1982ApJ...255L..39C

THE ASTROPHYSICAL JOURNAL, 255:L39–L43, 1982 April 1
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WHAT IS THE SECOND PARAMETER?: THE ANOMALOUS GLOBULAR CLUSTER NGC 7006

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Received 1981 October 19; accepted 1981 December 9

ABSTRACT

An infrared color-magnitude diagram for NGC 7006 and moderate dispersion digital optical spectra of eight of its members indicate a metal abundance of −1.5 dex with respect to the Sun. However, the ratio of red to blue horizontal-branch stars is quite large and is what would be expected for a cluster of much higher metallicity. We have determined molecular band strengths for CO in four stars, and CH and CN in five stars, and find that none of these molecular bands are anomalously strong compared to the same molecular features in other globulars of similar metallicity but varying horizontal-branch type. This is contrary to the behavior predicted if the C, N, and O abundances are the "second parameter" needed to explain anomalous horizontal-branch morphologies.

Subject headings: clusters: globular — galaxies: Milky Way

I. INTRODUCTION

Although the remote, halo globular cluster NGC 7006 is moderately metal-poor, its horizontal branch consists almost entirely of red stars (Sandage and Wildey 1967), a situation generally observed only in clusters with a considerably higher metal abundance. Qualitatively similar, though less extreme, behavior is observed in other globulars as well. Hence, an apparent need arises for a physical parameter other than heavy metal abundance which could vary from cluster to cluster and affect the morphology of the horizontal branch (van den Bergh 1967).

Theoretical studies of horizontal-branch evolution (e.g., Rood 1973; Faulkner 1966; Castellani and Tornambé 1977; Simoda and Iben 1970) have pointed to four easy ways to vary the ratio of red to blue horizontal-branch stars in clusters of the same metallicity via changes in (1) the helium abundance; (2) the abundance of the CNO group of elements; (3) the age of the cluster; or (4) the mass loss rate of pre–horizontal-branch giants. Unfortunately, it is so easy to affect the relative numbers of red and blue horizontal-branch stars with any of these four parameters that it is difficult to decide which observations, if any, can be made with sufficient sensitivity to detect cluster-to-cluster differences in these parameters. Indeed, many of the observations that have been made cannot be interpreted in a clear and unambiguous manner (see Kraft 1979 for a recent review of the situation). Inter alia, Hartwick and McClure (1972), on the basis of observations of CN strengths, and Cohen, Frogel, and Persson (1978, hereafter CFP) and Pilachowski (1978), on the basis of observations of infrared CO absorption, suggested that the abundance of the CNO group of elements plays an important role in horizontal-branch morphology.

Because of the extreme character of the horizontal-branch morphology of NGC 7006, as discussed by Sandage and Wildey (1967), molecular band data for its stars could be particularly informative. Membership and metallicity information, as well as CH and CN indices, are deduced from a set of moderate dispersion optical spectra of eight stars in NGC 7006. In addition, CO observations of four members and broad-band *JHK* data for seven members have been obtained. These latter data provide an independent estimate of the metallicity of the cluster.

II. OBSERVATIONS AND PHYSICAL PARAMETERS

The infrared data presented in Table 1 were obtained with the Cerro Tololo Inter-American Observatory (CTIO) InSb detector system on the 4 m telescope between 1978 October and 1981 June. These data have been transformed to the photometric system of Frogel *et al.* (1978) and thus are directly comparable to all other globular cluster data which have been published by us.

[1]Cerro Tololo Inter-American Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under National Science Foundation contract AST 78-27879.

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TABLE 1

PHOTOMETRY OF NGC 7006

	Observed[b]			Reddening Corrected[c]								
Star[a]	K	$J-K$	$H-K$	K_0	$(B-V)_0$	$(V-K)_0$	$(J-K)_0$	$(H-K)_0$	CO	M_{bol}[d,e]	T_{eff}	Notes[f]
I-1	12.21	0.92	0.16	12.20	1.65	3.34	0.89	0.15	0.07	−3.31	4080	2
II-46	13.14(6)	0.86(5)	0.13(3)	13.13	1.33	3.10	0.83	0.12	0.055(3)	−2.48	4200	...
II-103	12.97	0.80	0.10	12.96	1.36	3.12	0.77	0.09	0.02	−2.66	4200	2
III-40	14.09(3)	0.74(3)	0.17	14.08	1.07	2.73	0.71	0.16	...	−1.70	4430	...
III-46	13.35(3)	0.72	0.11	13.34	1.19	2.60	0.69	0.10	...	−2.49	4540	3
V19	12.22(3)	0.85	0.15	12.21	1.67	3.14	0.82	0.14	0.035	−3.38	4200	1,2
V54	13.23(3)	0.69	0.11	13.22	1.30	2.48	0.66	0.10	...	−2.66	4660	1,2

[a] Identification numbers are from Sandage and Wildey 1967.

[b] Numbers in parenthesis are observational uncertainties in units of hundredths of a magnitude when greater than 2.

[c] A value of $E(B-V) = +0.05$ was used (Zinn 1980).

[d] $(M-M)_v = 18.12$ was used (Harris and Racine 1979).

[e] The bolometric correction scale of Frogel, Persson, and Cohen 1981 was used.

[f] Notes.—(1) Median values of V and $B-V$ as given by Sandage and Wildey were used. (2) Observed twice. Values agree to within stated uncertainties. (3) V magnitude determined as discussed in text.

Zinn (1980) and Searle and Zinn (1978) both determined an $E(B-V)$ of 0.05, and this value was adopted here. Magnitudes, colors, and indices appropriately corrected are given in Table 1. BV photometry is from Sandage and Wildey (1967). Star III-46 was found to have discrepant infrared and optical magnitudes. An obvious inconsistency can be seen between the V magnitude tabulated by Sandage and Wildey (1967) and the appearance of this star on their chart. We redetermined its V magnitude from direct SIT frames obtained on the 60 inch (1.5 m) telescope on Palomar Mountain and found $V = 16.08 \pm 0.08$ mag, which value we adopt.

Since for variable stars the range in K is generally one-quarter or less of the range in V, the $(V-K)_0$ values for V19 and V54 given in Table 1, which were formed from the median V values given by Sandage and Wildey, should be representative of the median colors for these stars.

Spectrophotometric scans of the NGC 7006 stars were made on the 5 m Hale telescope at Palomar Mountain and on the 2.1 m du Pont telescope of the Las Campanas Observatory. An intensified Reticon linear array constructed by S. Shectman was used with a spectrograph which gave a resolution of 2 Å at each observatory. Members of other well-studied galactic globular clusters were observed on the same nights and with the same instrumental configurations. On these scans, we measured indices delineating the strength of the absorption of CN near 4200 Å and of CH in the G band:

$$I(\mathrm{CH}) = 1 - \frac{\mathcal{F}(c;\ 4290\text{–}4320\ \text{Å})}{\frac{1}{2}\left[\mathcal{F}(c;\ 4350\text{–}4370\ \text{Å}) + \mathcal{F}(c;\ 4235\text{–}4270\ \text{Å})\right]},$$

and

$$I(\mathrm{CN}) = 1 - \frac{\mathcal{F}(c;\ 4160\text{–}4210\ \text{Å})}{\frac{1}{2}\left[\mathcal{F}(c;\ 4115\text{–}4130\ \text{Å}) + \mathcal{F}(c;\ 4235\text{–}4270\ \text{Å})\right]},$$

where $c(p)$ is the count rate/pixel after sky subtraction and removal of pixel-to-pixel variations. The symbol $\mathcal{F}$ denotes the mean value of $c(p)$ over the indicated wavelength range, and the bandpasses are shifted according to the radial velocity of the globular cluster.

In Table 2 we list the measured CH and CN indices for the NGC 7006 stars. We also list ΣW, the sum of the

TABLE 2

OPTICAL DATA FOR NGC 7006 STARS

Star	I(CH) (%)	I(CN) (%)	ΣW (Å)	V_r[a,b] (km s^{-1})
I-1	...	...	7.7	−391
II-46	0.19	0.06	...	−329
II-93[c] ...	0.19	0.00	...	−344
II-103 ...	0.18	0.05	...	−341
III-40 ...	0.16	−0.03	...	−370
III-46 ...	0.19	−0.03	...	−387
V19.....	...	...	7.7	−351
V54.....	...	...	5.2	−360

[a] Heliocentric radial velocities (±25 km s^{-1}) obtained by cross-correlating scans with similar scans of other globular cluster giants.

[b] Nonmembers ($V_r > -160$ km s^{-1}): III-1, III-5, and III-51.

[c] $(V-K)_0$ assumed to be 3.1 on the basis of V, $B-V$. Infrared photometry impossible due to crowding.

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equivalent widths of several strong metallic absorption lines as defined by Cohen *et al.* (1980). All the stars listed in Table 2 are confirmed radial velocity members of this globular cluster.

III. THE ABUNDANCE RANKING OF NGC 7006

Sandage and Wildey (1967) initially placed NGC 7006 in a group of clusters with intermediate metallicity, e.g., M3 and M13, on the basis of the height of the giant branch above the level of the horizontal branch. More quantitative *relative* estimates of the metallicities of these three clusters by Hesser, Hartwick, and McClure (1977), Searle and Zinn (1978), and Zinn (1980) agree that in the mean the [Fe/H] of NGC 7006 is -1.5 dex, within ± 0.1 dex of that of M3 and M13.

There are, however, two discrepant abundance determinations. Canterna (1975) has found an [Fe/H] for NGC 7006 which is 0.6 dex less than that for M3. However, abundances based on the C, M, T_1, T_2 system generally show considerable scatter when compared with other ranking schemes, e.g., Searle and Zinn (1978), Zinn (1980); so this low value for NGC 7006 will not be considered further. McClure and Hesser (1981) have also derived a very low abundance for NGC 7006 based on indices measuring the absorption in the H and K lines of Ca II and DDO colors synthesized from a set of low-dispersion spectra. Both the H and K line indices, which use only a continuum interval longward of the absorption feature, and the synthesized DDO colors may be affected by a systematic difference noted by them in the slope of the continuum below 4300 Å between the NGC 7006 stars and the comparison globular cluster giants in M2.

Our Las Campanas spectra cover the region 4800–6000 Å. From them, we compute the index ΣW defined by Cohen *et al.* (1980), although, because of the higher dispersion of the NGC 7006 spectra, the scale will not be the same as that of the ΣW values in the reference cited. We plot in Figure 1 ΣW versus $(V-K)_0$ for 3 stars in NGC 7006, 15 stars in 47 Tuc, and 9 members of NGC 3201, where all spectra were taken with an identical instrumental configuration. Data for the two comparison globular clusters are from Cohen (1982). The metallicity of NGC 7006 is slightly above that of NGC 3201, determined by Da Costa, Frogel, and Cohen (1981) to be close to that of M3 and significantly below that of 47 Tuc. The Palomar spectra of 5 stars in NGC 7006 cover the region 3800–4900 Å and support this statement.

Based on a feature-by-feature comparison of both sets of spectra with stars in well-studied galactic clusters and on the globular metallicity scale of Cohen (1982), we assign NGC 7006 a metallicity of -1.5 dex. This is in good agreement with that given by the three previous reliable photometric determinations (Hesser, Hartwick, and McClure 1977; Searle and Zinn 1978; Zinn 1980).

Figure 2 is a $[K_0, (V-K)_0]$-diagram for the NGC 7006 giants from Table 1. The fact that four of the five nonvariable giants observed lie close to the M3 giant branch in Figure 2 (and, hence, in a log $[T_e, M_{bol}]$-plot as well), supports our spectroscopic determination of -1.5 dex, i.e., close to that of M3 and M13 (the M13 branch lies quite close to that of M3; cf. Table 7 of Frogel, Persson, and Cohen 1981, hereafter FPC) on the basis of physical arguments presented in CFP and FPC. The possibility that NGC 7006 is on the order of 10^9 yr younger than the other globulars (Searle and Zinn 1978)

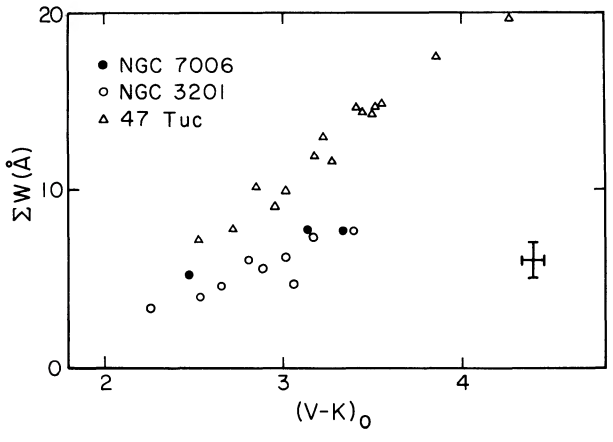

FIG. 1.—ΣW as a function of $(V-K)_0$ is shown for three members of NGC 7006, 15 giants in 47 Tuc, and 9 members of NGC 3201. The data for 47 Tuc and NGC 3201 are from Cohen (1982). The errors typical of each point are indicated.

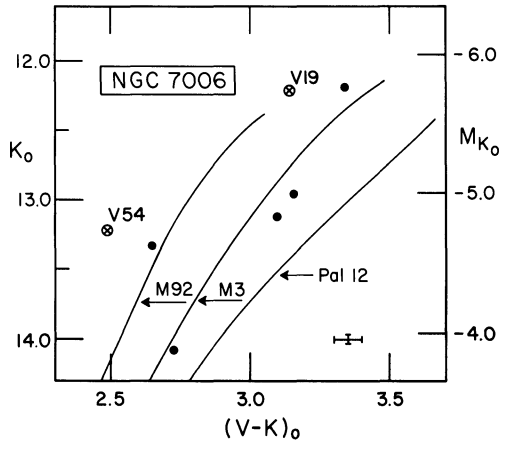

FIG. 2.—A color-magnitude diagram for stars observed in NGC 7006. The two red variables are indicated by crosses inside circles. Fiducial giant branches for three other clusters are shown (data from CFP; Cohen *et al.* 1980; Frogel, Persson, and Cohen 1981).

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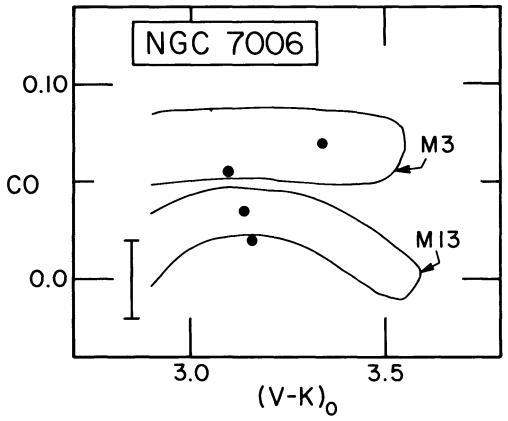

FIG. 3.—The CO indices for four giants in NGC 7006 as a function of $(V-K)_0$. The areas labeled M3 and M13 encompass all stars observed in those clusters with $(V-K)_0 > 2.9$ (CFP).

does not affect this conclusion (cf. the tracks of Ciardullo and Demarque 1977 and the $(V-K)_0, T_{\rm eff}$ calibration of CFP). A lower helium abundance for NGC 7006 as compared to other globulars, as proposed by Sandage and Wildey (1967), would have the effect of shifting the giant branch redward by only 0.05 mag in $(V-K)_0$ for ΔY of 0.05.

IV. MOLECULAR ABSORPTION

Observations of CO absorption in the giants of M3 and M13 by CFP and of these two clusters and M5 and M10 by Pilachowski (1978) led these authors to tentatively conclude that [CNO/Fe] is the second parameter which determines horizontal-branch morphology; stars in the two clusters with red horizontal branches were observed to have CO absorption significantly stronger than in the two clusters with predominantly blue horizontal branches. Since NGC 7006 seems to have a metallicity comparable to that of the mean of these four clusters, and since the ratio of red to blue horizontal-branch stars in NGC 7006 is greater than that of the other four, one might expect that the giants of this cluster would have strong CO absorption. Figure 3 shows that this is not the case—*the data indicate that the mean value of the CO indices of the NGC 7006 giants is intermediate to that of M3 and M13.*

Figures 4*a* and 4*b* show our measured CH and CN indices for five stars in NGC 7006 as a function of $(V-K)_0$. Data for stars in M15, NGC 3201, and NGC 288 (Cohen 1982; Frogel, Cohen, and Persson 1982; Da Costa, Frogel, and Cohen 1981) are also shown. NGC 3201 is a cluster with about equal numbers of red and blue horizontal-branch stars and a metallicity comparable to that of NGC 7006 (Da Costa, Frogel, and Cohen 1981). NGC 288 has a horizontal branch consisting almost entirely of blue stars and a metallicity only slightly greater than that of NGC 7006 (Cohen 1982; Frogel, Cohen, and Persson 1982). The CO strengths for the NGC 7006 stars are quite similar to those for stars in NGC 288 and NGC 3201 of the same $(V-K)_0$. Figures 4*a* and 4*b* clearly show that the CH and CN band strengths of the NGC 7006 stars are also not strong relative to those in NGC 288 and NGC 3201; if anything, the band strengths are somewhat weaker in NGC 7006 than in the former two clusters. This is consistent with Cowley, Hartwick, and Sargent's (1978) qualitative description of NGC 7006 as having "inter-

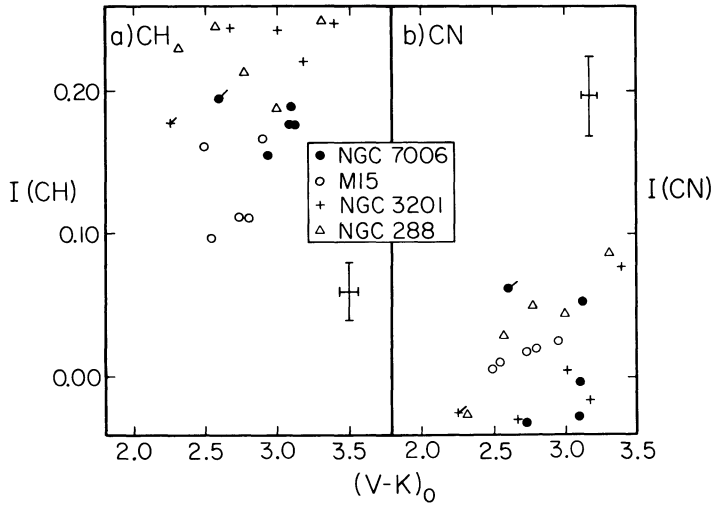

FIG. 4.—(*a*) CH indices and (*b*) CN indices for five stars in NGC 7006 are shown as a function of $(V-K)_0$. Comparison data for stars in M15, NGC 3201, and NGC 288 from Frogel, Cohen, and Persson (1982) are also displayed. The errors typical of each point are indicated. The two stars known not to be first ascent red giants are indicated by short diagonal lines.

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mediate metals and CN with strong CH" when one realizes, as shown in Figure 4, that CH becomes strong in all but the most metal-poor clusters.

In summary, NGC 7006 is a moderately metal-poor cluster with perhaps the reddest horizontal branch for its metallicity class. Our determination of the strengths of CO, CH, and CN absorption bands show that they are not strong when compared with those observed in giant stars in clusters of similar metallicities with quite different horizontal-branch morphologies. Thus, for this cluster, as for ω Centauri (Persson *et al.* 1980), there is no evidence from the available data that the abundances of C, N, and O are the long-sought second parameter.

We thank Jay Elias for assistance in obtaining some of these data and Ann Rosenthal for assistance in reducing the SIT frames. J. G. C. is grateful for time allocated on the du Pont telescope of the Mount Wilson and Las Campanas Observatory.

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