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CORRELATED CYANOGEN AND SODIUM ANOMALIES IN THE GLOBULAR CLUSTERS 47 Tuc AND NGC 6752

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ABSTRACT

Spectroscopic analyses have been made of echelle plates of pairs of CN-strong and CN-weak giants in the globular clusters 47 Tuc and NGC 6752. Our differential analysis reveals that in NGC 6752 sodium and aluminum are enhanced in the CN-strong stars by approximately 0.5 dex and 0.2 dex, respectively. All other elements studied (Mg, Si, Ca, Fe, and Ba) appear to have identical abundances in the two groups of stars. In 47 Tuc, only sodium shows any enhancement (by ~0.4 dex) in the CN-strong stars.

Since sodium and aluminum are not produced during the evolution of low-mass stars, these abundance enhancements in the CN-strong stars cannot be due to mixing. They must be primordial in origin and indicate that each protocluster gas cloud was not homogeneous during the epoch of low-mass star formation. A process by which both the sodium and cyanogen anomalies might be produced is described.

Subject headings: clusters: globular — stars: abundances — nucleosynthesis — stars: evolution

I. INTRODUCTION

In recent years it has become increasingly evident that within most globular clusters the evolved stars are not chemically homogeneous. With the exception of ω Cen where the Fe peak elements show a large abundance spread (Freeman and Rodgers 1975; Cohen 1980), the abundance anomalies appear in general to be restricted to the elements carbon, nitrogen, and oxygen. This suggests that the mixing of CNO–processed material into the surface layers is responsible for the abundance variations (see the review articles of Kraft 1979; McClure 1979). Recently Cohen (1978) and Peterson (1980) have shown that the abundances of other elements, in particular sodium, can show large star-to-star variations within one cluster, even though the abundances of the iron peak elements are apparently constant. Since sodium is not produced during the evolution of these low-mass stars, such variations must have existed in the protocluster gas cloud. It is unclear, however, whether these sodium abundance anomalies are related to those of carbon and nitrogen, since the abundances of these elements were not determined.

The purpose of this investigation was to provide further insight into these problems by seeking correlations, if any, between the CN variations and the abundances of the heavier elements. The southern globular clusters 47 Tuc and NGC 6752 provide ideal program objects since the distribution of CN band strength on the giant branch in these clusters is bimodal (Norris and Freeman 1979, Norris *et al.* 1981), i.e., stars are either "CN-strong" or "CN-weak." In addition, Norris *et al.* (1981) have already shown that in NGC 6752 the resonance lines of aluminum are systematically stronger in the CN-strong stars. The location of these lines in the wings of Ca II H and K precluded any abundance determination.

Our basic results are that in NGC 6752 the CN-strong stars not only have enhanced aluminum (by ~0.2 dex) but also enhanced sodium (by ~0.5 dex) when the weak lines of these elements were analyzed. In 47 Tuc, there is a sodium enhancement of approximately 0.4 dex in the CN-strong stars but no aluminum abundance variation was detected. None of the other elements studied vary between the two groups of stars in either cluster.

II. SPECTROSCOPIC OBSERVATIONS AND ABUNDANCE ANALYSIS TECHNIQUES

To minimize differences in effective temperature (T_{eff}) and gravity (log g), pairs of CN-strong and CN-weak stars with similar colors and magnitudes were chosen as program objects from the lists of Norris and Freeman (1979) and Norris *et al.* (1981). Three pairs of stars on the red-giant branch in NGC 6752 and two pairs of stars at the giant branch tip in 47 Tuc were observed with the 4 m echelle spectrograph at Cerro Tololo. At least two plates of each star were acquired. The plates were then traced with the PDS microdensitometer at Kitt Peak and reduced with the Kitt Peak FSTSCN program.

Elemental abundances of O, Na, Mg, Al, Si, Ca, Fe,

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and Ba were derived using the measured equivalent widths, interpolated models from the grid of Bell *et al.* (1976), and the line analysis program LINES (Sneden 1973). A microturbulent velocity of 2 km s^{-1} was assumed throughout the analysis. The *gf*-values came from Dominy (1980) for Fe I and Cohen (1978) for all other species. However, their absolute values were not a significant factor in the present analysis since we were principally concerned with *differential* effects between stars of similar $T_{\rm eff}$, log *g*, and [Fe/H]. A more detailed analysis to derive absolute abundances is being undertaken at present.

The effective temperatures of the 47 Tuc stars were obtained from their $(V - K)_0$ colors (Frogel, Persson, and Cohen 1981), while for NGC 6752, $(R - I)_0$ or $(B - V)_0$ colors were used if $(V - K)_0$ colors were not available (see Norris *et al.* 1981). Gravities were derived by assuming a mass of 0.8 $M_\odot$ and distance moduli of 13.03 (Hartwick and Hesser 1974) for 47 Tuc and 13.20 (Newell and Sadler 1978) for NGC 6752. Bolometric magnitudes came from Frogel *et al.* (1981) for the stars with infrared photometry, otherwise bolometric corrections from Bell and Gustaffson (1978) were used. The adopted atmospheric parameters for each star are given in Table 1. From our preliminary analysis these values are adequate to ±100 K in $T_{\rm eff}$, ±0.3 dex in log *g*, and ±1 km s^{-1} in microturbulent velocity.

III. ABUNDANCE RESULTS

Using the parameters in Table 1 and our equivalent width measures, we derived differential logarithmic abundances,

$$\Delta X = X_{\rm CN\text{-}strong} - X_{\rm CN\text{-}weak}\,,$$

where X is the logarithmic abundance of one of the elements analyzed. The values of ΔX are given in Table 2, where for each cluster the results for all the CN-strong and CN-weak stars have been averaged. The uncertainty in these tabulated values is ±0.1 dex, except in the case of abundance determinations based on one or two lines, where the error is ±0.3 dex.

To illustrate these abundance results we have plotted the equivalent widths for a CN-strong star against those for the same lines in the corresponding CN-weak star. For NGC 6752 we display (Fig. 1) the results for stars A8 and A3, while the 47 Tuc stars 5312 and 5309 are plotted in Figure 2. The increased strength of the Na lines in each CN-strong star is particularly evident.

TABLE 1

ATMOSPHERIC PARAMETERS

Cluster	CN-weak/ CN-strong	$T_{\rm eff}$	log *g*	Bol. Corr.
47 Tuc......	4418/3501	4000	1.0	−0.9
	5309/5312	4000	1.0	−0.9
NGC 6752...	CL1066/CS3	4250	0.9	−0.7
	A3/A8	4400	1.2	−0.6
	A30/CS118	4550	1.3	−0.5

NOTE.—Star numbers are from Lee 1977 for 47 Tuc; and Alcaino 1972, Cannon and Stobie 1973, and Cannon and Lee 1976 for NGC 6752.

TABLE 2

LOGARITHMIC ABUNDANCE DIFFERENCES

	ΔX	
X	47 Tuc	NGC 6752
Fe/H......	0.0	0.0
O/Fe......	−0.1[a]	[b]
Na/Fe.....	+0.4,[c] +0.3[d]	+0.5,[c] +0.4[d]
Mg/Fe.....	+0.1[a]	0.0[a]
Al/Fe......	−0.1[a]	+0.2[a]
Si/Fe......	+0.1	−0.1
Ca/Fe.....	0.0	0.0
Ba/Fe.....	−0.1[a]	0.0[a]

[a] Based on one or two lines per star.

[b] Not determined because stellar features contaminated by night-sky emission.

[c] Using D lines.

[d] Using χ = 2.1 eV lines.

For NGC 6752 our analysis shows that there is a significant enhancement of sodium and a smaller enhancement of aluminum in the CN-strong stars. The reality of the positive ΔX for aluminum is supported by the observations of Norris *et al.* (1981), who showed that the resonance lines of this element are also stronger in the CN-strong stars. All of the other elements studied appear to have the same abundances in both groups of stars to within the uncertainties of the determinations.

Sodium is also enhanced in the CN-strong stars in 47 Tuc, but there appears to be no corresponding enrichment of aluminum nor of any of the other elements studied. Additional support for the null aluminum difference is provided by the unpublished observations of Da Costa, which show that the Al resonance lines have similar strengths in CN-strong and CN-weak stars. Similarly, the lack of any significant magnesium abundance difference in either cluster is supported by the results of Norris (1978) and Norris *et al.* (1981), which indicated that the Mg *b*-lines have comparable strengths in both groups of stars.

The above results appear to be free from non–LTE effects, which have been discussed extensively by both Cohen (1978) and Peterson (1980). In particular, our selection of pairs of stars with similar atmospheric characteristics seems to ensure that, apart from any obscure atmospheric phenomenon, the abundance differences revealed in this work are real and correlated with cyanogen strength.

One other result of this analysis is that, in agreement with another abundance analysis of 47 Tuc stars (Pilachowski, Canterna, and Wallerstein 1980), we find that the [Fe/H] values for the individual stars are approximately −1.0 (cf. −0.4 to −0.6 from previous studies).

IV. IMPLICATIONS OF THE ABUNDANCE CORRELATIONS

The enhancement of nitrogen and the depletion of carbon in the CN-strong stars in these and other

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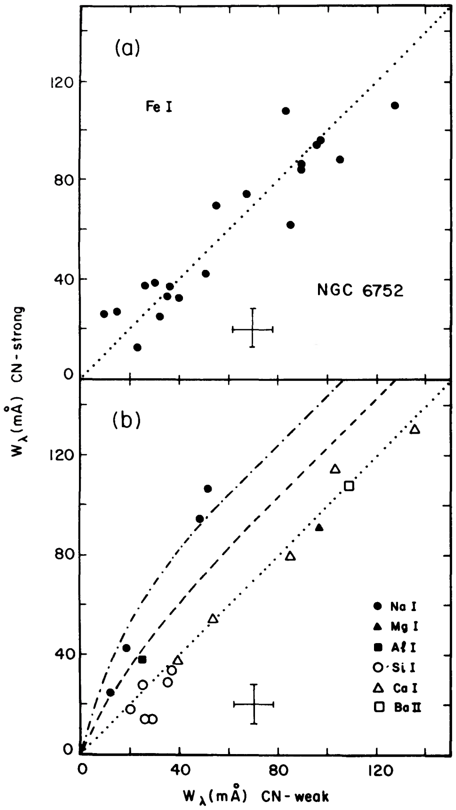

FIG. 1.—Equivalent width measurements of CN-strong (A8) and CN-weak (A3) stars in NGC 6752 for: (*a*) Fe I and (*b*) a range of other elements which are shown in the legend. The dotted line represents equal abundances in the two stars. The dashed and dot-dash lines in (*b*) are curves of growth that correspond to elemental enhancements in the CN-strong star of 0.3 dex and 0.6 dex, respectively. The error bars indicate the ±1 σ uncertainty in the measured equivalent widths.

clusters have usually been interpreted as the result of mixing of CN-processed material into the surface layers. Such mixing processes cannot produce the sodium (and aluminum) abundance enhancements seen in the CN-strong stars because these elements are not synthesized in significant amounts, if at all, during the evolution of low-mass stars. Thus, unless our knowledge of stellar evolution is seriously incomplete, we are forced to conclude that these sodium (and aluminum) abundance anomalies are primordial in origin. This is our most significant result: *the gas clouds from which the globular clusters 47 Tuc and NGC 6752 formed were not homogeneous.* The existence of similar sodium abundance variations led Cohen (1978) and Peterson (1980) to draw the same conclusions for the clusters M3 and M13, respectively.

Since for the stars studied here, there is a one-to-one correlation between CN-strong characteristics and primordial sodium abundance enhancements, it seems natural to assume that all the abundance variations in these clusters have a primordial origin. The alternative assumption, that only the stars with primordial sodium abundance enhancements mix, seems less satisfactory.

Given this assumption, can we place any constraints on the possible processes that caused these abundance variations? One such process is explosive nucleosynthesis; here massive stars that form in the protocluster gas evolve rapidly and enrich the remaining gas with the products of supernova explosions. Subsequent star formation then yields the CN-strong population of each cluster. There are, however, problems with this picture. First, unlike ω Cen, no Fe peak element abundance variations are observed, so that either the supernovae did not produce these elements or somehow only the sodium- (and aluminum-) rich material was retained in the cluster. Both these hypotheses seem unlikely. Second, there is no obvious way in this process to produce the correlation between the sodium and cyanogen enhancements. Third, the ejection velocities associated with these explosive processes are large and may be sufficient to halt star formation entirely by stripping the protocluster of all remaining gas. Hence it seems probable that in these clusters we are not seeing the results of explosive nucleosynthesis but rather the effects of a less violent enrichment process.

A more appealing scenario is that the abundance

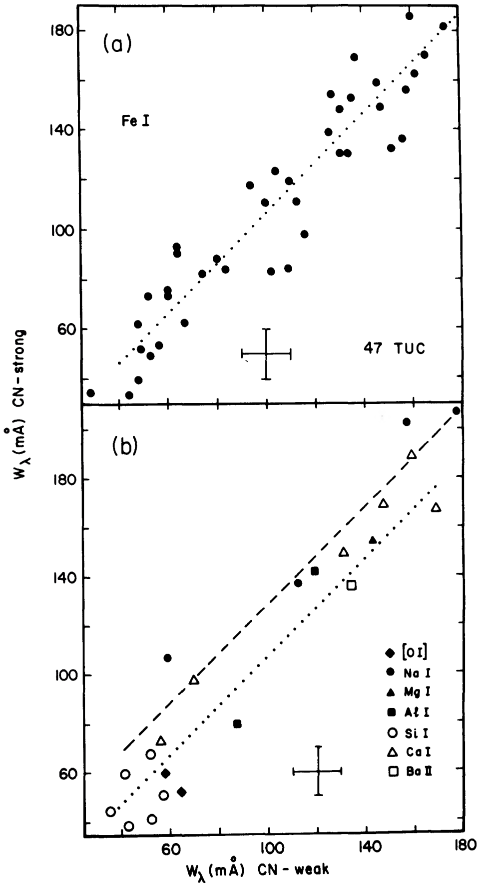

FIG. 2.—As for Fig. 1 except that stars 5312 (CN-strong) and 5309 (CN-weak) in 47 Tuc are plotted. For this pair of stars our analysis indicates that Fe is enhanced in the CN-strong star by 0.1 dex. This is indicated by the dotted line in both (*a*) and (*b*). In (*b*) the dashed line indicates the effect of a further 0.3 dex enhancement in the CN-strong star.

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anomalies arose within intermediate mass ($\sim$5–10 $M_\odot$) stars and, as a consequence of convective dredge-up and mass loss, were conveyed into the protocluster gas. The sequence of events may have happened as follows: during initial star formation in the protocluster gas cloud, a spectrum of stellar masses form but a sizable amount of gas remains. The low-mass ($<1\ M_\odot$) stars are assumed to provide the population of CN-weak objects that are now observed in these clusters. As the more massive stars ($\gtrsim 5\ M_\odot$) evolve, they lose material which may be enriched in CN-cycle products (e.g., Dearborn and Eggleton 1977; Paczyński 1973). This gas leaves the stars at relatively low velocities and will mix with the remaining protocluster gas increasing its N/C ratio.

Further, these intermediate mass stars undergo thermal pulses during their asymptotic giant-branch evolution, synthesizing ^{12}C, and if temperatures are sufficiently high, producing neutrons via the $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ reaction (see Iben 1975, 1976). As pointed out by Iben (1976), the low abundance of iron in globular cluster stars means that the majority of the liberated neutrons will be captured principally by ^{22}Ne and ^{25}Mg rather than ^{56}Fe, so that ^{23}Na, ^{26}Mg, and ^{27}Al will be synthesized. During the postpulse period, these elements are convected into the surface layers. In addition, if the ^{12}C is converted into ^{14}N at the base of the convective zone (Iben 1975), the surface abundances of these stars would show large enhancements of ^{14}N and ^{23}Na as well as smaller enhancements of ^{25,26}Mg and ^{27}Al. The enhancement in the total magnesium abundance will be negligible since the principal magnesium isotope, ^{24}Mg, is not synthesized by this process. Subsequent mass loss will distribute these enrichments into the remaining protocluster gas, from which CN-strong, Na-strong stars form. Star formation is eventually halted by the occurrence of supernovae which sweep the remaining gas from the cluster, carrying with it the products of explosive nucleosynthesis. Obviously, the mass of the stars that first become supernovae cannot significantly exceed the mass of the most massive stars that undergo thermal pulses. Otherwise star formation will be quenched before the proposed enrichment has occurred.

This scenario, although speculative, has the advantage of explaining both the correlation between the sodium and nitrogen abundance anomalies in these clusters and the lack of Fe peak abundance variations. Further, the time scale for this enrichment process is short since it does not become significant until the massive stars reach the giant branch and is terminated, along with star formation, by supernovae. This fact may explain the apparent bimodal distribution of CN strength among the stars in 47 Tuc and NGC 6752. In addition, since gas densities and stellar densities are highest in the central regions of the protocluster, it is likely that the bulk of this enrichment process will occur there, giving a natural explanation to a radial gradient in the relative number of CN-strong stars. Such a gradient has been observed in 47 Tuc (Norris and Freeman 1979).[2]

In conclusion, we hope that our results will spur theorists to calculate the models needed to explore the enrichment process described above. Observational astronomers are urged to search other globular clusters for abundance correlations similar to those found here.

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[2] Because of its much shorter relaxation time, NGC 6752 is not expected to show any radial gradients, even if such gradients existed at the time of cluster formation.

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