INFRARED COLORS, CO BAND STRENGTHS, AND PHYSICAL PARAMETERS FOR GIANTS IN M71

JAY A. FROGEL*
Cerro Tololo Inter-American Observatory†

S. E. PERSSON
Hale Observatories, Carnegie Institution of Washington, California Institute of Technology

AND

JUDITH G. COHEN
Kitt Peak National Observatory†
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ABSTRACT

Broad-band *J*, *H*, and *K* magnitudes and narrow-band CO and H_2O indices for 25 giant and horizontal-branch stars in the strong-lined globular cluster M71 are presented. These data are compared with similar data for M67 and for metal-poor globular clusters. In most photometric indices the M71 stars are intermediate between M67 and the metal-poor globulars, although the M71 giant branch extends to considerably cooler temperatures. Bolometric magnitudes and effective temperatures determined for the M71 stars also place this cluster between the other globulars and M67. A theoretical analysis of the CO indices indicates that M71 is metal deficient by 0.4 ($\pm$0.2) dex in the mean with respect to field giants.

The relationship between the CO indices and CN absorption strengths as determined from DDO photometry is as expected from empirically determined temperature dependences and theoretically determined abundance dependences.

Subject headings: clusters: globular — stars: abundances — stars: Population II

I. INTRODUCTION

This paper continues our program of infrared photometric observations of cluster stars (Cohen, Frogel, and Persson 1978, hereafter CFP). In CFP we presented data for giants in the metal-poor globulars M3, M13, and M92 and in the old disk open cluster M67. Here we present broad-band *JHK* data and intermediate-band CO and H_2O strengths for the brighter giants and some horizontal-branch stars in M71 (NGC 6838). From northern hemisphere sites, M71 is the most easily observable, strong-lined globular cluster (Morgan 1959). An extensive discussion of the *UBV* color-color and color-magnitude diagrams has been given by Arp and Hartwick (1971, hereafter AH). More recently, Hesser, Hartwick, and McClure (1977, hereafter HHM) presented observations on the DDO system of several of the giants in M71, and Mould and McElroy (1978) reported on observations of the 7120 Å TiO band. Searle and Zinn (1978) gave measurements of a number of reddening-independent metallicity indices in the blue.

Sections II, III, and IV describe the observations and present the physical parameters derived from them. In § V the M71 data are compared with those of the other clusters. Section VI describes a quantitative

technique for deriving C and O abundances from the CO indices and presents a comparison of the infrared data with DDO photometric data; § VII summarizes the conclusions.

II. OBSERVATIONS

The observations were made with the 5 m Hale reflector in 1977 September. The InSb detecting system and standard stars which define the photometric system have been described elsewhere (CFP; Frogel *et al.* 1978, hereafter Paper I; Aaronson, Frogel, and Persson 1978, hereafter Paper II). Seeing images which were typically 1″ permitted the use of focal-plane apertures with projected diameters of 10″.0 or 7″.5 for all of the observations. Because of the crowded nature of the field, we could not always eliminate background stars, which were 4 or 5 mag fainter than the program stars, from both signal and reference beams. Nevertheless, we believe the major source of error to be short-time-scale fluctuations in atmospheric transparency which resulted in poorer-than-normal repeatability of our standards. This is reflected in the errors noted in Table 1.

Table 1 contains the observed *J − H* and *H − K* colors and *K* magnitudes of the M71 stars observed. All stars on the giant branch (GB), asymptotic giant branch (AGB), and horizontal branch (HB) observed photoelectrically by AH (their Table 1) which could be observed by us without confusion problems were

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TABLE 1
M71 Photometry

| Star | Observed* | | | Reddening Corrected† | | | | | | | | Notes |
	K	$J-H$	$H-K$	K_0	$(U-V)_0$	$(B-V)_0$	$(V-K)_0$	$(J-H)_0$	$(H-K)_0$	CO	H_2O	
B	6.85	0.96	0.23	6.78	3.50	1.67	4.66	0.88	0.19	0.105	0.05	
A4	8.03	0.82	0.16	7.96	3.19	1.47	3.55	0.74	0.12	0.125	0.015	
A6	8.12	0.86	0.19	8.05	3.49	1.53	3.65	0.78	0.15	0.135	0.035	
S	9.19	0.78	0.14	9.12	2.70	1.30	3.12	0.70	0.10	0.08	---	
A9	9.03	0.80	0.16	8.96	2.67	1.31	3.37	0.72	0.12	0.095	---	
N	10.51	0.58	0.11	10.44	1.96	1.00	2.26	0.50	0.07	0.06	---	4
A7	10.17	0.64	0.14	10.10	2.35	1.18	2.76	0.56	0.10	0.08	---	
A5	10.53	0.62	0.14	10.46	2.46	1.17	2.62	0.54	0.10	0.075	---	
X	11.82	0.50	0.07	11.75	1.15	0.78	1.96	0.42	0.03	---	---	1,5
A3	11.87	0.49	0.11	11.80	1.07	0.75	1.97	0.41	0.07	0.045	---	5
C	11.58	0.59	0.13	11.51	1.41	0.88	2.26	0.51	0.09	0.07	---	
A2	11.59	0.62	0.12	11.52	1.66	0.96	2.41	0.54	0.08	---	---	
18	11.55	0.57	0.09	11.48	---	0.75	2.25	0.49	0.05	---	---	6
19	11.94	0.48	0.07	11.87	---	0.74	1.84	0.40	0.03	---	---	6
21	9.54	0.71	0.14	9.47	---	1.45	2.84	0.63	0.10	0.105	---	3
29	6.55	0.98	0.29	6.48	---	1.59	5.6	0.90	0.25	0.145	0.17	3,7
30	7.80	0.88	0.18	7.73	---	1.49	3.59	0.80	0.14	0.155	---	
45	8.12	0.88	0.17	8.05	---	1.59	3.60	0.80	0.13	0.11	0.045	
46	8.00	0.88	0.17	7.93	---	1.57	3.64	0.80	0.13	0.15	0.045	
75	11.96	0.66	0.07	11.89	---	0.95	2.24	0.58	0.03	---	---	3
76	11.01	0.63	0.13	10.94	---	1.12	2.49	0.55	0.09	---	---	3
77	8.44	0.87	0.17	8.37	---	1.58	3.57	0.79	0.13	0.14	---	3
78	9.30	0.72	0.15	9.23	---	1.34	2.87	0.64	0.11	0.08	---	3
79	10.82	0.64	0.10	10.75	---	1.21	2.56	0.56	0.06	0.12	---	3
113	8.03	0.90	0.18	7.96	---	1.62	3.81	0.82	0.14	0.165	0.04	2

*Errors are ±0.04, ±0.03, and ±0.03 for $J-H$, $H-K$, and K, respectively, unless otherwise noted. Errors are ±0.03 or less for CO and H_2O.

†UBV photometry from AH. We assumed a reddening of $E_{B-V} = 0.25$. The reddening-corrected CO and H_2O indices are 0.005 larger and 0.015 smaller, respectively, than the observed indices.

NOTES:
1. Error is ±0.05 mag in $J-H$.
2. Errors are ±0.05 mag in $J-H$ and ±0.04 mag in $H-K$ and K.
3. Errors are ±0.06 mag in $J-H$ and ±0.05 mag in $H-K$ and K.
4. Asymptotic giant branch (AH).
5. Horizontal branch (AH).
6. Probable HB (see Fig. 3 of AH).
7. This is a small-amplitude, long-period variable, according to Hogg (1978).

included in the present program. Additional GB and HB stars with photographic BV data from AH's Table 2a were also included.

III. REDDENING CORRECTIONS AND $(m - M)_0$

Estimates of E_{B-V} for M71 vary from 0.21 to 0.32 mag. Dickens and Rolland (1972) and Kron and Guetter (1976) have quoted the lower value. The former authors based their result on a refitting of AH's data to the color-magnitude diagrams of the metal-rich clusters 47 Tuc and NGC 6171. Kron and Guetter compared six-color photometry of M71 with that of other clusters. Racine (1973), on the other hand obtained $E_{B-V} = 0.32$ on the basis of mean colors for clusters as functions of Kinman's (1959) integrated spectral types, although such means were poorly determined for the metal-rich clusters. Cuffey (1973) presented UBV magnitudes and colors for 13 stars within several arcmin of M71. By fitting the three apparently early-type main-sequence stars (stars 6, 10, and 12) to a standard $(U - B, B - V)$-diagram, we

obtained a mean $E_{B-V} = 0.3$. Without a luminosity determination, however, the distances of these stars cannot be derived. We have elected to use an average value of $E_{B-V} = 0.25$ but regard it to be uncertain by ±0.05 mag. Color excess ratios are those found from van de Hulst's curve 15 (Johnson 1966a); corrections of +0.005 and −0.015 mag have been applied to the CO and H_2CO indices, respectively. The reddening- and extinction-corrected colors and magnitudes, denoted by a zero subscript, are given in Table 1.

Since our adopted value of E_{B-V} differs from that of AH, it is necessary to recalculate $(m - M)_0$. If the same technique used by AH is followed [viz., fit the observed main sequence of M71 to a sequence of field stars from Eggen and Sandage 1962 with the same $\delta(U - B)$ and with known distance], the resulting value for $(m - M)_0$ is 13.0 ± 0.2. Alternatively, we can compare the extinction-corrected horizontal-branch magnitudes of M71, 47 Tuc, and NGC 6171 (Hartwick and Hesser 1974; Sandage and Katem 1964; Lee 1977). In metal-rich cluster, M_v for horizontal-branch stars usually lies between 0.6 and 1.0 (the

TABLE 2

OBSERVED AND DERIVED PARAMETERS FOR M71 STARS

Star	−BC	M_{bol}	T_{eff}	log g	Notes
B	1.66	−3.13	3300	0.33	2
A4	0.95	−2.35	4000	0.98	
A6	0.97	−2.18	3950	1.02	
S	0.67	−1.34	4200	1.47	
A9	0.80	−1.38	4100	1.41	
N	0.21	−0.40	4900	2.12	
A7	0.47	−0.52	4500	1.92	
A5	0.36	−0.17	4600	2.10	
X	0.13	+0.69	5200	2.65	1
A3	0.11	+0.77	5200	2.68	
C	0.25	+0.63	4850	2.51	
A2	0.29	+0.75	4700	2.50	
18	0.23	+0.61	4900	2.52	
19	0.06	+0.76	5300	2.71	1
21	0.48	−1.08	4400	1.65	
29	2.58	−3.39	3050	0.09	1, 2
30	0.94	−2.53	3950	0.88	
45	0.92	−2.18	3950	1.02	
46	0.97	−2.31	3950	0.97	
75	0.21	+1.03	4900	2.69	
76	0.32	+0.22	4650	2.26	
77	0.92	−1.89	4000	1.16	
78	0.51	−1.32	4400	1.56	
79	0.35	+0.07	4650	2.20	
113	1.11	−2.25	3900	0.98	

BC and M_{bol} are obtained from the optical and infrared photometry with $(m-M)_0 = 12.9 \pm 0.2$. T_{eff} is derived as discussed in the text. Log g is derived from the values of M_{bol} and T_{eff}, and by assuming that $M = 1\,M_\odot$ for all the stars.

NOTES: 1. Only $V-K$ used for T_{eff} determination.
         2. T_{eff} obtained by comparing $(V-K)_0$ with Johnson (1966b).

above-cited authors; Harris 1976). By using 0.8 mag as a mean, we obtain $(m - M)_0 = 12.9$ for M71 from both 47 Tuc and NGC 6171. This value is adopted here.

IV. BOLOMETRIC CORRECTIONS, EFFECTIVE TEMPERATURES, AND SURFACE GRAVITIES

Bolometric corrections were computed as in CFP. For stars that did not have observations at U, the $U - V$ colors were predicted from a mean $(U - V, V - K)$-relationship. In any case, only a small fraction of the energy from these stars comes out below 4000 Å. Since no $R - I$ colors were available for the M71 stars observed, we predicted these colors from the relationships between $V - K$, $V - R$, and $V - I$ of Johnson (1966b). A comparison of the observed and predicted colors for the stars of CFP which have $R - I$ photometry was made in order to check the accuracy of this procedure. Table 2 gives the final values for the empirically determined bolometric

corrections. The absolute bolometric magnitudes M_{bol} in Table 2 are derived from these corrections—an $E_{B-V} = 0.25$, an $(m - M)_0 = 12.9$—and the V magnitudes of AH.

The effective temperatures T_{eff} were calculated from the model-derived mean relationships between $V - K$, $J - K$, and T_{eff} given in CFP. The values of T_{eff} implied by $V - K$ were given double weight because of the greater sensitivity of this index. Nevertheless, the spread in T_{eff} values for a given set of $V - K$ and $J - K$ values was generally 100 K or less. The adopted values for T_{eff} are given in Table 2. An uncertainty of ± 0.05 in E_{B-V} affects log T_{eff} and M_{bol} by ± 0.01 and ± 0.07, respectively. Surface gravities for the stars were computed on the assumption that they are all of $1\,\mathfrak{M}_\odot$. These values are also given in Table 2.

V. RESULTS

Most of the reddening- and extinction-corrected data are presented in several figures. We discuss these
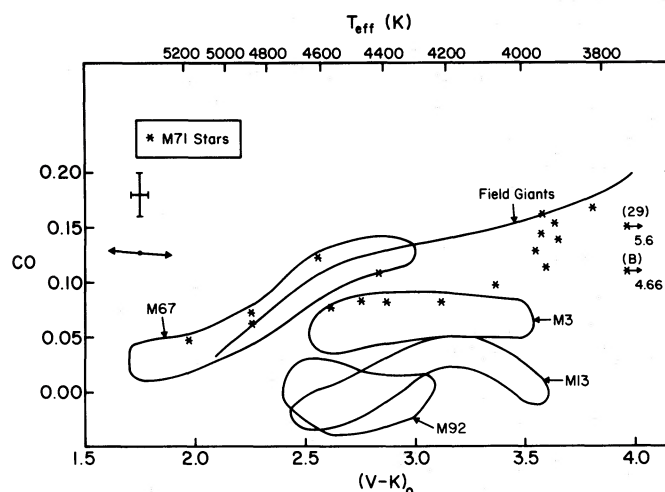
FIG. 1.—The reddening-corrected CO indices and $V - K$ colors are plotted for the M71 stars. Values of T_{eff} as a function of $V - K$ are from CFP. The error bars show nominal 1 σ_m errors in each coordinate. The effect of a ± 0.05 uncertainty in E_{B-V} is indicated by the arrows. Regions occupied by the cluster stars observed in CFP are delineated. The numbers near the M71 stars 29 and B are their $(V - K)_0$ colors.

first and then turn our attention to a comparison of the (log L, log T_{eff})-plot with model predictions.

a) CO and H_2O Absorption Indices

Figure 1 shows a plot of CO strengths versus $(V - K)_0$ and T_{eff}. The regions occupied by the stars studied in CFP are indicated. Since M71 is considered to be more metal rich than the globular clusters studied in CFP, it is not surprising that, in the mean, the CO strengths of the giant stars are greater than in the other globulars. Near $(V - K)_0 = 3.00$, the mean CO index for M71 is 0.09 mag, with some uncertainty due to either cosmic or observational scatter. Two stars in M71 (B and 29) are 1 and 2 mag redder, respectively, than any of the stars in the other clusters. (Recall that, for the other clusters, the reddest known stars were observed by CFP.) This demonstrates that infrared colors are much more effective than UBV colors in providing temperature resolution at the red end of the giant branch. These two stars have CO indices 0.07 and 0.10 mag, respectively, below the mean field-giant line at the same $(V - K)_0$. Star 29 has an H_2O index of 0.17 mag. This value is 0.06 mag greater than the mean for field giants at this $(V - K)_0$ and is greater than the H_2O index for any of the other cluster stars observed by CFP. Such a combination of strong H_2O, weak CO, and red $V - K$ is characteristic of Mira variables (Frogel 1971). For the other stars in Table 1 for which H_2O was measured, the values of this index are consistent with their $(V - K)_0$ colors. On the basis of 4 m echelle spectra, the radial velocity of M71 is -25 ± 2 km s^{-1}, in good agreement with that found by Jenner and Kwitter (1977). Of the M stars found near M71 by Stephenson (1961), stars B, 27 (the Mira variable Z Sge), and 46 are definite V_r members, while star 29 is a probable member.

Five of the stars in Table 1 (plus 10 from CFP) have also been observed by Pilachowski (1978). Although there is qualitative agreement, quantitative comparison of her results with ours is not possible, because she transformed her observations to a system different from that defined in Paper I. On the basis of her observations of six M71 stars, Pilachowski concluded that the CO indices for M71 and the mean field giants are indistinguishable. However, as discussed above, Figure 1 shows that, for $V - K > 2.5$, nearly all of the stars have CO indices lower than that of the mean field-giant line.

b) Color-Color Plots

In Figure 2 the $[(U - V)_0, (V - K)_0]$-plane is reproduced from CFP but with the addition of the M71 stars. The M71 giants tend to lie between the mean field-giant line (or the locus of the M67 stars) and the locus of the metal-poor cluster stars, although the scatter for the M71 stars is greater than that for the other clusters.[1]

For a given T_{eff}, the variation in $(U - V)_0$ due to line blanketing as [Fe/H] increases is large for [Fe/H] between 0.0 and -1.5 but small for [Fe/H] < -1.5 (CFP). Thus the locations of the M71 stars are consistent with a metallicity for M71 intermediate between that for field giants and M67 on the one hand and that for metal-poor globulars on the other.[2]

[1] Such scatter can arise, in part, from photometric problems in the extremely crowded field, nonuniform reddening, or inclusion of nonmembers.

[2] Estimates of the metallicity of M67 have ranged from super–metal rich (Spinrad and Taylor 1969) to somewhat metal poor (Griffin 1975; Bessell 1972; Eggen and Sandage 1964; Eggen 1977). Measurements of CN blanketing on the DDO system of the M67 giants led Janes (1974) to conclude that these stars are between normal field giants and Hyades giants in abundance. A recent photometric investigation of
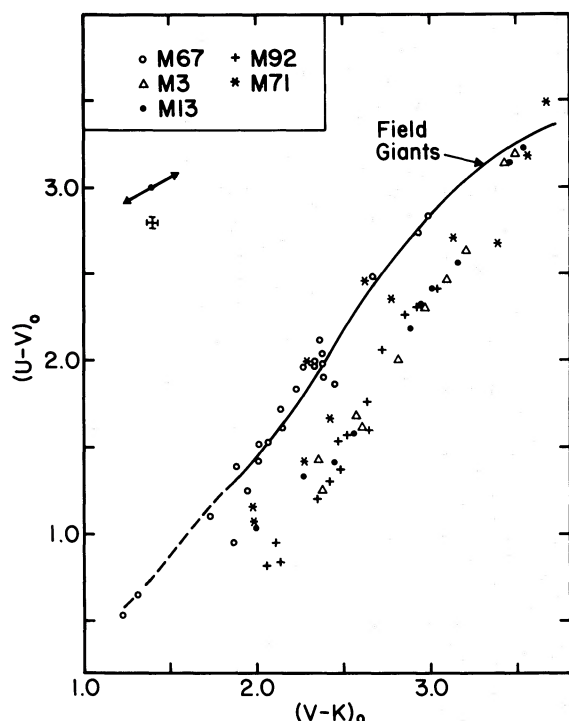
FIG. 2.—The reddening-corrected colors for the M71 stars and all the stars from CFP are shown. The mean field-giant line is from Paper I with the dashed portion from Johnson (1966a). Error bars and reddening vectors are as in Fig. 1.
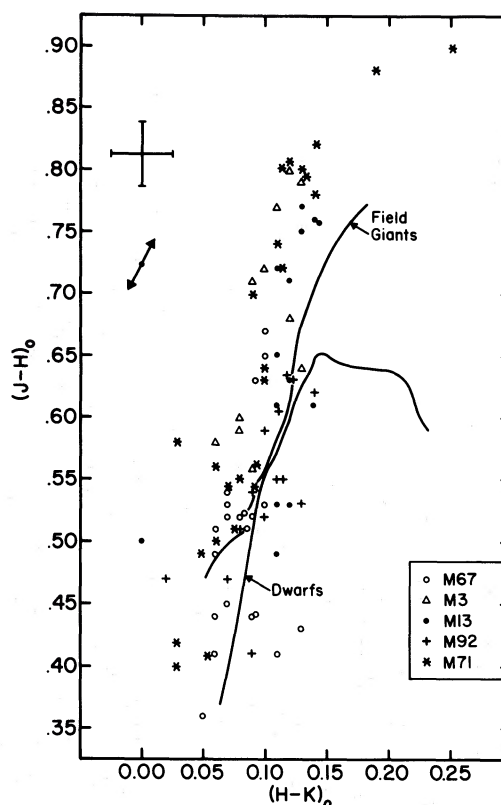

FIG. 3.—Same as Fig. 2

Adoption of the extremes of the error in E_{B-V} of ± 0.05, however, would force the M71 stars to lie close to one sequence or the other.

Figure 3 plots the $[(J - H)_0, (H - K)_0]$-colors for the M71 stars of Table 1 together with the data from CFP. We see that the M71 stars intermix with the stars from CFP, extend the globular cluster sequence to redder colors, and continue the displacement from the mean relation for field giants. There is an indication that the reddest nonvariable stars in 47 Tuc (Glass and Feast 1973) are also displaced above the mean field-giant line; such a comparison is difficult, however, because of the differences in the photometric systems used. We are unable at present to explain the relative locations of the various clusters in Figure 3.

The locus of points for the M71 stars in the $[(J - K)_0, (V - K)_0]$-plane is very similar to that of the metal-poor clusters, which, in turn, is essentially the

the main sequence of several nearby clusters by Taylor (1978) indicates a solar abundance for M67. The CO indices for the M67 stars also imply a metallicity which is indistinguishable from that of the mean field giants, as does the position of the M67 stars in the $(U - V, V - K)$-plot (Fig. 2), which overlaps that of the mean field-giant lines. Thus it is reasonable to conclude that the metallicity of M67 is between 0.0 and -0.15 dex with respect to that of the mean field giants (see § VI for details).

mean locus of field giants. The reader is referred to Figure 2c of CFP for details.

c) (log L, log T_{eff})-Diagram

The bolometric luminosities and T_{eff} (Table 2) are plotted in Figure 4. Also shown are the mean relations for the four clusters from CFP and three evolutionary tracks for metal-deficient stars from Rood (1972). The small, circled area represents the M67 clump stars, which are usually interpreted as the old disk population equivalent of the horizontal branch (e.g., Cannon 1970). The M71 giant branch again lies between giant branches of the metal-poor clusters and M67, a result that is relatively insensitive to the adopted reddening. This location is consistent with M71 being intermediate in metallicity between M67 and the metal-poor clusters. Globular cluster metallicity estimates based on the relative positions of the red-giant branch are essentially independent of age for ages between 10 and 16×10^9 years (see, e.g., Ciardullo and Demarque 1977).

VI. CNO ABUNDANCES

We consider in this section what can be deduced about the CNO abundances in M71 and other globular clusters both from the narrow-band CO photometry presented here and in CFP and from DDO
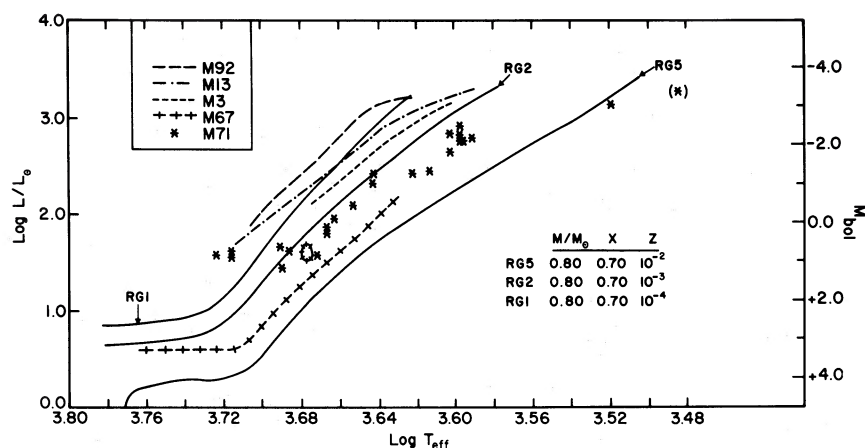
Fig. 4.—The empirical bolometric luminosity–effective temperature plot for the M71 stars. The mean giant branches for the clusters observed by CFP are also plotted. The small, enclosed area represents the M67 clump stars. The evolutionary tracks labeled RG1, RG2, and RG5 are from Rood (1972). Note that the position of the long-period variable star 29 in M71 is uncertain.

photometry. In § VIa a procedure for converting observed CO indices into quantitative measures of the abundances of C and O is described. The C and O abundances of the M71 stars are derived in § VIb and are compared with the qualitative results of § V. In § VIc the C and O abundances are derived for M3, M13, and M92 from the photometric CO indices combined with the results of Cohen (1978). Section VId discusses the correlation between the CO index and several DDO indices.

a) Procedures

A method for obtaining quantitative CO abundances from the 2.4 μm CO index has been developed by using opacity distribution function (ODF) spectra[3] in this wavelength region from the Bell et al. (1976) and Gustafsson et al. (1975) grids of models for K giants. For a sequence of models of varying Z (defined here so that $Z_\odot = 1$) at a fixed T_{eff} and g, the mean absorption A_{CO} with respect to an interpolated continuum over the ODF region which includes the first fundamental CO band was expressed as

$$A_{CO}(Z)/A_{CO}\odot = Z^{MMF}, \qquad (1)$$

where MMF is the metallicity multiplication factor (Cohen 1978). Equation (1) defines a relationship between $\log Z$ and $\log [A_{CO}(Z)/A_{CO}\odot]$ which is similar to that of a classical curve of growth; the function MMF is the slope of the resulting curve at each value of $\log [A_{CO}(Z)/A_{CO}\odot]$. With the use of the models in the Bell and Gustafsson grid (Bell et al. 1976), a curve was plotted of the deduced MMF values as a function of A_{CO}. For different values of T_{eff} and $\log g$, all the model sequences lie along the same (MMF, A_{CO})-curve shown in Figure 5. For A_{CO} larger than the maximum of 15% obtained from the Bell and Gustafsson grid, MMF = 0.1 was adopted. For stars of the same T_{eff}

[3] The ODF fluxes for these models were kindly provided by Dr. Bengt Gustafsson.

and similar gravities but different CO absorptions, this curve can be used to derive the difference in CO abundance.

In order to actually use Figure 5 on the observed 2.4 μm CO indices of this paper and of CFP, two corrections must be made. First, the observed CO index is defined with respect to only one continuum point, so it must be corrected for the change in the continuum slope of the observed star as compared with that of Vega, defined to have a CO index of 0.00 mag. The maximum correction for giants hotter than 3700 K is 0.03 mag. The observed (reddening-corrected) CO index plus this small correction, converted from a magnitude to an absorption, shall be called $A_{CO}*$. Second, the ratio between the "observed"
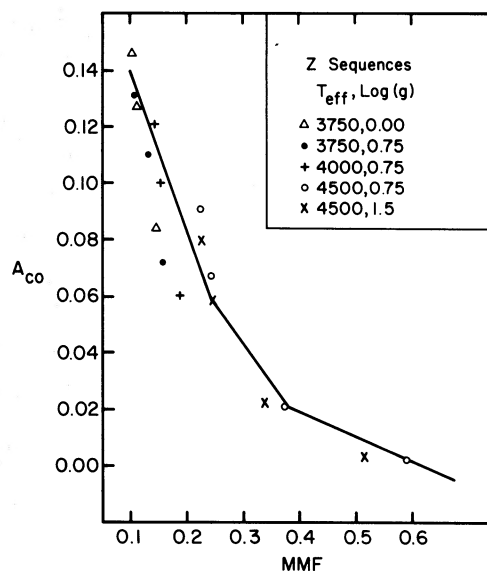

Fig. 5.—Calculated values of CO absorption as a function of the MMF. See text for description.

A_{CO}^* values for field giants and the theoretically derived A_{CO} values (compared at the same T_{eff}) is approximately 1.2 over the range 3750–5000 K.[4] Therefore, A_{CO}^* is scaled down by this factor.

The Bell and Gustafsson ODF spectra were calculated assuming solar C/N/O/Fe for $Z = 1.0$, 0.3, 0.1, 0.01, and 0.001. Thus an interpolation formula is required for nonsolar C/N/O/Fe. Molecular equilibrium calculations were made by using the code of Kurucz (1970) for the network of molecules involving C, N, and O. Although the results cannot be directly transformed into photometric indices, they are expected to give the proper sense of the behavior of these indices for stars hotter than 3500 K. The models indicate that, in the temperature range of the grid of CFP, CO is completely associated only in the outermost layers of the atmosphere. For $Z = 1$–0.01 and for C/O < 1, the simplest interpolation formula that fits the molecular equilibrium calculations of the CO column density through the atmosphere above $\tau(1 \mu m) = 0.3$ is $N(CO) \propto N(C) \times [N(O)^{1/2}]$. This formula is accurate to within 0.1 dex for C, N, and O varied by factors smaller than 3 from their relative solar values. For CN, the situation is simpler, and a suitable interpolation formula is $N(CN) \propto N(C) \times N(N)$ for small relative variations in C, N, and O abundances.

Thus, in principle, an observed CO index can yield only the product $N(C) \times [N(O)]^{1/2}$, while the observed DDO CN index could determine the product of the C and N abundances. When all of the uncertainties are considered, the resultant products of abundances for individual stars have an accuracy of ± 0.4 dex. Thus the analysis can be used meaningfully only in a statistical sense to obtain the mean $C \times O^{1/2}/(C \times O^{1/2})_\odot$ for a group of stars in a cluster.

b) M71

Before applying the above techniques to M71, we note that, because of the effects of convective mixing in evolved stars, those stars which are used to define the mean field-giant line (cf. Figs. 1 and 2) and which are assumed to have solar Fe/H (± 0.15 dex) probably do not have solar CNO abundances. An observational study of CNO ratios among bright field giants by Lambert and Ries (1977) shows that they have solar oxygen abundance, $[C] = -0.25$ dex and $[N] = +0.35$ dex;[5] we shall henceforth assume that their results apply to the mean field-giant line shown in Figures 1 and 2. These changes from solar ratios are in qualitative agreement with theoretical predictions by Dearborn, Bolton, and Eggleton (1975) of the effects of convective mixing in evolved stars of solar metallicity. Such predictions for the effects of mixing

on CNO ratios in metal-poor stars, although urgently needed, are not available. However, from the observations of Sneden (1974), a similar enhancement of N and decrease in C is found in metal-poor K giants as compared with metal-poor K dwarfs. Furthermore, there is some evidence that metal-poor field K giants have [O/Fe] larger than solar (Lambert, Sneden, and Ries 1974; Conti et al. 1967).

By using the analysis of the CO index discussed in § VIa, we derive $[C \times O^{1/2}]_{mf}$, where mf refers to the mean of bright field giants, not the Sun, and is used for CNO only. We define $[C \times O^{1/2}]/1.5$ as $[C * O]$, where the denominator is a normalization factor used to make $[C * O]$ numerically directly comparable to the conventional [Fe], so that we derive from 17 stars in M71 (excluding the two extremely red stars) $[C * O] = -0.4 \pm 0.2$ dex. Table 3 summarizes estimates for the metallicity of M71. The first four values are based on the measurement of the effect of *heavy* metals on the spectra of individual stars, while the last two involve the CNO abundances.[6] In summary, it is reasonable to conclude that the heavy-metal abundance of M71 is a factor of 2 down from solar with an uncertainty of perhaps ± 0.2 dex. The CO results are in good agreement with the other metallicity determinations, thus implying that the M71 stars may have the same C/O/Fe as the mean field K giants used to calibrate the narrow-band system.[7]

The above results are in agreement with the qualitative conclusions of § V where we compared M67 and M71, with the assumption that M67 has near-solar abundances. If the lower metallicities suggested for M67 by Griffin (1975), Bessel (1972), and Eggen (1977) are correct, however, M67 will have an anomalously high (CO and CN)/Fe ratio, about 0.4 dex higher than that of the mean field giants and than that of M71. Unfortunately, the available analyses are too limited to allow an accurate determination of the heavy-element abundance of M67 relative to M71. A detailed abundance analysis of stars in these two clusters is in progress by one of us (J. G. C.).

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[4] Such a discrepancy could arise from incorrect transition probabilities for the CO band chosen by Bell and Gustafsson. Nonsolar CNO ratios due to convective mixing are in the wrong sense and cannot eliminate the necessity for this correction (see § VIb).

[5] $[X] = \log (X/H)_{star} - \log (X/H)_\odot$.

[6] Although the values are certainly in agreement, in view of the quoted errors, those two which indicate a solar abundance warrant some further comments. Butler's (1975) determination is based on only one star: one of AH's "blue stragglers," which is assumed to be a cluster member and is also assumed to have an atmospheric structure similar to that of the RR Lyrae stars upon which the ΔS calibration is based. HHM's determination of [Fe/H] is based on a similarity of heavy-element blanketing, as determined from DDO photometry, in M71 and NGC 6352 and on the abundance of NGC 6352 derived by Hartwick and Hesser (1972b) of [Fe/H] = $+0.1 \pm 0.1$ based on $\delta(U - B)$. However, inspection of HHM's Figure 1d would not seem to rule out a $C_0(38 - 42)$ blanketing for M71 several hundredths of a magnitude *less* than that for NGC 6352. The measurement of the CN strengths via DDO photometry could not be used for a metallicity determination in these clusters because of the large scatter in this index (HHM).

[7] Since only the product $[C \times O^{1/2}]$ is determined, there are C/O ratios different from that of the mean field giants that will produce the observed CO index; these cannot be eliminated without additional data.

TABLE 3

METALLICITY DETERMINATIONS FOR M71

[Fe/H]	Method	Source
-0.3 ± 0.3	$\delta \ (U-B)$	Arp and Hartwick (1971)
-0.04 ± 0.2	ΔS	Butler (1975)
-0.3 ± 0.3	(C, M, T_1, T_2)	Canterna (1975)
0.0	DDO	HHM
$-0.4 \pm 0.2*$	TiO	Mould and McElroy (1978)
$-0.4 \pm 0.2\dagger$	CO	This paper
-0.2 ± 0.1	Line blanketing in the blue calibrated to ΔS	Searle and Zinn (1978)

*Also defined with respect to the mean of bright field giants.
†This is $[C * O]_{mf}$, defined with respect to the mean of bright field giants; $[C * O] \approx -0.6 \pm 0.2$ with respect to the Sun (see Lambert and Ries 1977).

c) M3, M13, and M92

The narrow-band CO measurements of CFP for stars in M3, M13, and M92 can be converted into $[C * O]$ abundances via the techniques described above. Table 4 displays the deduced mean $[C * O]_{mf}$ for each globular cluster. Column (2) gives the mean $[C * O]_{mf}$ deficiency with respect to the mean field giants. Column (3) corrects the mean field giants to the Sun by using the results of Lambert and Ries (1977). Column (4) lists the spectroscopically determined [O] with a correction for O in CO based on the $[C * O]$ deduced from the observed CO (this paper; Cohen 1978). Column (5) contains [C] obtained from combining the CO and O determinations, i.e., $[C] = 1.5 \times [C * O] - 0.5 [O]$ (deduced from cols. [2] and [4]). Column (6) is the spectroscopic Fe abundance (Cohen 1978). Although [Fe] is larger in M13 than in M3, [C] and $[C * O]$ are larger in M3 than in M13. This result is consistent with the discussion in CFP, Cohen (1978), and Pilachowski (1978). The rather large errors preclude any further discussion of C and O abundances.

d) Comparison with DDO Photometry

Figures 6a and 6b compare the CO, CN $[C_0(41 - 42)]$, and DDO metal-blanketing index $[C_0(38 - 42)]$ for individual stars from Table 1 here; from CFP; and from Osborn (1973), Janes (1974), and HHM. Additional new DDO photometry is given in the Appendix. Figure 6a shows that there is a general trend for the abundances of Fe, Ti, and the other elements which strongly contribute to ultraviolet line blanketing to be correlated with the CO abundance. In Figure 6a the M13 stars, as expected, show weak CO for their ultraviolet blanketing. Two moderately discrepant M92 points are III–13 and VII–18, both of which have an ultraviolet color too red for the CO strengths. These are the coolest giants in M92 observed on both systems, and the excessively red ultraviolet color index could be due to Rayleigh scattering rather than line blanketing. The same effect can be seen in Figure 2: for the coolest giants the ultraviolet excess of the M92 giants is less than would be expected when compared with the M3 or M13 giants of the same $(V - K)_0$, while for the hotter giants the M92 stars have

TABLE 4

C AND O ABUNDANCES FOR GIANTS IN METAL-POOR GLOBULARS

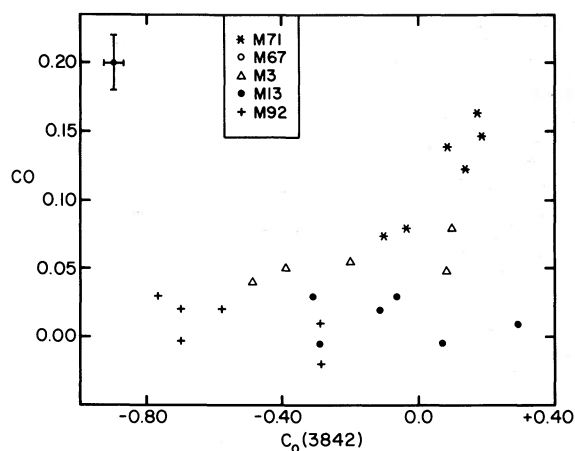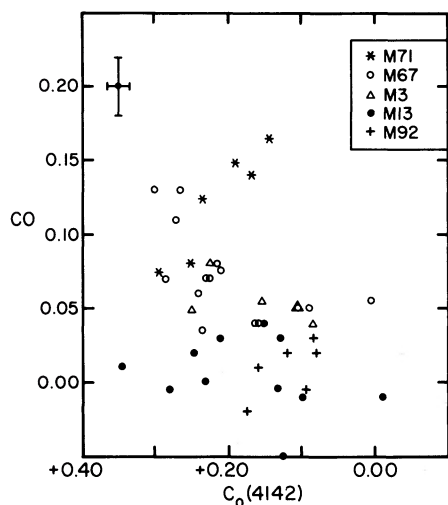|	$[C * O]_{mf}$ (dex)	$[C * O]$ (dex)	$[O]_{corr}$ (dex)	$[C]$ (dex)	$[Fe]$ (dex)
M3	-1.2 ± 0.3	-1.35 ± 0.3	-1.4 ± 0.3	-1.3 ± 0.4	-1.8 ± 0.1
M13	-1.95 ± 0.3	-2.1 ± 0.3	$\leq -1.4 \pm 0.3$	$\geq -2.4 \pm 0.4$	-1.6 ± 0.1
M92	$\leq -2.1 \pm 0.3$	$\leq -2.3 \pm 0.3$			-2.3 ± 0.1
Source	CO (CFP)	CO + Lambert and Ries (1977)	Cohen (1978) + $[C * O]$	$[O]_{corr}$ + $[C * O]$	Cohen (1978)

FIG. 6a

FIG. 6b

FIG. 6.—The reddening-corrected CO indices from this paper and from CFP are plotted against the DDO indices which measure the effects (a) of metal blanketing and (b) of CN absorption. Error bars are 1 σ_m.

larger ultraviolet excesses than those of similar M3 and M13 giants.

In Figure 6b consider first the locations of the stars in the metal-poor clusters—M92, M13, and M3. As pointed out by HHM, these stars have no observable CN. In fact, it can be shown that, for these stars, the dependence of $C_0(41 - 42)$ as a function of temperature as measured by $C_0(45 - 48)$ (HHM) or $(V - K)_0$ (CFP and here) is due largely to the change in continuum slope as T_{eff} changes. Thus, for M3, M13, and M92, Figure 6b is really displaying only the variation of the observed CO strengths. We note, however, that M13 IV–25 (Appendix) has a $C_0(41 - 42)$ which is about 0.1 mag greater than expected for its T_{eff} as measured by its $(V - K)_0$, for example. Perhaps this is a mild example of the phenomena observed in several other clusters by HHM and by Hesser, Hartwick, and McClure (1976).

Now consider M67 and M71, the two most metal-rich clusters in this figure. Taken together, the stars from these clusters define a sequence of monotonically increasing CO but which exhibits a definite peak in the CN strength. Recall that, in normal field giants, CN absorption reaches a maximum at about K3 and then declines for later spectral type (e.g., Griffin and Redman 1960). K3 corresponds to $V - K = 2.9$, CO = 0.12, and $T_{eff} \approx 4400$ K (Paper I; Fig. 1 here). In order to investigate the dependence of CN absorption on Z and CO, the values of $N(CO)$ and $N(CN)$ [the column densities of CO and CN above $\tau(1\ \mu m) = 0.3$] were predicted from the molecular equilibrium calculations of § VIa. Figure 7 shows three sequences of $N(CO)$ versus $N(CN)$ corresponding to three values of $Z/Z_\odot$. The dependence of $N(CN)$ on $N(CO)$ in Figure 7 is qualitatively similar to that seen for the M67 and M71 stars in Figure 6b. Note that, for $Z/Z_\odot = 1$, the maximum value of $N(CN)$ occurs at about 4500 K, in agreement with the observed maximum absorption strength at K3 and with other such calculations (see, e.g., Dolan 1965). Also, the maximum value of $N(CN)$ occurs in stars of cooler T_{eff} as $Z/Z_\odot$ is reduced.

In Figure 6b the M67 stars define a line of CO increasing with CN; the coolest stars (those which have the largest CO indices) have $T_{eff} = 4300$ K (CFP), not quite cool enough for the falloff in CN to begin. However, for M71, the coolest stars have $T_{eff} = 3800$ K (Table 2), and the CN decline is apparent. Since the observed values of $C_0(41 - 42)$ for the metal-poor clusters are influenced primarily by the continuum slope rather than by true CN differences, no meaningful comparison with Figure 7 can be made for these stars. Thus it is possible that a small part of the dispersion in CN indices in Figure 1 of HHM is due to the CN turnover shown in Figure 7. This is true only for the coolest stars in the more metal-rich clusters such as 47 Tuc and M71.
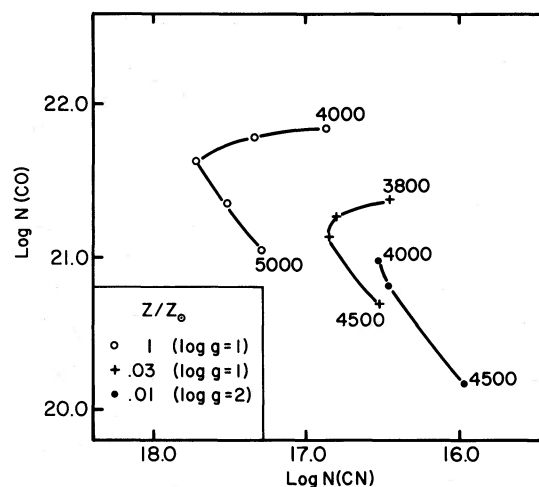

FIG. 7.—Column densities of CO and CN predicted by molecular equilibrium calculations for sequences of models of varying $Z/Z_\odot$. The highest and lowest temperatures for each sequence are indicated.

VII. SUMMARY AND CONCLUSIONS

We have presented observations of *JHK* colors and CO and H_2O line indices for a selection of giant and horizontal-branch stars in the strong-lined globular cluster M71. These data are used to derive M_{bol} and T_{eff} for the stars. A theoretical calibration, based on the Bell and Gustafsson (Bell *et al.* 1976) ODF spectra, is presented for the narrow-band CO index. The product of $N(C)$ and $[N(O)]^{1/2}$ is deduced from the observations of the M71 stars and those stars considered in CFP. A theoretical analysis of the expected behavior of CO and CN as a function of T_{eff} and metallicity is also described. The basic results of this work can be summarized as follows:

1. In a $(U - V, V - K)$-plot the M71 stars lie intermediate between the metal-poor globulars and the locus of solar-neighborhood field giants.

2. In spite of the fact that its population is considerably sparser than that of the metal-poor clusters, M71 has a giant branch which extends to considerably cooler T_{eff}.

3. A $(\log L, \log T_{eff})$-plot is in qualitative agreement with Rood's (1972) red-giant evolutionary tracks. However, detailed comparison with stellar models is difficult because of the problems of convection and the possible sensitivity of these evolutionary tracks to variations in the Z_{CNO}/Z ratio.

4. The abundance of the M71 giants as deduced from the CO indices indicates a metal deficiency of -0.4 dex in the mean with respect to field giants. For the M3, M13, and M92 giants, CO data and spectroscopic O abundances yield C abundances which support the skewed abundance distribution for M3 and M13 discussed by Cohen (1978).

5. A comparison of our CO data with published CN data (on the DDO system) indicates that, if the metallicity of M67 is solar, the photometric indices are consistent with the giants in M92, M3, and M71 having the same C/O ratios as the M67 giants and the mean field giants (to within a factor of 3). If the metallicity (Fe/H) of M67 is below solar, near that of M71, then CNO/Fe is higher in M67 than in M71.

6. M3 has an abnormally large CNO/Fe ratio as compared with M13; but compared with the mean field giants at solar metallicity, we cannot determine from the photometry alone which is the peculiar cluster.

7. The behavior of the CN and CO column densities as a function of T_{eff} and metallicity can explain the dependence of $C_0(41 - 42)$ on T_{eff} for the cooler stars in the more metal-rich clusters.

8. For the clusters of CFP and the present paper, the data do not yet show signs of the discontinuity between globular clusters and old disk open clusters which is noted in other studies (e.g., Hartwick and Hesser 1972*a*; Demarque and McClure 1977), although this conclusion is sensitive to the adopted values of the reddening.

TABLE 5

DDO PHOTOMETRY OF M3, M13, AND M71 STARS

	C (3841)	C (4142)	C (4245)
__M3__			
AA	-0.167	0.252	1.047
__M13__			
IV-25	-0.040	0.345	1.115
II-90	-0.352	0.249	1.009
II-76	-0.431	0.130	0.826
III-18	-0.414	0.134	0.859
III-63	-0.266	0.211	0.960
I-18		-0.012	0.660
I-23		0.126	0.664
I-24		0.099	0.785
I-48		0.232	0.939
II-67		0.284	1.055
III-73		0.165	0.840
__M71__			
A4	-0.029	0.251	1.266
46	+0.069	0.205	1.319

APPENDIX

Additional DDO photometry for M3, M13, and M71 stars with infrared CO observations from CFP or the present work was obtained with the 1.5 m telescope at KPNO during 1978 May–June using the Mark II computer photometer and the fainter G–M standard stars from McClure (1976). M13 I–24, II–90, and IV–25 were observed on two nights each; the remaining stars were observed only once. The photometric errors of the photometry listed in Table 5 are ± 0.02 mag.

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JUDITH G. COHEN: Kitt Peak National Observatory, P.O. Box 26732, Tucson, AZ 85726

JAY A. FROGEL: Cerro Tololo Inter-American Observatory, Casilla 63-D, La Serena, Chile

S. E. PERSSON: Hale Observatories, 813 Santa Barbara Street, Pasadena, CA 91106