremely large optical depths. C I lines are also formed at these extreme depths (because of their high excitation potential and the neutrality of carbon), and abundances derived for these lines also appear to contain a systematic error of 0.3 dex (§ V). Both discrepancies correspond to a temperature overestimate of 350 K in deep layers.

There is a substantial difference in the temperature gradient at depth between the HSRA model and the ATLAS model of the Sun computed by Kurucz (1974). According to his Figure 1, the HSRA model is hotter by nearly 400 K at optical depths just less than unity. While the HSRA temperature gradient is probably too steep (Vernazza, Avrett, and Loeser 1976), that of the ATLAS models is dependent (Kurucz 1974) on the choice 2.0 for the ratio of mixing length to scale height in the treatment of convection. Relyea and Kurucz (1978) have shown that this is likely to be in error. The present inability to specify more accurately the correct solar temperature distribution causes the solar abundance derived from such high-excitation C I lines to be uncertain by ±0.15 dex. Our use of inconsistent temperature gradients in solar and K-dwarf models appears to be responsible for the discrepant C I and Fe II abundances.

Excitation temperatures were used to derive stellar effective temperatures. Where a given species includes lines of both low and high excitation potential, the excitation temperature may be found by demanding that abundances deduced from each line be independent of excitation potential. With the data available here, the species Fe I, Co I, and Ni I have suitable lines. From these, we find 5400 ± 150 K for both 70 Oph A and 14 Her.

IV. ABUNDANCE RESULTS

With temperature, gravity, and microturbulence established, element abundances were found from an unweighted average over all lines of each species. Solar abundance models were used for 70 Oph A, and the $3X$ solar model for 14 Her, with interpolation to the appropriate temperature in each case.

The results are listed in Table 1. Column (1) gives the species and its nuclear charge, with the number of lines included in the abundance analysis in parentheses. The negative of the logarithm of the metal-to-hydrogen ratio is presented in columns (2), (3), and (5). Columns (4) and (6) give [M/H], the logarithm of the metal-to-hydrogen ratio with respect to the Sun. The latter is found by subtracting the solar values of abundances (col. [2]) from the stellar values. A similar subtraction of the 70 Oph A from the 14 Her abundance values gives the logarithm of the abundance enhancement in 14 Her with respect to the standard K dwarf, which is presented in column (7) of Table 1.

The overall abundance level found for 70 Oph A is solar, as expected. Whether 14 Her is compared directly with the Sun or with the standard, it appears to be a genuinely metal-rich star. Metals are typically up by 0.35 dex, corresponding to a factor of 2.2. An uncertainty of 0.10 dex is expected in this result, owing to the effect of temperature on abundance, which we now examine.

The effective temperature of 5400 K we have inferred from the excitation of neutral lines is in good agreement with that of 5350 K indicated from the $R - I$ color measured by Jacobsen (1970) based on the conversion for Hyades dwarfs given by Johnson (1966). Oinas (1974), however, derived 5180 K from narrow-band continuum scans, after making a substantial correction for line blanketing. He then found [Fe/H] = 0.2, as did Perrin, Cayrel de Strobel, and Cayrel (1975), who used the same temperature. Hearnshaw (1976) used 5250 K, the average of the two temperatures, and came up with [Fe/H] = 0.35. Our WIDTH calculations show that, as temperature is lowered by 150 K, the abundance derived from most neutral lines (namely, Ca I, Ti I, V I, Cr I, and Mn I) drops by 0.12 dex. The decrease is 0.05 dex for Fe I, however, because its ionization equilibrium is shifting toward neutrality (§ III). Similarly, the decrease is less than 0.07 dex for Si I, Co I, Ni I, and Cu I, because their ionization potentials are also high enough that the ionized species is no longer totally dominant.

Calculations such as these show that the abundance derived from lines of ionized species increases, rather than decreases, as temperature drops. If gravity is held constant, the effect is 0.07 dex for Cr II and 0.10 dex for Fe II. Since the Fe II and Cr II abundances decrease by 0.24 dex as $\log g$ drops by 0.5 dex, an adjustment of 0.4 dex in $\log g$ per 150 K will be needed to restore the equilibrium between Cr I and Cr II. A random error of 0.10 dex in $\log g$ will also be expected, if gravity is deduced (as here) from five Cr II lines with an error of 0.10 dex per line.

From these considerations several important observations can be made on the uncertainty in relative abundances. Width errors tend to dominate for species of one or two lines; an error of 0.10 dex is expected. Other errors dominate for species with five or more lines. These can be kept to a minimum by intercomparing groups of species whose lines have a similar dependence on temperature and gravity, as determined from their ionization and excitation potentials. The best determined abundances, generally to 0.05 dex, are those for the even-Z neutral species; the ionized/neutral ratio is good only to 0.20 dex, given the 150 K error in temperature and an assumed gravity of $\log g = 4.5$.

TABLE 1

LOGARITHMIC METAL ABUNDANCES IN 14 HERCULIS, 70 OPHIUCHI A, AND THE SUN

Species (1)	Sun (2)	70 Ophiuchi A (3)	70 Ophiuchi A (4)	14 Herculis (5)	14 Herculis (6)	14 Herculis (7)
6 C I (2)	3.74	3.90	−0.16	3.78	−0.04	0.12
14 Si I (3)	4.56	4.60	−0.04	4.32	+0.24	0.28
20 Ca I (1)	5.59	5.55	+0.04	5.39	+0.20	0.16
22 Ti I (12)	7.54	7.50	+0.04	7.17	+0.37	0.33
24 Cr I (10)	6.87	6.85	+0.02	6.50	+0.37	0.35
24 Cr II (4)	6.34	6.39	−0.05	5.91	+0.43	0.48
26 Fe I (17)	4.53	4.52	+0.01	4.17	+0.36	0.35
26 Fe II (5)	4.43	4.70	−0.27	4.33	+0.10	0.37
28 Ni I (11)	6.26	6.26	0.00	5.88	+0.38	0.38
39 Y II (2)	9.31	9.35	−0.04	8.97	+0.34	0.38
60 Nd II (1)	9.85	9.90	−0.05	9.50	+0.35	0.40

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V. THE RELATIVE CARBON ABUNDANCE OF 70 OPHIUCHI A AND 14 HERCULIS

The relative abundance of carbon is rather poorly determined with respect to the neutral species because of its unusually high ionization and excitation potentials. Unlike all other elements considered here, carbon is overwhelmingly neutral, because its ionization potential is extremely high (11.2 eV as compared to 7.9 for Fe I). And the permitted C I lines in the optical region all have extremely high excitation potentials—7.7 eV for the pair used here. In consequence, a 150 K decrease in temperature increases the deduced C I abundance by 0.12 dex. If the C I abundance were compared to the Fe I abundance, which decreases by 0.06 dex, a temperature error of 0.18 dex would result; width errors (and gravity errors in stars not known to be dwarfs) would bring this to about 0.3 dex overall.

Clearly this error could be lessened by comparing C I with abundances deduced from ionized species. The difficulty here has to do with stratification effects. Because of the extremely high excitation potential, the C I lines tend to be formed at very great optical depths, deeper than is typical of the run of ionized lines observed here. (In hotter stars, however, a few lines of Mg II and Si II are measurable which have excitation potentials high enough that they too are formed deep.)

Except in stars where such lines may be used for abundance comparison, the relative abundance of carbon is subject to large errors due to uncertainties in atmospheric structure at great depth, as discussed above. In this particular case, Fe II lines are also formed deep because of the depth dependence of the Fe II species number density (§ III). A reasonably accurate relative carbon abundance can be derived by comparing the C I abundance with the Fe II abundance; systematic errors due to uncertainties in deep layers will cancel. This comparison gives [C/Fe] = 0.11 dex for 70 Oph A and −0.14 dex for 14 Her. Uncertainties in these values run about 0.12 dex, owing primarily to the 0.10 dex error from width measurements of the two C I lines. The 150 K temperature uncertainty introduces an error of 0.05 dex; an error of 0.2 km s^{-1} in stellar microturbulence also contributes 0.05 dex. A systematic decrease of 0.10 dex would occur in both stellar [C/Fe] values, if solar microturbulence were chosen as 1.0 rather than 0.5 km s^{-1}.

To within these uncertainties, both 70 Oph A and 14 Her have the solar value of the carbon-to-iron ratio. Overdeficiencies of carbon would have been inferred, if Cr II had been used for comparison: [C I/Cr II] = −0.11 dex for 70 Oph A and −0.36 dex for 14 Her.

The use of C I lines provides an important check on previous analyses of the carbon abundance in G and K dwarfs, because C_2 or CH features have previously been used in all studies of large numbers of such stars. Despite the greater number of features, the errors inherent in such determinations are at least as great as the errors noted above in our result. This is a consequence of the sensitivity of the molecular features to temperature, gravity, and abundance uncertainties, which is rather different from that of atomic lines, as discussed below.

According to calculations for hotter dwarfs (Peterson and Sneden 1978), the abundance inferred from CH features at constant gravity goes down by 0.20 dex as temperature drops by 150 K. The concurrent reduction in metallicity leaves [C/Fe] lower by 0.12 dex. If surface gravity is treated as a free parameter, the effect is reduced to 0.03 dex. To determine gravity correctly, however, the metal abundance of the model must match that of the star, as long as metals are the dominant electron contributors. A discrepancy of 0.4 dex in [Fe/H] between model and star causes an error of 0.5 dex in $\log g$, which alters [C/Fe] by 0.12 dex.

These results pertain as long as CO formation has a negligible effect on the number density of free carbon atoms. Because of the stability of the CO molecule, its formation controls the free carbon density once CO is about as abundant as free C. The sensitivity of other carbon molecules to temperature and gravity tends to be counteracted by the similar sensitivity of CO, which alters the free carbon density in the opposite sense.

However, in this situation the carbon abundance deduced from molecules other than CO becomes very sensitive to the oxygen abundance, which is rarely measured directly and so must be assumed. Various plausible assumptions of the constancy of the relative oxygen abundance are usually made; however, (1) the relative abundance of oxygen may be variable from star to star; (2) uncertainties in solar relative abundances enter directly; (3) the size of carbon anomalies is invariably larger if [O/C] = 0 is assumed rather than [O/Fe] = 0. For these reasons, serious systematic errors may arise when CO formation is appreciable.

CO formation is strongly favored by low temperatures, because of the very high dissociation constant of this molecule, and by high abundances of carbon and oxygen, which both enter into the molecular dissociation equilibrium. In dwarfs of solar metallicity, our ATLAS calculations of atomic and molecular number densities indicate that CO is more abundant than C at moderate atmospheric optical depths when $T_{\rm eff} <$ 5500 K. If all metals decrease in lockstep to 0.5 dex below the solar value, this critical $T_{\rm eff}$ for CO formation in dwarfs drops to about 5300 K. Similarly, in dwarfs where metals are uniformly enhanced by 0.5 dex, the critical value of $T_{\rm eff}$ is raised to about that of the Sun. If carbon and/or oxygen is overabundant with respect to the iron-peak elements, CO formation is further favored. Only if carbon and/or oxygen is overdeficient, or if surface gravity is significantly less than that of a dwarf, or generally if the carbon abundance exceeds the oxygen abundance, does CO fail to control the free carbon density at moderate optical depths in stars cooler than the appropriate value of the critical effective temperature.

Both 70 Oph A and 14 Her are somewhat cooler than this but not greatly so. In such a situation the use of the C I lines to determine the carbon abundance avoids the systematic errors which may be incurred if the CH or C_2 features are used, because of the dependence of the degree of CO association on optical depth.

According to the ATLAS calculations, free carbon is more abundant than CO at large optical depths, where the C I lines are formed, while CO is more plentiful than free carbon at moderate optical depths, where CH and C_2 lines are formed (Greene 1969; Hearnshaw 1975).

VI. THE CARBON-TO-IRON RATIO IN UNEVOLVED DISK STARS

Before comparing the consistency of our C I results with the previous molecular determinations of the carbon abundance in these and other disk dwarfs, we attempt to reconcile the differences among previous studies concerning the behavior of the carbon abundance as a function of overall metallicity in unevolved disk stars. In an extensive spectroscopic investigation of CH features in about 60 F and G dwarfs and subgiants, Hearnshaw (1974*a*, *b*, 1975) concluded that the relative abundance of carbon depended significantly on the overall metallicity, with $[\mathrm{C/Fe}] = -0.1 + 0.5 * [\mathrm{Fe/H}]$. Bell and Branch (1976), however, have discussed the incompatibility of this result with their photoelectric measurements of the C_2 (1, 0) Swan band in about 20 disk dwarfs. These indicated a normal C/Fe ratio in all but perhaps the most metal-rich stars, where carbon might be slightly but not extremely overabundant. More recently, Clegg (1977) has analyzed the CH features from his spectra of nine F and G disk dwarfs, finding "a weaker (if any) correlation between [C/Fe] and [Fe/H] than Hearnshaw."

However, both the size and the significance of the trend seen in Hearnshaw's data depend greatly on whether stars are included in which CO formation is appreciable. We have rederived the dependence of [C/Fe] on [Fe/H] from Hearnshaw's data, eliminating those stars cooler than the critical effective temperature for CO formation in dwarfs with lockstep abundance variations. Expressed in terms of the difference $\Delta\theta_{\mathrm{ex}}$ between stellar and solar inverse excitation temperatures tabulated by Hearnshaw, our criterion for excluding a star was $\Delta\theta_{\mathrm{ex}} = 0.03 - 0.06 * [\mathrm{Fe/H}]$. If Hearnshaw's assumption $[\mathrm{O/C}] = 0$ is correct, in all but the most evolved of these stars or the ones most overdeficient in C and/or O, CO formation will control the free carbon density. Using a least-squares fit to determine the coefficients in the relation $[\mathrm{C/Fe}] = a + b * [\mathrm{Fe/H}]$, we have found $a = -0.145 \pm 0.023$ and $b = 0.126 \pm 0.075$, from 41 stars with $-0.7 \leq [\mathrm{Fe/H}] \leq 0.4$.

This result is biased to the extent that the temperature criterion may unnecessarily exclude stars overdeficient in C (or O). However, Hearnshaw (1975) noted that "the sensitivity of [C/H] to the adopted (O/C) ratio indicates the extent to which carbon atoms are locked up in CO," and he provided tabulations for each of the 60 stars of the value of [C/H] inferred assuming $[\mathrm{O/C}] = -0.5$, 0.0, and 0.5. The change in [C/H] provides a ready criterion for exclusion which incorporates his C and O abundance levels as well as his surface gravities and effective temperatures. We have repeated the derivation excluding all stars for which [C/H] increases by 0.20 dex or more as [O/C] increases from 0.0 to 0.5, or, equivalently, for which [C/H] decreases by at least 0.07 dex as [O/C] decreases from 0.0 to -0.5, where carbon is more abundant than oxygen. All of the stars excluded by the temperature criterion were also excluded by this criterion, except two subgiants with low surface gravities ($\log g \leq 3.75$) and one dwarf with $[\mathrm{Fe/H}] = -0.71$. The result was $a = -0.150 \pm 0.024$ and $b = 0.135 \pm 0.074$, for 44 stars with $-0.7 \leq [\mathrm{Fe/H}] \leq 0.4$.

After exclusion by either criterion of stars whose carbon abundances are subject to the errors accompanying appreciable CO formation, Hearnshaw's data yield a slope $b = 0.13 \pm 0.075$, which lies 5 standard deviations away from 0.5 but within 2 of 0.0. Both the size of this slope and its uncertainty are entirely compatible with the results of Bell and Branch (1976) and Clegg (1977). The overabundances seen by Bell and Branch (1976) are quite small, averaging 0.1 dex for a half-dozen stars with $[\mathrm{Fe/H}] > 0$. In particular, for 14 Her $[\mathrm{C/Fe}] = 0.05$ was deduced when $[\mathrm{Fe/H}] = 0.5$ was inferred from $\delta(U - B)$, as for their other stars. Taking $[\mathrm{Fe/H}] = 0.2$ from the available spectroscopic analyses of 14 Her resulted in $[\mathrm{C/Fe}] = 0.15$. Clegg (1977), who derived $[\mathrm{C/Fe}] = 0.0$ in his single metal-rich star, also found an offset $a = -0.15$.

From these investigations we infer a weak dependence, if any, and a negative offset, if any, of [C/Fe] on [Fe/H] among unevolved disk stars. Our analysis of C I in 70 Oph A and 14 Her is completely compatible with this.

Finally, we note that there is minimal dependence of [C/Fe] on [Fe/H] among unevolved stars of the halo population, according to a recent study of a dozen hot, high-velocity dwarfs and subgiants by Peterson and Sneden (1978), who found a mean value of $[\mathrm{C/Fe}] = -0.1 \pm 0.2$, with a slope $b = -0.01 \pm 0.08$, for nine stars with $-2.3 \leq [\mathrm{Fe/H}] \leq -0.6$. However, it remains for future investigations to determine whether [C/Fe] might depend upon other parameters than [Fe/H], such as age, orbital eccentricity, or distance from the center of the Galaxy, among unevolved stars of the galactic disk.

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APPENDIX

Table 2 gives the line parameters and equivalent widths in 14 Her and 70 Oph A.

TABLE 2

LINE PARAMETERS AND EQUIVALENT WIDTHS IN 14 HERCULIS AND 70 OPHIUCHI A

14 HERCULIS					70 OPHIUCHI A				
λ(Å)	E.P. (eV)	log gf*	EW (mÅ) 14	EW (mÅ) 70	λ(Å)	E.P. (eV)	log gf*	EW (mÅ) 14	EW (mÅ) 70
				C I					
5380.32	7.68	−1.47 XS	12	9	5052.15	7.68	−1.10 XS	20	17
				Si I					
5517.55	5.08	−1.20 XS	18	11	5488.99	5.61	−0.53 KP	34	18
5493.24	5.08	−1.20 XS	37	16					
				Ca I					
5260.39	2.52	−1.90 WS	62	52					
				Ti I					
5460.51	0.05	−2.36 CB	50	34	5219.71	0.02	−1.90 CB	73	65
5453.65	1.44	−1.14 CB	34	26	5201.10	2.09	−0.22 CB	56	31
5426.26	0.02	−2.48 CB	46	...	5087.06	1.43	−0.55 CB	85	60
5351.07	2.78	+0.50 CB	39	21	4964.73	1.97	−0.37 CB	39	24
5295.78	1.07	−1.25 CB	58	37	4928.34	2.15	+0.27 CB	81	56
5259.97	2.74	+0.33 CB	32	14	4926.15	0.82	−1.71 CB	35	19
				V I					
5240.88	2.37	+0.23 CB	30	11	4832.43	0.00	−1.98 CB	71	46
4880.53	1.19	−1.16 CB	37	21	4831.65	0.02	−1.87 CB	83	50
				Cr I					
5344.76	3.45	−0.47 CB	34	14	5214.13	3.37	−0.22 CB	42	28
5318.78	3.44	−0.07 CB	46	32	5200.18	3.38	+0.07 CB	56	36
5304.18	3.46	−0.20 CB	46	26	4936.34	3.11	+0.33 CB	75	57
5287.18	3.44	−0.47 CB	37	21	4885.95	3.09	−0.44 CB	56	34
5238.97	2.71	−0.89 CB	54	34	4836.86	3.10	−0.53 CB	44	27
				Mn I					
5457.47	2.16	−2.04 CB	43	16	5399.48	3.85	+0.17 CB	87	57
5413.68	3.86	+0.05 CB	54	39	5377.61	3.84	+0.47 CB	93	63
				Fe I					
5461.56	4.44	−1.57 XS	48	31	5320.04	3.64	−2.47 XS	48	36
5460.88	3.07	−3.52 XS	24	16	5295.32	4.41	−1.45 XS	60	39
5441.35	4.31	−1.59 XS	64	48	5294.55	3.64	−2.62 XS	43	26
5436.60	2.28	−3.37 XS	79	61	5293.96	4.14	−1.69 XS	60	45
5436.30	4.39	−1.33 XS	66	50	5288.53	3.69	−1.61 XS	93	81
5432.96	4.44	−0.53 XS	99	80	5285.13	4.43	−1.49 XS	56	41
5406.78	4.37	−1.30 XS	66	54	5243.78	4.26	−0.96 XS	97	78
5379.58	3.69	−1.61 XS	97	79	5228.38	4.22	−1.00 XS	96	71
5376.84	4.29	−2.05 XS	37	26	5223.19	3.63	−2.24 XS	60	46
5326.82	4.41	−1.95 XS	41	21	5213.35	4.39	−2.13 XS	26	16
5321.11	4.43	−1.12 XS	68	56	5197.94	4.30	−1.35 XS	75	52
				Co I					
5352.05	3.58	+1.14 XS	66	43	5280.63	3.63	+1.19 XS	58	24
5342.71	4.02	+1.77 XS	62	43	5230.22	1.74	−0.53 XS	59	45
5325.28	4.02	+1.08 XS	26	14	5212.69	3.51	+1.09 XS	52	31
5301.05	1.71	−0.67 XS	64	37	4966.58	0.43	−2.86 XS	19	10
				Ni I					
5453.24	4.09	−0.70 C	34	24	4976.14	3.61	−0.85 C	56	43
5452.85	3.84	−1.12 C	48	37	4965.17	3.80	−0.76 C	59	37

TABLE 2—*Continued*

14 HERCULIS					70 OPHIUCHI A				
λ(Å)	E.P. (eV)	log *gf**	EW (mÅ) 14	EW (mÅ) 70	λ(Å)	E.P. (eV)	log *gf**	EW (mÅ) 14	EW (mÅ) 70
5435.87	1.99	−1.89 C	83	63	4935.83	3.94	+0.32 C	79	63
5259.49	3.74	−1.35 C	24	11	4925.57	3.65	−0.18 C	99	71
5220.30	3.74	−0.66 C	52	41	4913.98	3.74	+0.00 C	79	65
5197.17	3.90	−0.57 C	60	34	4831.18	3.61	+0.31 C	90	80
5082.35	3.66	+0.07 C	90	85	4829.03	3.54	+0.30 C	93	78
4976.33	1.68	−2.59 C	73	57					
				Cu I					
5220.09	3.82	−0.40 CB	39	19	5218.21	3.82	+0.38 CB	77	59
				Sc II					
5318.36	1.36	−1.92 CB	26	14	5239.82	1.45	−0.60 CB	71	52
				Cr II					
5308.43	4.07	−1.77 JT	34	26	5237.32	4.07	−1.27 JS	60	. . .
5305.87	3.83	−2.00 JT	26	17	4884.60	3.86	−2.08 JS	34	16
				Fe II					
5425.26	3.20	−3.17 XS	39	27	5284.11	2.89	−3.04 XS	68	56
5414.07	3.22	−3.54 XS	20	17	5234.63	3.22	−2.41 XS	79	73
5325.56	3.22	−3.24 XS	38	27					
				Y II					
5200.42	0.99	−1.05 CB	54	43	5087.43	1.08	−0.87 CB	58	50
				Nd II					
5319.82	0.55	−0.96 CB	19	13					

* SOURCE.—C, Corliss 1965. CB, Corliss and Bozman 1962. JT, Tech 1971. JS, value on Tech 1971 scale as indicated by the solar line strength. KP, Kurucz and Peytremann 1975. WS, Wiese *et al.* 1969. XS, value on arbitrary scale as indicated by the solar line strength.

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