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THE GIANT BRANCH OF THE GLOBULAR CLUSTER NGC 3201

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ABSTRACT

Infrared photometry has been obtained for 26 stars in the field of the globular cluster NGC 3201. For 14 of these stars, optical spectra have also been obtained. These observations show that the giant branch of this cluster possesses an intrinsic width of 0.13 mag ($\pm 1\ \sigma$) in $(V-K)_0$. We conclude however, that variable reddening across the cluster with $\sigma[E(B-V)] = 0.023$ is the most likely explanation of this result. In particular, the observed intrinsic width cannot be due to a range in heavy metal abundance, since there is no star-to-star scatter in the strengths of various strong metal lines.

There is a range in G band (CH) strength at constant $(V-K)_0$ that correlates with CO strength: stars with weak CH also have weak CO. Comparisons with published synthetic spectra show that star-to-star variations in carbon abundance of less than a factor of 3 are sufficient to explain the range in G-band strengths. With the exception of two stars, no significant scatter was found in the strengths of the $\lambda 3883$ CN band.

The position of the giant branch in the infrared C-M diagram and the strengths of metal lines in the optical spectra indicate that the overall metal abundance of NGC 3201 is comparable to those of M3, M5, and NGC 6752. This is significantly more metal-poor than the preliminary abundance determined from echelle plates by Pilachowski, Sneden, and Canterna.

Subject headings: clusters: globular — stars: abundances — stars: late-type

I. INTRODUCTION

The color-magnitude (C-M) diagram of the cluster NGC 3201 possesses the characteristics of a typical moderately metal-poor globular cluster (Menzies 1967; Alcaino 1976; Lee 1977). In particular, it contains a large number of RR Lyrae stars and an even distribution of stars from blue to red along the horizontal branch, features which are reminiscent of the northern clusters M3 and M5.

A closer inspection of the C-M diagram of Lee (1977), however, reveals an unusual feature. Above visual magnitude 13, the giant branch stars scatter over a large range in $(B-V)$. Fainter than this magnitude the width of the giant branch in $(B-V)$ is consistent with the small errors in the photometry. Since this C-M diagram is based on a total of 26 plates and since most of the brighter stars were measured photoelectrically, Lee (1977) concluded, as did Menzies (1967), that the dispersion in $(B-V)$ on the upper giant branch is too large to be attributed to observational error.

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The location and the intrinsic width of the upper giant branch of this cluster is best investigated with infrared photometry because of the greater sensitivity of infrared colors to effective temperature. Consequently, we have obtained *JHK* photometry of 26 stars in the field of this cluster. At the same time measurements were also made at the strengths of the 2.29 μm CO molecular band, since many globular clusters show strong star-to-star variations in the strengths of molecular bands involving the elements C, N, and O (see review articles of Kraft 1979 and McClure 1979 and references therein).

Optical spectra of a subset of the stars observed in the infrared have also been obtained. These spectra allow confirmation of cluster membership and also enable the determination of the strengths of the CN and CH molecular bands. An investigation of correlations between the optical and infrared band strengths is then possible.

The remainder of this paper is divided into six sections. Sections II and III describe the infrared and optical observations, respectively. Section IV discusses the color-magnitude diagram and the width of the giant branch. Section V investigates the molecular band strengths, and § VI discusses the metal abundance of the cluster. The results are summarized in § VII.

TABLE 1

NGC 3201 PHOTOMETRY

Star[a]	Observed[b]			Reddening Corrected[c]								Notes
	K	(J-K)	(H-K)	K_0	$(U-V)_0$	$(B-V)_0$	$(V-K)_0$	$(J-K)_0$	$(H-K)_0$	H_2O	CO	
1117	7.97	0.97	0.18	7.89	2.74	1.32	3.18	0.84	0.13	0.015	0.04	2, 5
3204	8.67	0.91	0.17	8.59	2.20	1.16	2.84	0.78	0.12	0.055	0.06	2
3218	8.50	0.95	0.18	8.42	2.56	1.29	3.09	0.82	0.13	0.05	0.065	2, 5
1309	10.23	0.72	0.14	10.15	1.08	0.75	2.25	0.59	0.09	....	0.00	2, AGB
1312	7.59	1.01	0.19	7.51	2.99	1.46	3.40	0.88	0.14	0.025	0.035	2, 5
1314	7.98	0.92	0.17	7.90	2.50	1.25	3.01	0.79	0.12	0.005	0.045	2, 5
1315	10.27	0.73	0.14	10.19	1.25	0.83	2.27	0.60	0.09	....	0.02	2, ACB
2321	11.11	0.76 (3)	0.15 (3)	11.03	1.18	0.83	2.25	0.63	0.10	....	0.015	2
3304	11.19 (3)	0.71 (3)	0.11 (3)	11.11	1.04	0.79	2.13	0.58	0.06	....	....	2
4318	8.84 (3)	0.88 (3)	0.16 (3)	8.76	2.18	1.17	2.92	0.75	0.11	....	0.065	2, 5
4319	8.67	0.91	0.16	8.59	2.42	1.24	3.06	0.78	0.11	....	0.02	2, 5
1410	9.42	0.86 (3)	0.15	9.34	1.93	1.05	2.67	0.73	0.10	....	0.04	2, 5
2405	9.09	0.89	0.17	9.01	2.00	1.10	2.81	0.76	0.12	0.055	0.08	3, 5
3401	9.05	0.88	0.16	8.97	2.04	1.09	2.88	0.75	0.11	....	0.065	2, 5
3405	10.49 (3)	0.77 (3)	0.13	10.41	1.42	0.88	2.40	0.64	0.08	....	0.00	2
3414	9.64	0.81	0.15	9.56	1.64	0.97	2.63	0.68	0.10	....	0.02	3
4403	10.71 (3)	0.76 (3)	0.12	10.63	1.29	0.85	2.33	0.63	0.07	....	0.01	2
1501	9.37 (3)	0.87	0.18	9.29	1.73	0.99	2.70	0.74	0.13	....	0.065	2, 5
3504	9.93 (4)	0.85 (3)	0.14	9.85	1.56	0.94	2.55	0.72	0.09	....	0.025	2
3522	9.25	0.82	0.15	9.17	1.81	1.06	2.70	0.69	0.10	....	0.05	2, 5
4507	9.14	0.89	0.19	9.06	2.11	1.14	2.80	0.76	0.14	0.06	0.065	2
4524	8.15	0.88	0.18	8.07	2.58	1.29	3.04	0.75	0.13	....	0.05	2, 5
1626	9.24	0.86	0.15	9.16	1.74	1.04	2.73	0.73	0.10	0.055	0.055	3
2608	8.39	0.92	0.17	8.31	2.21	1.19	3.15	0.79	0.12	0.05	0.06	3
3616	8.96	0.90	0.16	8.88	2.06	1.13	2.76	0.77	0.11	0.05	0.075	3
3217	6.72	1.24	0.31	6.64	2.79	1.43	5.85	1.11	0.26	0.085	0.225	1, 2, 4

[a] Identification numbers are from Lee 1977.

[b] Observational uncertainties are given in units of hundredths of a magnitude when greater than ± 2 in K, $(J-K)$, $(H-K)$, H_2O, and CO. The uncertainty in $(V-K)_0$ is ± 3 unless the uncertainty in K is greater than 3.

[c] A reddening value of $E(B-V) = 0.28$ was used. This corresponds to $E(H_2O) = 0.015$ and $E(CO) = -0.01$.

NOTES.—(1) $(K-L)_0 = 0.24 \pm 0.04$. (2) Photoelectric *UBV* values from Lee 1977. (3) Photographic *UBV* values from Lee 1977. (4) Radial velocity nonmember. (5) Radial velocity member.

II. INFRARED OBSERVATIONS

Infrared photometric measurements were made for all uncrowded stars in NGC 3201 with photoelectric values of $(B-V) > 1.0$ from Lee (1977) and which lie in his rings 3–5 so as to increase the *a priori* probability of cluster membership. Four red stars which lie farther from the cluster center, in rings 1 and 2, were also observed. Their membership was checked from radial velocity data as discussed below. Finally, to increase further the sample of red stars, five stars with only photographic observations in rings 4–7 were also observed.

All of the infrared data were obtained on the 4.0 and 1.5 m telescopes of the Cerro Tololo Inter-American Observatory between 1979 January and 1980 April with the CTIO InSb detector system. On both telescopes f/30 oscillating secondary mirrors were used. Guiding was accomplished with an on-axis Quantex integrating TV system looking through an IR/visual beam splitter. The data have been reduced to the globular cluster star photometric system of Cohen, Frogel, and Persson (1978) (hereafter CFP) and Persson *et al.* (1980). The reduced infrared magnitudes and broad band colors for the NGC 3201 stars are given in columns (2)–(4) of Table 1. Multiple observations of three of the stars on both telescopes showed a scatter consistent with the quoted uncertainties in Table 1.

We have adopted Racine's value (quoted by Harris 1976) of $E(B-V) = 0.28$ for the reddening of NGC 3201. This value is essentially identical to that $[E(B-V) = 0.27]$ determined by Zinn (1980*a*). The lower value $[E(B-V) = 0.21]$ given by Lee (1977) has not been used since it results in an inconsistent placement of the NGC 3201 stars in Figures 1 and 3. Color excess ratios are those found from van de Hulst's curve 15 (Johnson 1966). The observed values of the CO and H_2O indices were *corrected* by $+0.01$ and -0.015 respectively. Magnitudes, colors, and indices corrected for the adopted reddening are listed in columns (5)–(12) of Table 1. Lee

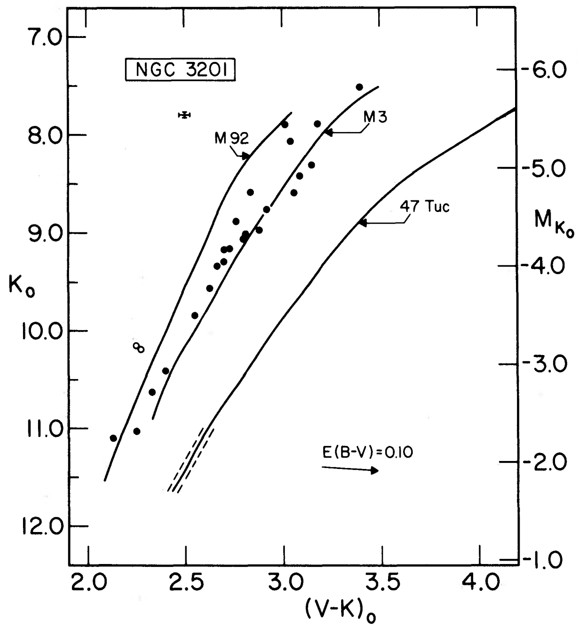

FIG. 1.—A color-magnitude diagram for the NGC 3201 stars from the reddening and extinction corrected data of Table 1. The two asymptotic giant branch stars observed are shown as open symbols; fiducial giant branches for the other clusters are from Frogel, Persson, and Cohen (1981) and CFP. The short dashed lines are typical dispersions about the fiducial lines for stars in M92, M3, and 47 Tuc. A reddening vector appropriate to the color and *apparent* magnitude scales is shown. A typical 1 σ error bar is displayed.

(1977) gives a mean V magnitude of 14.8 for the RR Lyrae variables in NGC 3201. If we assume that $M_{V_0} = +0.6$ for these stars, then $(m - M)_0 = 13.35$ for the cluster.

Table 2 contains various physical parameters for the stars observed. Temperatures, luminosities, and surface gravities have been computed as discussed in Persson *et al.* (1980) and in CFP. The relationships between various reddening and extinction corrected colors, magnitudes, and indices are illustrated in Figures 1–3 and will be discussed below.[2]

III. OPTICAL OBSERVATIONS

Of the 26 stars observed in the infrared, 14 have also been observed spectroscopically at optical wavelengths. Data for 12 stars were obtained by G. D. C. in 1979 June with the Shectman Photon-Counting Image Intensifier/Reticon system attached to the Cassegrain spectrograph of the 2.5 m du Pont telescope at Las Campanas Observatory. Each observation consisted of a simultaneous measurement of the star plus nearby sky through a pair of apertures. The star was alternately observed through the two apertures and the contributions of the night sky and the cluster background removed in the subsequent processing of the data.

[2] We will not consider the $(J - K)_0$ or $(H - K)_0$ colors nor the H_2O indices, as their behavior is essentially identical to that for the stars in the metal-poor clusters M3, M13, and M92 which have been discussed in CFP.

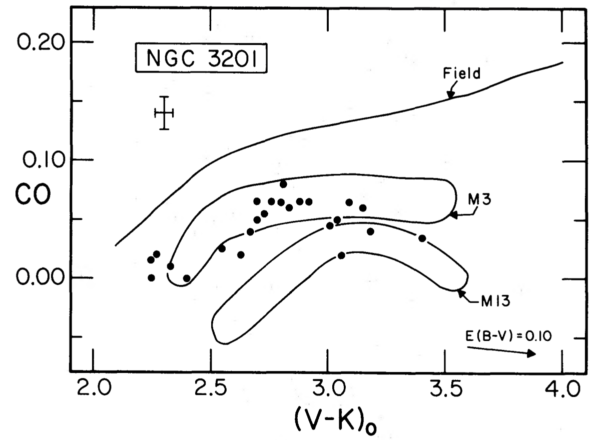

FIG. 2.—Reddening corrected CO indices and $(V - K)_0$ colors for the NGC 3201 stars are shown. The regions occupied by stars in the metal poor cluster M3 and M13 (CFP) are also shown. The mean field line is for giants of presumably solar composition.

The reduced spectra cover a wavelength range of approximately 3500–6000 Å with a resolution of 5 Å (FWHM) and signal-to-noise per resolution element of $\sim$ 20 at λ3900. Spectra of two stars in M5 (I-20 and I-68, Arp 1962) and two stars in NGC 6752 (CS3 and A12, Cannon and Stobie 1973; Alcaino 1970) were also obtained during this observing run. Observations each night of the spectrophotometric standards of Stone (1977)

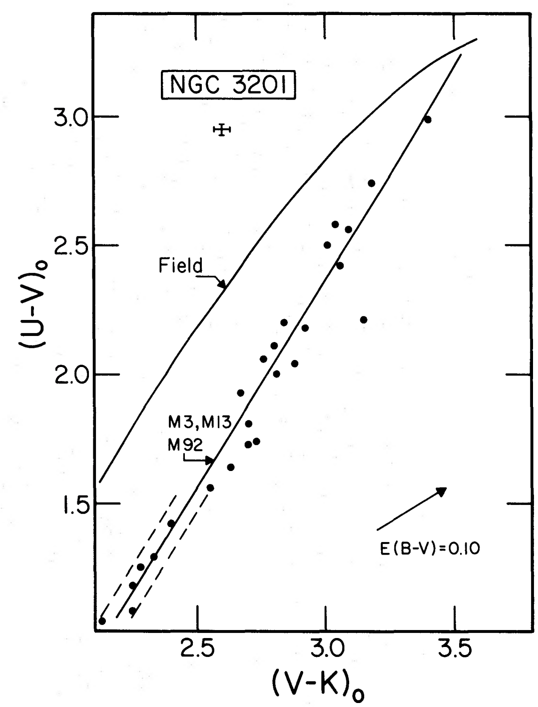

FIG. 3.—The relation between the reddening corrected $(U - V)_0$ and $(V - K)_0$ colors for the NGC 3201 stars are shown. The mean relations for field giants and for giants in the three metal-poor clusters (CFP) are indicated. The dashed line segments represent the dispersion about the mean for stars from all three of the metal poor clusters.

TABLE 2

PHYSICAL PARAMETERS FOR NGC 3201 STARS[a]

Star	BC_V	M_{bol}	log T_e	log g ($M=0.8 M_{\odot}$)	Notes	Star	BC_V	M_{bol}	log T_e	log g ($M=0.8 M_{\odot}$)	Notes
1117	-0.80	-3.08	3.621	0.6		3414	-0.51	-1.67	3.653	1.3	
3204	-0.60	-2.52	3.640	0.9		4403	-0.36	-0.75	3.681	1.8	
3218	-0.75	-2.59	3.624	0.8		1501	-0.53	-1.89	3.648	1.2	
1309	-0.34	-1.29	3.688	1.6	AGB	3504	-0.46	-1.41	3.658	1.4	
1312	-0.94	-3.38	3.608	0.5		3522	-0.54	-2.02	3.649	1.2	
1314	-0.70	-3.14	3.631	0.6		4507	-0.58	-2.07	3.642	1.1	
1315	-0.34	-1.23	3.686	1.6	AGB	4524	-0.73	-2.97	3.629	0.7	
2321	-0.32	-0.39	3.688	2.0		1626	-0.56	-2.02	3.647	1.2	
3304	-0.28	-0.39	3.697	2.0		2608	-0.80	-2.69	3.621	0.8	
4318	-0.66	-2.33	3.634	1.0		3616	-0.55	-2.26	3.645	1.1	
4319	-0.74	-2.44	3.626	0.9							
1410	-0.51	-1.85	3.651	1.2							
2405	-0.59	-2.12	3.641	1.1							
3401	-0.64	-2.14	3.636	1.1							
3405	-0.39	-0.93	3.675	1.7							

[a] We used $(m-M)_o = 13.35$ (Lee 1977).

enabled all spectra to be placed on a relative photometric scale. These spectra have been used to confirm cluster membership of the stars observed and to investigate the strengths of molecular features. Examples of the spectra of the NGC 3201 stars are shown in Figure 4.

Additional spectra of five stars were obtained by J. G. C. at Las Campanas in 1979 December. However, since the instrumental setup was different, these spectra have been used solely to confirm the cluster membership of the two stars, 1309 and 1314, not included in the June observations.

a) Radial Velocities and Cluster Membership

The large radial velocity of NGC 3201 (+493 km s^{-1}, Kinman 1959) provides an excellent means of discriminating cluster members from field stars. The radial velocity of each of the 14 stars observed has been determined using cross-correlation techniques similar to those of Da Costa *et al.* (1977). Spectra of the field giants HD 102596 (K3 III, Evans, Menzies, and Stoy 1959) and FDS V-1092 (K0 III, Evans *et al.* 1964), obtained at the same time as the June cluster observations, were used as radial velocity standards for the cross-correlations. The resulting velocities for 12 stars are listed in Table 3; the uncertainty in these values, unless otherwise noted, is approximately ± 8 km s^{-1}. For stars 1309 and 1314, radial velocities of 482 ± 12 km s^{-1} and 497 ± 15 km s^{-1} were derived. It is clear from these velocities and those of Table 3 that with the exception of the very red star 3217, all of the stars with optical spectra are cluster members.

The spectrum of the field star 3217 shows strong TiO bands and, together with its infrared colors, is consistent with a spectral type of M4 III. If we assume an infrared luminosity of $M_{K_0} = -6.0$ (Elias 1978) and that the cluster reddening is applicable to this star, then it lies 1240 pc in front of NGC 3201 at a height of 500 pc above the galactic plane.

TABLE 3

OPTICAL DATA

Star	V_r(km s^{-1})	S(CN)	W(G)	Σ(W)	Notes
		NGC 3201			
1117.......	497	0.49	8.3	9.2	
3218.......	483	0.34	10.0	8.15	
1312.......	483	0.51	8.6	8.9	1
4318.......	477	0.34	8.8	7.15	
4319.......	497	0.12	7.8	8.05	
1410.......	452	0.51	8.5	6.3	2
2405.......	494	0.30	9.6	7.7	
3401.......	496	0.23	9.4	7.7	
1501.......	495	0.20	8.8	7.1	
3522.......	494	0.19	9.4	6.0	
4524.......	499	0.42	9.7	7.95	
3217.......	7	...	...	...	3,4
		M5			
I-20	49	0.72	9.1	9.3	
I-68	61	0.37	9.4	10.8	
		NGC 6752			
A12	−50	0.35	8.7	8.3	
CS3	−37	0.55	8.4	7.2	

NOTES.—(1) Kinman 1959 gives $V_r = 487 \pm 7$ km s^{-1}. (2) Uncertainty in $V_r = \pm 25$ km^{-1} because of zero point drift during exposure. (3) Spectral type M4 III. (4) Uncertainty in $V_r = \pm 30$ km s^{-1} because of spectral type difference between star and radial velocity standards.

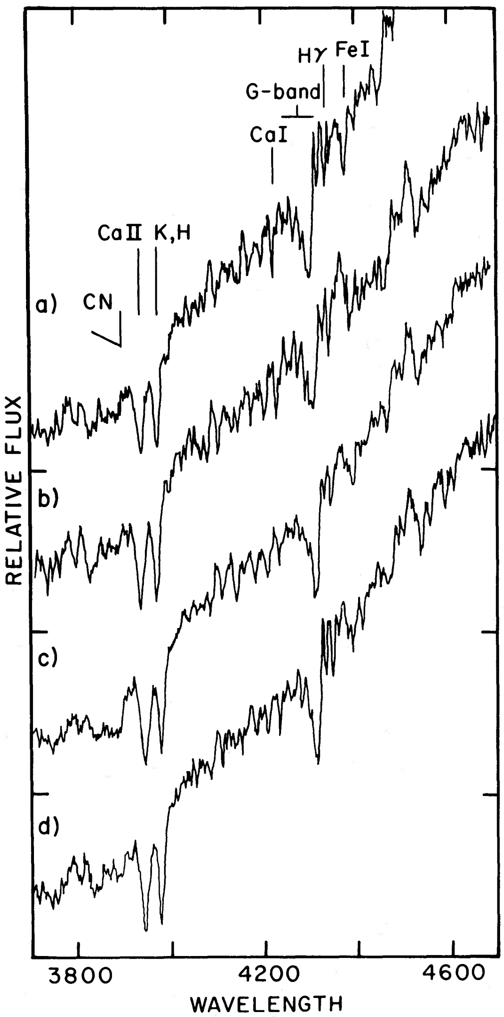

FIG. 4.—Spectra of NGC 3201 giants (*a*) star 3218; (*b*) CN-weak, CH-weak star 4319; (*c*) CN-strong star 1410; (*d*) star 3522.

b) CN *Band Strengths*

To obtain a quantitative estimate of the strengths of the cyanogen bands in these stars we have calculated an index S(CN) from each spectrum. This index compares the flux below the band head of the violet CN band at ~ 3880 Å with that in the continuum to the red. Specifically, in the rest frame of the star,

$$S(\mathrm{CN}) = -2.5 \log \int_{3860}^{3880} F_\lambda d\lambda \Big/ \int_{3895}^{3915} F_\lambda d\lambda$$

(cf. Norris *et al.* 1981). The values of S(CN) for 11 stars in NGC 3201 and for the stars observed in M5 and NGC 6752 are given in Table 3 and plotted in Figure 5 against $(V-K)_0$. The $(V-K)_0$ values for the M5 and NGC 6752 stars come from unpublished data by Frogel, Persson, and Cohen. The uncertainty in the S(CN) values is estimated as 0.06 mag based on the number of counts in each wavelength band and on the night-to-night repeatability of the observations of the photometric standards. A similar index for the blue CN band ($\lambda \approx 4216$) was not calculated because this feature is not seen on our low resolution spectra.

c) CH *Band Strengths*

To determine the relative strengths of CH features in our spectra, we have chosen to measure the equivalent width of the G-band. Such a measurement on low resolution spectra of cool stars can be difficult because of the uncertainty in the placement of the continuum. However, because all of the spectra have the same resolution and similar signal-to-noise ratio, a consistent placement of a (pseudo) continuum is possible, thereby allowing a comparison of G-band strength among the stars observed. Following Norris and Zinn (1977) we have used the (rest frame) wavelength intervals $\lambda\lambda$4250–4280 and $\lambda\lambda$4320–4340 to define this continuum. The results of the measurements, denoted by $W(G)$, are listed in Table 3 and plotted against $(V-K)_0$ color in Figure 6 and against the CO index in Figure 7. The estimated uncertainty in the W(G) values is ± 0.5 Å, with the greatest contribution coming from the uncertainty in the placement of the continuum.

d) *Metal Line Strengths*

The optical spectra can also be used to derive an estimate of the relative heavy element abundance for NGC 3201 and to search for star-to-star abundance variations. To do this, equivalent widths of a number of strong metal line blends have been measured and an index $\Sigma(W)$ formed by summing the measured widths.

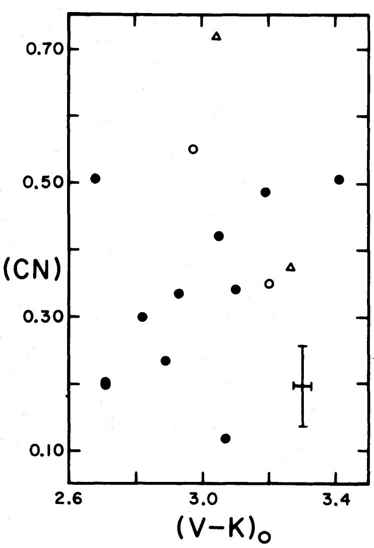

FIG. 5.—The dependence of the cyanogen index S(CN), which increases with increasing band strength, on $(V-K)_0$. *Filled symbols*, stars in NGC 3201; *open circles*, stars in NGC 6752; *open triangles*, stars in M5. A typical error bar is shown. The two stars that stand off the mean relationship for the NGC 3201 stars are 1410 (CN-strong) and 4319 (CN-weak).

The lines measured were λ4226 Ca I, λ4383 Fe I, λ5170 Mg I blend, λ5208 Cr I, Fe I blend, and λ5270 Fe I, Ca I blend. Again, the similar nature of the spectra enabled a consistent continuum placement. The lines have also been measured in the spectra of the stars observed in M5 and NGC 6752. The H and K lines of Ca II were not included in the $\Sigma(W)$ index because, for the NGC 3201 stars, the interstellar contribution to the width of these lines is not negligible. The values of $\Sigma(W)$ for each star is given in Table 3; the estimated uncertainty in these values is ± 0.5 Å with, as for the W(G) values, most of the uncertainty coming from uncertainty in the continuum placement. In Figure 8, these $\Sigma(W)$ values are plotted against $(V-K)_0$.

IV. THE COLOR-MAGNITUDE DIAGRAM

Figure 1 is a color-magnitude diagram for the NGC 3201 stars. The fiducial giant branches of the other three clusters are from the tabulation in Frogel, Persson, and Cohen (1981). The data for M3 and M92 are from CFP with slight changes in the $E(B-V)$ and $(m-M)_0$ values as noted in Frogel *et al.* (1981). The short dashed lines at the bottom of the 47 Tuc giant branch represent the typical 1 σ dispersion about the fiducial lines for the stars in all three clusters. This dispersion is independent of luminosity and consistent with the observational errors alone.

It is immediately apparent from this figure that the NGC 3201 stars show a scatter in $(V-K)_0$ at constant K_0 that is 2–3 times greater than that expected from the observational uncertainties alone. Such a scatter has been observed previously in the infrared only in the C-M diagram of the exceptional cluster ω Cen (Persson *et al.* 1980). To quantify this scatter, the dispersion in $(V-K)_0$ about a mean giant branch line drawn through the NGC 3201 stars in Figure 1 was calculated. We find $\sigma = 0.076$ mag. Allowing for a dispersion of 0.040 mag due to observational errors (both Lee's and ours), this observed dispersion appears to imply that the giant branch of NGC 3201 has an intrinsic width in $(V-K)_0$ of $\sigma_0 = 0.065$ mag. If this width is taken literally, it implies an effective temperature dispersion at constant luminosity on the giant branch of NGC 3201 of almost 50 K. However, before we can make this interpretation, we must investigate the more mundane possibility that this dispersion in $(V-K)_0$ is the result of reddening variations across the cluster.

Since $E(V-K)/E(B-V) = 2.78$, the dispersion in $(V-K)_0$ could be accounted for by reddening variations with $\sigma_{E(B-V)} = 0.023$ mag. Given the relatively high reddening of this cluster [$E(B-V) = 0.28$], dispersion in reddening does not seem unlikely. We now turn to the optical data of Lee (1977) to investigate this possibility further. If the intrinsic width of the giant branch of this cluster is truly zero, then the observed width in $(B-V)$, σ_{obs}, is determined by the observational errors σ_ϵ and by the reddening variations σ_R with $\sigma_{\text{obs}}^2 = \sigma_\epsilon^2 + \sigma_R^2$. If we adopt $A_V/E(B-V) = 3.0$, then σ_R is given by $\sigma_R = (1 + 3/S)\sigma_{E(B-V)}$ where S is the slope of the giant branch in the C-M diagram. Since S decreases with increasing luminosity, it is apparent that reddening variations will have a larger effect on the width of the giant branch at higher luminosities than at lower luminosities. This is precisely the type of effect required to explain the results of Lee (1977) and Menzies (1967) that the dispersion on the upper giant branch in $(B-V)$ is larger than that at fainter magnitudes. Adopting $\sigma_{E(B-V)} = 0.023$, $\sigma_\epsilon = 0.026$ (Lee 1977), and giant branch slopes from the C-M diagram of Lee (1977), we predict observed dispersion in $(B-V)$ of 0.052 mag for the giants with $V \leq 13$ and 0.041 mag for the giants with $14 \leq V \leq 15$. The calculated dispersions about a mean giant branch

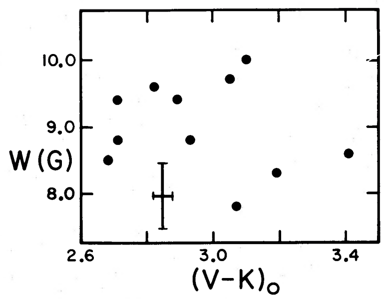

FIG. 6.—The equivalent width of the G-band (CH) is plotted against $(V-K)_0$ for the NGC 3201 stars. The bars indicate typical error sizes.

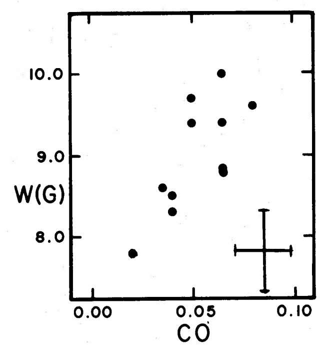

FIG. 7.—The relation between CH and CO strengths is shown. Typical error bars for both quantities are given.

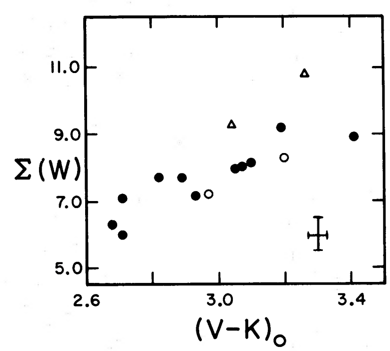

FIG. 8.—The behavior of the metal line strength $\Sigma(W)$. *Filled symbols,* NGC 3201 stars; *open circles,* stars in NGC 6752; *open triangles,* stars in M5.

line in the C-M diagram of Lee (1977) for these magnitude intervals are 0.053 and 0.040, respectively.

The agreement between the observed dispersions and those predicted on the basis of assumed reddening variations is remarkably good and indicates that *reddening variations are indeed the most likely cause of the dispersion in $(V-K)_0$ colors of the NGC 3201 giants.* We note though that especially for the fainter group of stars, the observed dispersion in $(B-V)$ depends strongly on the boundaries defining the sample. We considered all stars within ± 0.12 mag of the mean giant branch so that all giants brighter than $V = 13$ were included in the calculation. This same width was used to define the stars to be included at fainter magnitudes, but had we restricted ourselves to stars within ± 0.075 mag of the giant branch only, the observed dispersion at these magnitudes could be explained by the observational errors alone.

The interpretation that reddening variations are responsible for the dispersion in $(V-K)_0$ is further supported by the fact that the deviation of the stars from the mean lines in Figures 1 and 3, when measured along the appropriate reddening vectors, are correlated. In other words, stars lie off the mean line for metal-poor stars in Figure 3 by the amounts predicted if the giant branch deviations in Figure 1 are interpreted as the result of reddening variations.

The alternative interpretation of the dispersion in $(V-K)_0$ of the giants in NGC 3201 is that it results from a spread in heavy element abundance (cf. ω Cen, Persson *et al.* 1980). According to the theoretical tracks of Sweigart and Gross (1978), the spread in $(V-K)_0$, if it is interpreted as a spread in T_{eff}, implies a spread in [Fe/H] of approximately 0.025 dex if the mean value of [Fe/H] for NGC 3201 is about -1.4 (see § VI). However, there are at least two apparent problems with this interpretation. First, observations of RR Lyraes in NGC 3201 by Cacciari and Freeman (1980) have been interpreted by them as indicating no star-to-star calcium abundance variations greater than their observational uncertainties of ± 0.1 dex in [Ca/H]. Second, our own data (Fig. 8), discussed below, also indicate no star-to-star variation in heavy metal abundance to within similar limits. Thus we can rule out heavy element abundance variations as a cause of the spread in $(V-K)_0$ on the giant branch of NGC 3201.

To sum up, it appears most likely that the scatter in $(V-K)_0$ at a given K_0 among the giants in NGC 3201 is caused by reddening variations across the cluster with $\sigma_{E(B-V)} = 0.023$ mag. Consequently, since the physical parameters of the giants given in Table 2 have been derived from colors and magnitudes corrected for the mean cluster reddening only, the effective temperatures listed could be in error by as much as 100 K, while the bolometric magnitudes could have uncertainties as large as 0.1 mag.

The small variations in reddening found here probably occur in all clusters with large color excesses. Hence, we caution that abundance determinations for such clusters based on analyses of spectra of a limited number of bright giants whose effective temperatures are derived from observed broad band colors may be biased by the stochastic effects induced by reddening variations.

V. MOLECULAR BAND STRENGTHS

a) *The* CO *and* CN *Bands*

Figure 2 displays the dependence of the stellar CO indices on $(V-K)_0$. The envelopes labeled M3 and M13 encompass essentially all of the stars observed in these clusters (10 and 12, respectively). Stars from the more metal-rich clusters M71 and 47 Tuc generally lie between M3 and the field line. At any given $(V-K)_0$, the scatter in the CO indices for these clusters is consistent with that expected from the observational uncertainty alone. However, in NGC 3201 we note that while the dependence of CO on $(V-K)_0$ is similar to that of M3 for $(V-K)_0 < 3.0$, the stars redder than this have CO indices which are significantly weaker than that expected from the M3 distribution. This point will be discussed further below.

Figure 5 plots the S(CN) values against $(V-K)_0$, i.e., T_{eff}. The overall trend shown by the NGC 3201 stars in this diagram can be attributed to increasing CN strengths with decreasing temperature and increasing luminosity since CN shows a positive luminosity effect. For the majority of the stars observed, there is little variation at a given T_{eff} in the CN band strengths, nor is there any strong evidence for a bimodal band strength distribution as has been found in NGC 6752 and 47 Tuc (Norris *et al.* 1981; Norris and Freeman 1979). Two stars however, are exceptional; one, 1410, appears to be a "CN-strong" star similar to those present in NGC 6752.[3] The second, 4319, appears to have anomalously weak CN bands. If it were not for its high radial velocity (cf. Table 3), this star would probably be regarded as a lower luminosity field star; it is, however, a cluster member and deserves further study at higher resolution to investigate the anomalously weak strength of its CN bands.

In 47 Tuc, Frogel *et al.* (1981) found a strong anticorrelation between CO and CN band strengths. They concluded that the most likely explanation for this anticorrelation was that the flux in the continuum filter used in defining the CO index was being blocked by excess CN absorption. In NGC 3201, however, we find no such anticorrelation between CO and CN band strengths, neither for the anomalous stars in Figure 5 nor for the stars with $(V-K)_0 > 3.0$ which may have weak CO. This result is not surprising since the CN-blocking effect would not be expected to be operative in a metal-poor cluster where the absolute strength of the bands is considerably less (Frogel *et al.* 1981).

[3] The stars in M5 and NGC 6752 for which we have data have also been observed by Zinn (1977) and Norris *et al.* (1981) respectively. According to Zinn, star I-20 in M5 possesses strong CN bands while star I-68 has "normal" CN band strength. Similarly, star CS 3 belongs to the "CN-strong" group of stars on the giant branch of NGC 6752, while star A12 is a member of the "CN-weak" group (Norris *et al.* 1981). Since all of these clusters have similar overall abundances (see § VI), the locations of these stars in Figure 5 relative to the NGC 3201 stars are consistent with the conclusions of the above cited authors.

To summarize, we find the CO indices of the NGC 3201 giants to be similar in strength to those in M3 (Fig. 2) with little or no intrinsic scatter at constant $(V-K)_0$. It appears, though, that the reddest stars have CO indices which are weaker than would be expected from a comparison with M3. There is no obvious relationship between the CO and CN indices. With two exceptions, the CN band strengths also show no scatter and follow the behavior expected from luminosity and temperature variations.

b) The CO *and* CH *bands*

Figure 6 displays the dependence of the G band (CH) absorption on $(V-K)_0$. In a similar manner to the CO strengths, the G-band strengths of the hotter stars show a scatter that is consistent with the estimated errors, while the cooler stars exhibit a *range* of G-band strengths that is approximately twice the uncertainties. To investigate this scatter, the G-band strength index was plotted against the CO index. This is shown in Figure 7. Here we see a good correlation; the stars with smaller CO indices have generally weaker G bands and vice versa. This indicates that, first, the scatter in the W(G) values seen in Figure 6 is not due to an underestimate of the measurement errors but is real, and, second, that the dispersions in the G-band strengths and in the CO indices probably share a common origin.

This behavior of the CO and CH bands could be explained if the atmospheric carbon abundance varies among the stars observed. Such carbon abundance variations have been suggested as the explanation of the G-band variations seen among the giants in many other globular clusters (Zinn 1973; Norris and Zinn 1977; Zinn 1977). Carbon abundance deficiencies appear able to explain the field weak G-band stars (Cottrell and Norris 1978; Sneden *et al.* 1978). Such stars are also known to have significantly weaker CO indices than normal giants of the same temperature (Hartoog, Persson, and Aaronson 1977). Hence it seems plausible that the atmospheres of the NGC 3201 giants observed are deficient in carbon by varying amounts.

Can we determine the size of these carbon abundance variations? Unfortunately no calibration of the CO index in terms of carbon or overall metal abundance exists at present, so we can use only the G-band variations to provide such an estimate. To do this we utilized the published synthetic spectra of Bell, Dickens, and Gustafsson (1979) and Dickens, Bell, and Gustafsson (1979).

The G band index W(G) for the synthetic spectra calculated with $T_{\rm eff} = 4000$ K and $\log g = 1.5$ (cf. Table 2) was measured in exactly the same way as for the observed spectra.[4] The differences in W(G) between the spectra with [C/Fe] = 0.0 and [C/Fe] = −0.5 are 3.2 Å for [Fe/H] = −1.0 and 3.5 Å for [Fe/H] = −2.0. Similar differences occur between the [C/Fe] = −0.5 and the [C/Fe] = −1.0 spectra. Hence if [Fe/H] ≈ −1.5 for NGC 3201, a carbon abundance range of a factor of 3 should lead to a range in the observed W(G) values of a little more than 3 Å. This is larger than the range of W(G) values seen in Figure 6. We conclude, then, that the observed scatter in the W(G) index can be explained by carbon abundance variations of less than a factor of 3. It should be emphasized that we have not derived an estimate of the actual carbon abundance [C/H] in these stars, but only an estimate of the range in this elemental abundance. This range is considerably less than that found in the metal-poor clusters M92 and NGC 6397 (Bell, Dickens and Gustafsson 1979) but is consistent with the factor of 2 range found for the giants in NGC 6752 (Da Costa and Cottrell 1980; Norris *et al.* 1981) and in 47 Tuc (Norris and Cottrell 1979). Without a calibration we cannot tell if this carbon abundance range can also account for the CO index variations.

One possible explanation for the range in carbon abundances is that it results from the mixing into the atmospheres of varying amounts of material in which carbon has been processed into nitrogen. As a consequence of this mixing one might expect to see a strengthening of the CN bands with weakening CH (or CO) as is observed in NGC 6752 (Norris *et al.* 1981). However, this not observed here nor is an anticorrelation between C and N abundances observed in some other clusters (e.g., M93, Carbon *et al.* 1981), known to have large carbon abundance ranges. Nonetheless, these carbon abundance variations have been attributed to mixing.

In summary, the observations of molecular features in the spectra of giants in this cluster are consistent with the presence of a carbon abundance range of a factor of 3 or less which may be the result of mixing. Confirmation of this hypothesis must await until the application of spectrum synthesis techniques (cf. Da Costa and Cottrell 1980 or Carbon *et al.* 1981) yields actual carbon and nitrogen abundances for these stars.

VI. THE METAL ABUNDANCE OF NGC 3201

In this section we will discuss the relevance of these new infrared and optical data to the question of the metal abundance of NGC 3201.

As discussed in § III*d*, we have formed an index $\Sigma(W)$ for each of the stars observed spectroscopically. The values of this index, which is the sum of the equivalent widths of a number of metal lines, are plotted in Figure 8 against $(V-K)_0$. The $\Sigma(W)$ values for the NGC 3201 stars define a tight sequence, and this indicates that there is no star-to-star variation in heavy element abundance among the giants in this cluster. Within the uncertainties, these $\Sigma(W)$ values are also consistent with those for the stars observed in M5 and NGC 6752, implying that the overall metal abundance of NGC 3201 is similar to that of these two clusters. The same result has been found by

[4] Because the resolution of the synthetic spectra (0.6 Å) is much higher than that of the observed spectra (5 Å), the values of W(G) derived from the synthetic spectra are not strictly comparable with the observed W(G) values. We assume however, that the *differences* in W(G) caused by changing the carbon abundance will be to first order, independent of the resolution of the spectra.

Zinn (1980*a*, *b*) who established an abundance ranking for globular clusters based on narrow band integrated photometry. In addition, Cacciari and Freeman (1980) have found that the Ca II line strengths of the NGC 3201 RR Lyraes are identical to those of the RR Lyraes in M5. Thus Figure 8, the results of Zinn (1980*a*, *b*), and those of Cacciari and Freeman (1980) are in agreement and indicate that the abundance of NGC 3201 is closely similar to those of M5 and NGC 6752. For these clusters Pilachowski, Wallerstein, and Leep (1980) (hereafter PWL) and Pilachowski, Sneden, and Canterna (1980) (hereafter PSC) have derived iron abundances from analyses of high dispersion echelle spectra. They find [Fe/H] $= -1.33 \pm 0.1$ for M5 and [Fe/H] $= -1.3 \pm 0.2$ for NGC 6752.

Another approach to the metallicity of NGC 3201 is via the location of the GB in a C-M diagram relative to that of other clusters, since aside from age differences, the giant branch location is dependent primarily on the heavy metal abundance. Lee (1977) has already noted the close similarity of the C-M diagrams of NGC 3201 and M3. This result is strengthened in Figure 1 because of the more direct relations between the observed quantities M_{K_0} and $(V - K)_0$ and the physical parameters M_{bol} and T_{eff} than between the latter two quantities and M_{V_0} and $(B - V)_0$. Thus, the implication of Figure 1 is that the [Fe/H] value for NGC 3201 must be the same or perhaps slightly less than that of M3 for which PWL give an abundance of [Fe/H] $= -1.55 \pm 0.1$. As before, this latter abundance is based on an analysis of high dispersion echelle spectra.[5] Thus the color-magnitude diagram implies an abundance for NGC 3201 slightly less than but not inconsistent with that derived above. The DDO photometry of Dawson (1980) is also consistent with his result.

Finally, we note that in a $(U - V)_0$, $(V - K)_0$ diagram (Fig. 3), the NGC 3201 stars are indistinguishable in location from stars in the metal-poor clusters M3, M13, and M92. As discussed in CFP and Frogel, Persson, and Cohen (1979), only for clusters significantly more metal rich than these three will line and molecular blanketing begin to affect the $(U - V)_0$ color and thus cause the stars to lie closer to the field or solar abundance line in Figure 3. In particular, stars in M71 and 47 Tuc (Frogel *et al.* 1979, 1981) lie between the two lines in Figure 3.

Thus we interpret the data discussed in this section as implying that the [Fe/H] value of NGC 3201 must be close to an average of those for the clusters M3, M5, and NGC 6752. In particular, it is worth emphasizing that none of the above data would allow NGC 3201 to be as metal rich as 47 Tuc for which Pilachowski, Canterna, and Wallerstein (1980) give [Fe/H] $= -1.2$. Hence our results contrast strongly with those of PSC who derived a preliminary abundance for NGC 3201 of [Fe/H] $= -1.0 \pm 0.2$, again based on echelle plates and an analysis similar to that used in deriving the other [Fe/H] values quoted above.[6]

The contrary nature of these results is disturbing. If the higher abundance for NGC 3201 derived from the echelle spectra is correct, then for the first time we have an example of a globular cluster in which the effective temperature of the giant branch is *not* determined primarily by the heavy element abundance but by some other parameter. If future work reveals the existence of more such clusters, then the interpretation of "abundance" indicators that are primarily determined by effective temperature, such as the strength of strong lines on low resolution spectra, integrated colors, or line strength indices, will become very difficult.

VII. SUMMARY

Observations of broad band *JHK* colors and narrow band CO and H_2O indices have been obtained for 26 giants in the field of the globular cluster NGC 3201. For 14 of these stars, optical spectra have also been obtained. From these observational data the following conclusions have been drawn:

1. In the infrared C-M diagram, the giant branch of this cluster shows an intrinsic width that is not due to photometric errors or questions of cluster membership. It was concluded that this intrinsic width is most likely caused by reddening variations across the cluster and not by a spread in heavy metal abundance.
2. There is considerable scatter in the CH strength indices for the NGC 3201 stars, and the CO indices show an unusual variation with temperature. At a given $(V - K)_0$, the variations in the two indices are correlated, which suggests that they are caused by a range in atmospheric carbon abundance among the stars. An upper limit of a factor of 3 to the size of this abundance range was derived.
3. The metal abundance of NGC 3201 is closely similar to an average of the values for M3, M5, and NGC 6752; we estimate [Fe/H] $= -1.4 \pm 0.2$. This metal abundance is significantly less than the preliminary value given by PSC from echelle data.

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[5] Cohen (1978) gives [Fe/H] $= -1.81$ for M3 also from an analysis of echelle plates. However, we prefer the PWL value here so that the echelle [Fe/H] values under discussion form a consistent set.

[6] It is unlikely that at least the conclusions based on Figures 1 and 3 can be affected by an uncertainty in the adopted value of the reddening. If the assumed value of $E(B - V)$ is increased beyond 0.28 in order to move the stars in Figure 3 closer to the metal-rich domain, the effect in Figure 1 will be just the opposite, namely the NGC 3201 stars would move closer to the M92 fiducial line. Thus yet another problem would be introduced. As matters stand now, the locations of NGC 3201 stars in Figures 1 and 3 are consistent with each other.

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