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CYANOGEN STRENGTHS OF GLOBULAR CLUSTER POST–MAIN-SEQUENCE STARS

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ABSTRACT

CN strengths in the peculiar clusters ω Cen and M22 and the metal-rich clusters 47 Tuc, M71, and NGC 6352 are found to vary markedly from star to star. The strong variations in CN strength found earlier for ω Cen by Norris and Bessell and by Dickens and Bell are shown to extend to fainter stars, although expected correlations of CN strength with position in the color-magnitude (C-M) diagram are less evident in our sample. Several CN and metal-strong stars were also observed in M22. We conclude that CN, once it appears in globular clusters, can vary much more than it does in equivalent Population I samples, a result we briefly examine in light of current understanding regarding physical processes in the stars themselves and of models of galactic chemical evolution.

Subject headings: clusters: globular — stars: abundances

I. INTRODUCTION AND OBSERVATIONS

Globular cluster stars provide a unique probe of the chemical content of the galactic halo, and thereby a key element in the evaluation of theoretical models of chemical evolution in the Galaxy. Over the past few years independent programs at the Cerro Tololo and Hale Observatories have provided photoelectric photometry on the David Dunlap Observatory (DDO) intermediate-band system (McClure 1976) of post–main-sequence stars in 17 globular clusters. Details of the work are being prepared for publication, but some results of immediate impact on currently active areas of cluster and galactic evolution research warrant separate discussion. In particular, we will compare the CN strengths of giant stars in metal-poor (M92, M13, M3), metal-rich (47 Tuc, M71, NGC 6352), and peculiar[1] (ω Cen, M22) globular clusters with those for Population I stars.

NGC 104 (47 Tuc), NGC 5139 (ω Cen), NGC 6352, and NGC 6656 (M22) were observed with DDO filters and a variety of pulse-counting photometric instrumentation (single- and dual-channel) on the 0.9 and 1.5 m telescopes at CTIO. The observations were transformed to the equatorial DDO system (McClure 1976), and consistency with previous Population II studies was checked by independently measuring M5 and M10 giants studied by Osborn (1973). DDO indices for stars in NGC 6341 (M92), M22, and NGC 6838 (M71) were synthesized from observations obtained with the multi-channel scanner (Oke 1969) on the 5 m Hale telescope; both Osborn's (1973) Population II stars and the new equatorial standards (McClure 1976) were used for the transformations. No difficulties were encountered in transforming the scanner measures to the filter-defined DDO system. Observations were made with diaphragm sizes between 9″ and 13″, depending upon the seeing and zenith distance, and sky measurements were made in at least two independent nearby locations. The great majority of the stars discussed here have observations on two or more nights, and we estimate the indices plotted here to have a precision in the means of ∼2 percent. Various consistency checks provide assurance that the northern and southern hemisphere observations are on the same system. Photoelectric B, V measurements have been obtained for all stars observed at Tololo.

The DDO cluster observations were corrected for reddening as follows: 47 Tuc (0.03 mag; Hesser and Philip 1976); ω Cen (0.11 mag; Cannon and Stobie 1973; Norris and Bessell (1975) and Bessell and Norris (1976), hereafter collectively referred to as NB); NGC 6352 (0.23 mag; Hesser 1976); M71 (0.31 mag; Arp and Hartwick 1971); M92 (0.02 mag; Sandage 1970); M22 (0.34 mag; Hesser 1976).[2] The relation $E(B - V)_{\mathrm{Red\ Giant}} =$

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[1] Omega Centauri has been shown to have abnormally broad sequences in the C-M diagram (Woolley 1966; Cannon and Stobie 1973; Cannon and Kontizas 1974); M22 has a gently sloping giant branch that is usually characteristic of high metals, even though most of the horizontal-branch stars are blue (Butler *et al.* 1974).

[2] Photoelectric B, V photometry of 16 giants by Eggen (1972) and 24 by us indicate that the *slope* of the M22 giant branch

$0.94E\ (B-V)_{\text{Blue Star}}$ was used to convert the listed blue-star reddenings to those appropriate for red giants.

II. RESULTS AND DISCUSSION

The principal finding to be discussed here is that CN strengths can apparently vary much more widely among evolved stars of a globular cluster, even for those occupying a small region of the $(V, B-V)$-plane, than they do for evolved stars in open clusters or for field stars of a given metal abundance [as measured by $\delta(U-B)$]. This result may best be appreciated in the form of $C(41-42)_0 - C(45-48)_0$ and schematic C-M diagrams for the globulars observed (Fig. 1). The CN strengths measured by $C(41-42)$ are somewhat gravity-dependent, but gravity effects are minimal over a significant portion of this diagram, as shown by the normal lines for Population I stars. For ω Cen and 47 Tuc we have also plotted stars observed by Bessell and Norris (1976) and McClure and Osborn (1974), respectively. The present observations of ω Cen are of a nearly independent region of the C-M diagram from that studied by NB. In the case of 47 Tuc, the average cyanogen anomaly (Janes 1972), $\langle\delta(\text{CN})\rangle$, is $-0.081 \pm$

does not differ greatly from that found by Arp and Melbourne (1959), a conclusion in accord both with the latest photographic photometry (Evans 1975, Fig. 2) and with the contention (Butler *et al.* 1973) that it is a peculiar cluster (see n. 1).

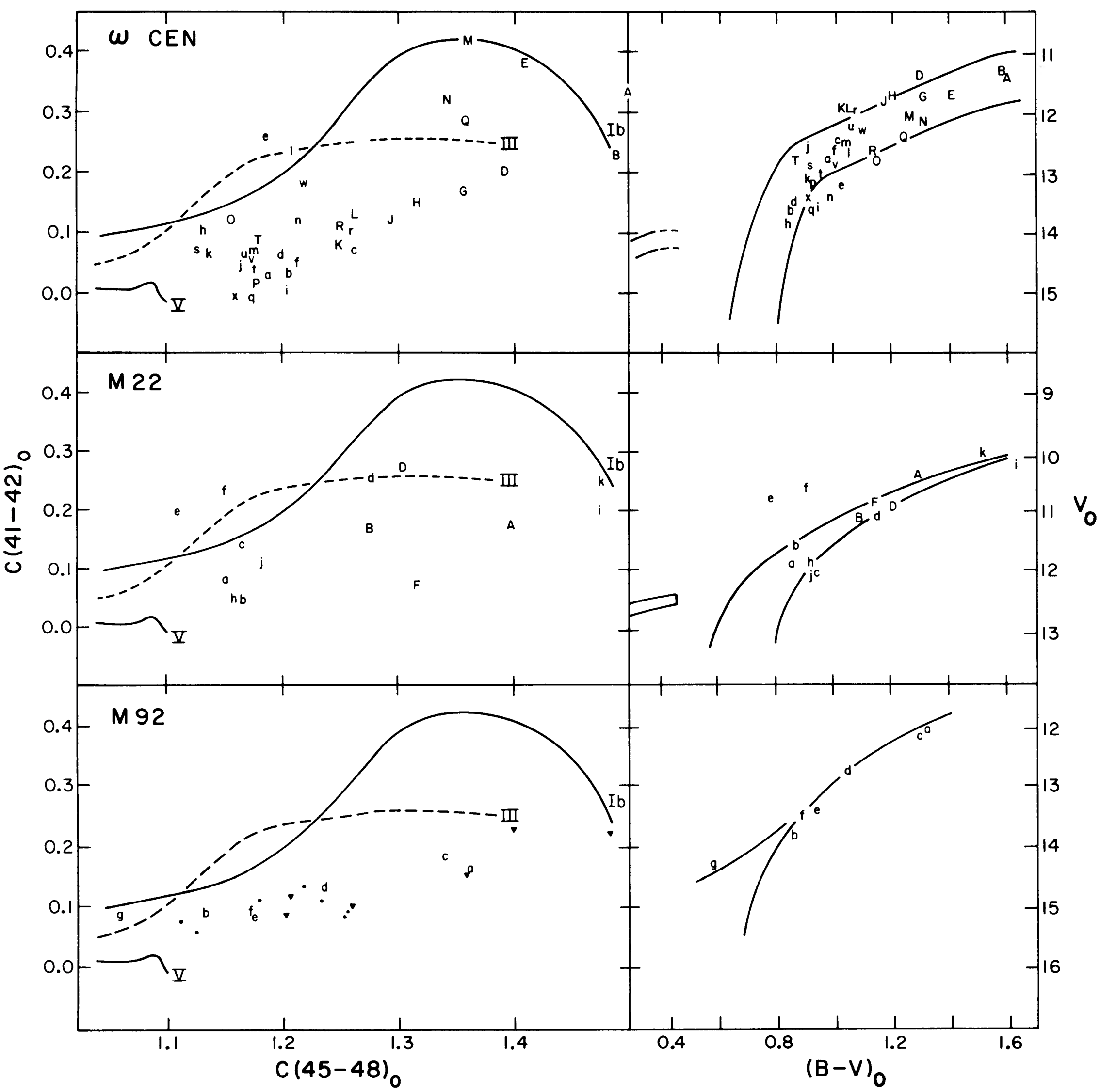

FIG. 1.—The same symbols are used to plot stars in both the $C(41-42)_0 - C(45-48)_0$ (predominantly CN strength versus T_{eff}) and the schematic C-M diagrams for six globular clusters; the most recent photoelectric V, $B-V$ values are used for the C-M diagrams. Minuscule letters in 47 Tuc represent stars from Hartwick and Hesser (1974) and Hesser and Hartwick (1976), while capital letters are stars from McClure and Osborn (1974). Observed stars in NGC 6352, M22, M71, and M92 are from the C-M studies of Hartwick and Hesser (1972), Arp and Melbourne (1959), Arp and Hartwick (1971), and Sandage and Walker (1966), respectively; additional points on the M92 DDO but not its C-M diagram are giants in the metal-poor clusters M3 (▽) and M13 (•). The ω Cen stars (Geyer 1967; Woolley 1966) typically lie 12′ from the cluster center; capital letters are stars from Bessell and Norris (1976).

0.078 and -0.074 ± 0.064 mag in the new and the McClure and Osborn observations, respectively. Stars of the metal-poor ([Fe/H] < -1.5) clusters M92, M13, and M3 (Osborn 1973; Butler 1975; Canterna 1975) define a narrow, CN-poor locus, while the stars of the peculiar clusters ω Cen and M22 display CN strengths ranging from those characteristic of stars as metal-deficient as any galactic Population II stars to those as metal-enriched as ordinary disk stars. In addition, the available data suggest that CN strengths scatter widely for stars of the metal-rich clusters 47 Tuc, M71, and NGC 6352.[3] It has been noted previously that intermediate-metal-abundance clusters like M5 (Osborn 1973) and NGC 362 (McClure and Norris 1974) also

[3] Note added in proof.—Bell, Dickens, and Gustafsson (1975) have obtained spectra of 47 Tuc giants that also show the existence of CN strength variations; they suggest that nitrogen enhancement of a factor of 10 may be responsible in some cases.

show CN strength variations in excess of observational errors. The impression we receive from all these data is that for the most metal-poor clusters very little CN is observed, but for clusters that are sufficiently metal-rich to have significant CN absorption present, the CN strengths can vary widely from star to star. In addition, the DDO data for the ultraviolet spectral region indicate that the peculiar clusters ω Cen and M22 are exhibiting large variations from star to star in overall metal abundances that the other clusters with widely varying CN strengths do not show.

The strikingly different behavior of CN strengths in either the metal-enriched or peculiar globulars from that of Population I stars is emphasized by Figure 2*a*, where we plot the $C(41-42)_0 - C(45-48)_0$ diagram for field stars (selected from the catalogs of Hansen and Kjaergaard 1971 and Janes 1972) having $-0.6 \geq$ [Fe/H] ≥ -0.8, i.e., similar to 47 Tuc; and Figure 2*b* for

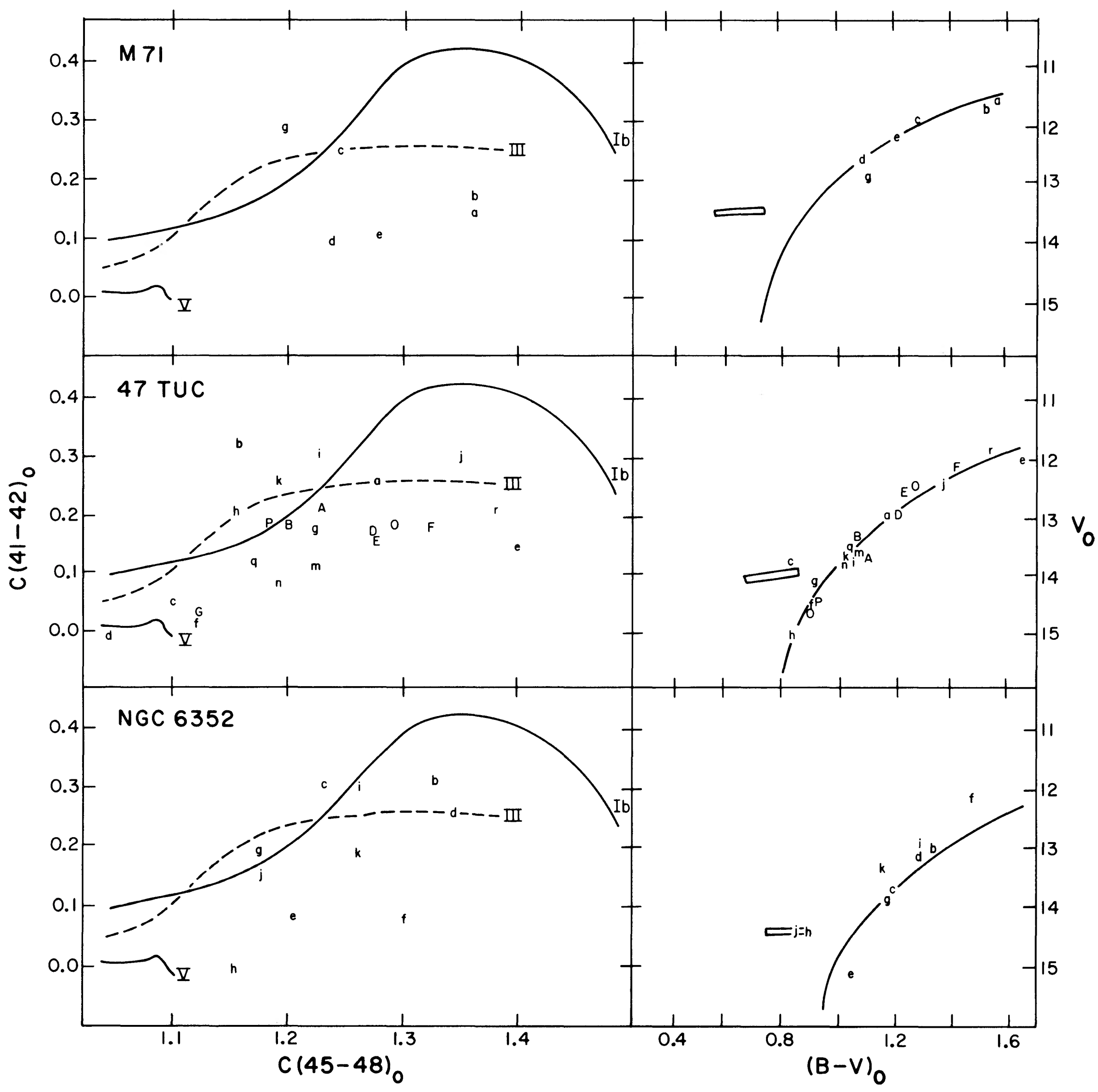

FIG. 1.—*Continued*

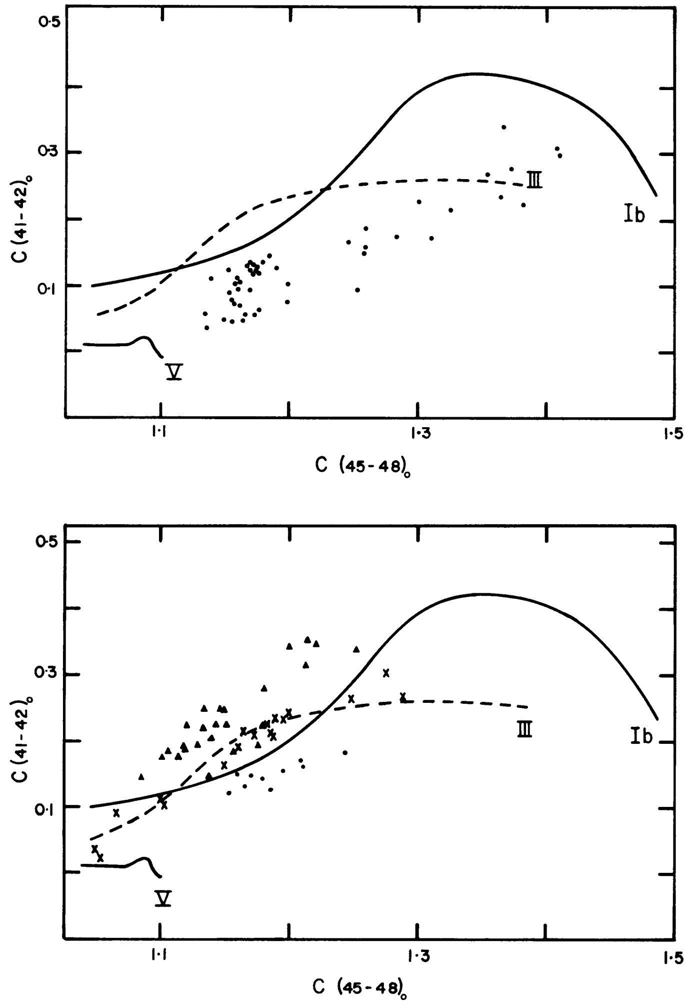

FIG. 2.—The same CN diagram as Fig. 1 for (*a*) field stars of the same [Fe/H] as 47 Tuc, and (*b*) stars from the metal-poor open cluster NGC 2420 (•) the old disk cluster M67 (×), and the CN-rich intermediate-age cluster NGC 2477 (△).

stars in the metal-poor open cluster NGC 2420, whose $\langle\delta(\mathrm{CN})\rangle$ and $\langle\delta(U-B)\rangle$ are approximately equal to that of 47 Tuc (McClure, Forrester, and Gibson 1974; Demarque and McClure 1976), the CN-rich intermediate-age cluster NGC 2477 (Hartwick, Hesser, and McClure 1972), and M67 (Janes 1974). Clearly, the open cluster and field stars define sharper loci in this diagram than do the 47 Tuc stars.

Inspection of the spectral scans (Hartwick and McClure 1976) suggests that CN strengths can vary independently from those of other metals in the 3800 Å region. Freeman and Rodgers (1975) and NB have emphasized that stars in an advanced evolutionary stage in ω Cen may be manifesting effects of (i) primordial abundance gradients due to successive generations of star formation, and/or (ii) mixing of internally produced elements to the stellar surface. While our data generally complement and extend the findings of NB, a tendency they found for stars with the reddest $B-V$ colors (presumably the most metal-rich) to have the largest CN strengths does not persist clearly into the lower-luminosity region sampled by our measures. Whether this is the result of some unappreciated observational errors or of physical processes in the stars themselves cannot be resolved without further observations. Somewhat similar behavior is manifested by the stars of M22, where background subtraction difficulties *may* be affecting the results somewhat more than for the other clusters.[4]

The most important suggestion of this work is that not all stars with the same (M_V, $B-V$) values in a

[4] It is curious to note that the average $\delta(\mathrm{CN})_{\mathrm{M22}}$ for the stars observed at Tololo, -0.10 ± 0.13 mag, if taken at face value would imply a metal-abundance [Fe/H] ~ -0.6 (or, if two stars are eliminated, -0.9), consistent with the observation of a gently sloped giant branch. However, the stars selected for observation at Hale, which tended to lie somewhat higher up the M22 giant branch, yielded a higher percentage of metal-poor stars, in agreement with the findings of Canterna (1975; $[\mathrm{Fe/H}]_{\mathrm{M22}} = -2.0$ from broad-band colors of the giants) and Butler (1975; $[\mathrm{Fe/H}]_{\mathrm{M22}} = -1.7$ from spectroscopy of the RR Lyrae stars). Finally, for completeness we note from Arp (1959, Fig. 1) that the giant branch of M22 must be almost devoid of field stars.

cluster necessarily have had identical chemical and/or structural histories. Perhaps CN strength variations could in part be due to differing angular momenta of individual stars at formation being carried over into mixing or other processes at later evolutionary stages. Zinn (1973*a*) has also pointed out that scatter might be explained if the C/O ratio in a cluster hovers about a critical value (near unity), so that small perturbations due to mixing or primordial inhomogenieties might nonlinearly amplify (Schadee 1968) the amount of CN present in the atmosphere.

Overall abundance ratio differences between field and nuclear bulge stars have been implicit in many past discussions of galactic evolution (Schwarzschild and Spitzer 1953; Schmidt 1963; Truran and Cameron 1970, among others). However, two important new results seem consistent with the idea that the chemical abundance ratios (or at least those involving C,N, and O) in the material from which the metal-rich globular clusters formed might have differed significantly from those of the material from which the Population I stars (for which CN photometry is available) formed. Harris (1976) and Woltjer (1975) have shown that irrespective of [Fe/H] the space-density distribution functions for galactic globulars are spherically distributed with respect to the galactic center; that is to say, there are not halo and disk globulars, but rather halo and nuclear-bulge globulars. Harris has also shown that near the galactic center, clusters of widely differing metal abundance all occur with roughly equal frequencies, consistent with the view that the matter from which they formed was not necessarily well mixed (e.g., Hartwick and McClure 1976). A natural consequence of Larson's (1976) hydrodynamical calculations for the formation of spiral galaxies is that lines of constant heavy-element abundance as a function of distance from the galactic center need not imply constant element abundance ratios. Stars and clusters of the nuclear bulge population would have been formed predominantly from remnants of gas that had been processed through a very rapid phase of enrichment by massive (or supermassive) stars. At greater distances from the center, the star-forming material would have been principally enriched by a much slower phase of star formation, where ejecta from low-mass stars assume greater importance. While highly speculative at this stage, a solution along the above lines might be consistent not only with the erratic CN strengths found here but also with the observation (Hartwick and Hesser 1972*a*,*b*, 1973; Demarque and McClure 1976) that the C-M diagrams of metal-rich globular clusters are not congruent with those of the oldest disk clusters.

Clearly, recent work on globular clusters with C-M diagrams as "simple" as that of M92 (Zinn 1973*a*, *b;* Auer and Demarque 1976) or as unusual as that of ω Cen (Freeman and Rodgers 1975; NB; Dickens and Bell 1976) has amply demonstrated that the physical interpretation of the observed phenomena in post–main-sequence globular cluster stars is very complicated and raises some disconcerting doubts about interpretations of C-M diagrams, main-sequence fitting techniques, etc. Broadly based observational attacks emphasizing spectra and precision photometry for statistically significant samples of stars in a small number of clusters would appear to be among the best avenues for improvement in our understanding of the evolution of Population II stars, and consequently of the chemical evolution of the galactic halo.

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