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# THE ANTICORRELATION OF CYANOGEN AND CH ON THE GIANT BRANCH OF 47 TUCANAE

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## ABSTRACT

We present CN and G band measurements for 112 stars on the red giant and asymptotic giant branches of 47 Tucanae. The data support the hypothesis (at the $2 \times 10^{-5}$ significance level) that there is an anticorrelation between CN and CH on the red giant branch (RGB) as has been previously reported for the horizontal-branch stars in this cluster. There seems little need to invoke the occurrence of mixing phenomena during the transition of a star from $M_v \sim 0.0$ on the RGB to the horizontal branch and later evolutionary phases, as has been suggested for the more metal-poor clusters such as M92. We also highlight the finding of Bell, Hesser, and Cannon that there appears to be an anticorrelation of CN and CH in their best observed CN-strong, CN-weak pair of stars at the turnoff of this cluster. *We emphasize, however, that no primordial scenario has yet been devised which can explain the details of the carbon nitrogen anticorrelation implied by these data.*

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

## I. INTRODUCTION

There is growing evidence that most of the chemical inhomogeneity of 47 Tucanae has its origins in phenomena which were active at or before the formation of the cluster. Among this material is the existence of sodium abundance variations among the giants (Cottrell and Da Costa 1981), the range in cyanogen band strengths in stars at the main-sequence turnoff (Hesser 1978; Hesser and Bell 1980; Bell, Hesser, and Cannon 1983), and a radial gradient in the cyanogen strengths of the red giants (Norris and Freeman 1979; see also Norris and Smith 1981). There is, on the other hand, evidence from stars more luminous than $M_v \sim +1$ that not only is the distribution of cyanogen bimodal, but also that there exists a general anticorrelation between the abundances of carbon and nitrogen (Norris 1978; Norris and Cottrell 1979; Norris and Freeman 1979, 1982). The evidence for the anticorrelation is based on analysis of horizontal-branch (HB) and asymptotic giant branch (AGB) stars among which differences of $\sim +0.9$ dex in the abundance of nitrogen are accompanied by differences of $\sim -0.3$ dex in that of carbon. These latter phenomena set constraints on any primordial explanation of all of the observations. It is, for example, difficult to explain a bimodality and C/N anticorrelation in terms of a primordial effect in which the nitrogen-enriched, carbon-depleted group has formed from material enriched by the ejecta of an earlier generation of nitrogen poorer, carbon richer stars (cf. Cottrell and Da Costa 1981). In particular, it is difficult to produce the carbon depletion in the later generation (Norris *et al.* 1981; Smith and Norris 1982).

As noted above, the evidence for a C/N anticorrelation in 47 Tuc is based exclusively on analysis of stars on the HB and AGB—the more advanced evolutionary phases observed in globular clusters. Previous efforts to provide relevant information for red giant branch (RGB) stars has not produced a positive result (Norris 1978, Fig. 5). This was attributed to the fact that the CH features which comprise the G band and which are used as a carbon abundance indicator are saturated and are therefore less sensitive to carbon abundance variations on the RGB than on the HB. This is supported to some extent by the spectrum synthesis calculations of Dickens, Bell, and Gustafsson (1979, Fig. 9) which show that the sensitivity of G band strength to carbon abundance decreases by a factor of $\sim 2$ in passing from temperatures applicable to the HB ($T_{\rm eff} \sim 5000$ K) to those on the RGB ($T_{\rm eff} \sim 4000$–$4500$ K). If indeed there is no anticorrelation on the RGB, an alternative explanation is that the effects seen on the HB and AGB result from the mixing of CN-cycled material (in which the carbon has been processed to nitrogen) into the outer stellar layers, and that the effect becomes more marked with more advanced evolution. A situation of this kind has been suggested by Carbon *et al.* (1982) to explain the increasing carbon depletion which appears to accompany more advanced evolutionary phases in the very metal-poor cluster M92.

The purpose of the present paper is to report the results of a search for an anticorrelation of CN and CH among stars on the RGB of 47 Tuc using data of higher quality than previously available, in the magnitude range $-1.4 < M_v < 0.2$. The data and analysis are presented in §§ II and III, respectively. Statistical analysis shows that the hypothesis that CN and CH are anticorrelated on the RGB is accepted at the $2 \times 10^{-5}$ confidence level (where here and in what follows we adopt the notation of Siegel 1956). In § IV we discuss the implications of this result.

## II. OBSERVATIONAL MATERIAL

Our sample consists of two distinct data sets. The first comprises material obtained with the Anglo-Australian Telescope (AAT), while the second was obtained by using the du Pont Telescope at Las Campanas Observatory. In the first sample spectra are available for 75 stars on the RGB and AGB of 47 Tuc. Data on 61 of these were obtained in 1978 and have already been utilized in an analysis of the cyanogen distribution of this cluster (Norris and Freeman 1979). These have been supplemented by material on a further 14 stars observed during 1981 and 1982. In all cases the material was obtained with the RGO Cassegrain spectrograph/Image Photon Counting System combination. The spectra were obtained with grating configurations which yielded reciprocal dispersions of either 25 or 33 Å mm$^{-1}$, and corresponding resolutions of $\sim$1.2 or 1.5 Å (FWHM). The second series of spectra, which is comprised of data on some 60 objects, was obtained with the Cassegrain spectrograph/Schectman Photon Counting Image Intensifier System attached to the du Pont Telescope. The reciprocal dispersion and resolution of this material were 30 Å mm$^{-1}$ and 1.4 Å, respectively. The complete sample in the $[V, (B-V)]$-plane is shown in Figure 1. We also give the line from Hartwick and McClure (1980) which separates the AGB from the RGB. If one adopts an apparent distance modulus of 13.46 for 47 Tuc (Harris and Racine 1979) one finds that our sample covers the magnitude range $-1.4 < M_v < 0.2$.

From each spectrum we measure a G band strength defined by

$$W(\mathrm{G}) = \int_{4290}^{4318} (1 - I_\lambda/I_{4318}) d\lambda ,$$

where $I_\lambda$ is the intensity at wavelength $\lambda$ and $I_{4318}$ is the mean of the five maximal intensities in the wavelength range $\lambda\lambda$4314–4322 Å. In an effort to remove the effect of slight differences in resolution within the sample, we have smoothed the spectra using an appropriate Gaussian to decrease the resolution to 3 Å (FWHM) and rebinned the data in increments of 0.5 Å width. This has the effect of permitting a more stable determination of the pseudo-continuum intensity $I_{4318}$, which is the greatest source of error in the determination of $W$(G). The procedure also facilitates the combination of the

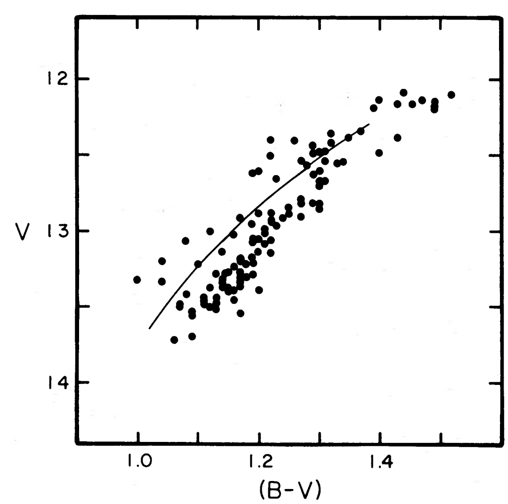


FIG. 1.—The color-magnitude diagram for the sample of giants discussed in this work. The line separating AGB and RGB stars has been taken from Hartwick and McClure (1980).

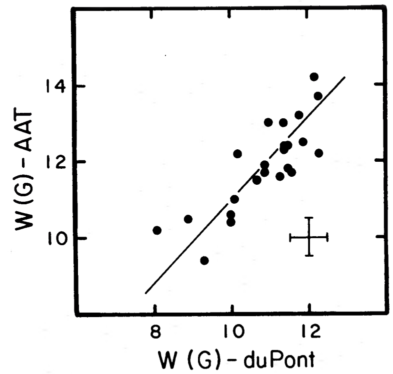


FIG. 2.—Comparison of G band strengths measured from the AAT and du Pont data samples.

AAT and du Pont data sets. Figure 2 shows a comparison of $W$(G) for 23 RGB and AGB stars common to the two samples. (We would note for completeness that the AAT material was reduced by J. N. at Steward Observatory, while the du Pont data were analyzed at Yale by G. D. C.) The tight relationship suggests that the above procedure permits measurement of a well-defined G band strength. The line in Figure 2 is the least squares fit to the data and was used to place the du Pont data on the AAT system. We may use Figure 2 to determine an error of measurement. The root-mean-square departure from the least squares line in the figure is 0.7 Å, which may be compared with the standard deviation for a single observation of 0.5 Å determined for both data sets from stars having multiple observations. We adopt 0.7 Å as our error of measurement.

Cyanogen band strengths are available for all of the stars in the AAT data set (Norris and Freeman 1979). For the remaining 35 stars in the du Pont sample we have measured $C$(4142) from the spectra as described by Norris and Freeman (1979), using the data for 23 objects in Table 1 having known values of $C$(4142) to standardize the results. We estimate that these values should be accurate to 0.025 mag, similar to the value of 0.03 mag obtained by Norris and Freeman (1979) for their more heterogeneous data sample.

Finally, in an effort to obtain information which might give some means of removing field stars from our sample, we have measured the Ca II H and K index $A$(Ca) (see Norris *et al.* 1981) defined by

$$A(\mathrm{Ca}) = 1 - 0.956 \int_{3916}^{3985} I_\lambda d\lambda \bigg/ \left( \int_{3883}^{3916} I_\lambda d\lambda + \int_{3985}^{4018} I_\lambda d\lambda \right) .$$

Our hope was that, for a given $(B-V)$, field stars might have values significantly different from those of cluster members. We found that for stars further than 3′ from cluster center our data had a standard deviation of 0.012 for both samples, which may be compared with a typical value of $A$(Ca) of 0.50 and a range of 0.12. For the inner stars the agreement was not so good, almost certainly as a result of problems of accounting for cluster background, and we decided to measure $A$(Ca) for only the outer stars. For this latter subset there are 16 objects in common between the AAT and du Pont samples and, excluding one quite discrepant star (L4509) and L3516, for which we did not measure $A$(Ca) for the du Pont data, we found the measures well correlated by $A(\mathrm{Ca})_{\mathrm{AAT}} = A(\mathrm{Ca})_{\mathrm{duP}}$

TABLE 1

Observational Data for 112 Stars in the Field of 47 Tucanae

| Star (1) | $V$ (2) | $B-V$ (3) | $C4142$ (4) | $W$(G) (5) | $A$(Ca) (6) | $n$[a] (7) | Comment (8) |
|---|---|---|---|---|---|---|---|
| 1201 ....... | 12.85 | 1.30 | 0.21 | 12.7 | 0.470 | 100 | Field |
| 1301 ....... | 12.60 | 1.20 | 0.29 | 10.2 | 0.477 | 200 | AGB |
| 1309 ....... | 13.20 | 1.04 | 0.27 | 11.3 | 0.459 | 100 | AGB |
| 1316 ....... | 13.17 | 1.19 | 0.08 | 12.5 | 0.496 | 100 | |
| 1406 ....... | 13.45 | 1.11 | 0.26 | 9.6 | 0.484 | 101 | |
| 1408 ....... | 13.53 | 1.09 | 0.35 | 10.2 | 0.475 | 010 | |
| 1506 ....... | 13.27 | 1.15 | 0.10 | 12.8 | 0.490 | 101 | |
| 1510 ....... | 12.15 | 1.43 | 0.36 | 11.9 | 0.488 | 010 | Field |
| 1513 ....... | 12.41 | 1.32 | 0.33 | 10.7 | 0.485 | 011 | AGB |
| 1518 ....... | 13.06 | 1.08 | 0.12 | 12.2 | 0.454 | 100 | AGB |
| 1522 ....... | 13.56 | 1.09 | 0.10 | 11.8 | 0.436 | 010 | Field |
| 1604 ....... | 13.01 | 1.21 | 0.15 | 12.6 | 0.499 | 001 | |
| 1628 ....... | 12.94 | 1.22 | 0.15 | 12.5 | 0.481 | 101 | |
| 2306 ....... | 12.55 | 1.33 | 0.15 | 13.1 | 0.504 | 200 | |
| 2416 ....... | 12.66 | 1.31 | 0.15 | 13.0 | 0.529 | 001 | Field |
| 2426 ....... | 12.10 | 1.52 | 0.30 | 13.2 | 0.495 | 100 | Field |
| 2428 ....... | 13.23 | 1.16 | 0.13 | 12.4 | 0.476 | 001 | |
| 2525 ....... | 12.43 | 1.29 | 0.24 | 11.8 | 0.473 | 010 | AGB |
| 2528 ....... | 13.50 | 1.13 | 0.43 | 13.6 | 0.472 | 011 | |
| 2603 ....... | 12.90 | 1.27 | 0.14 | 12.6 | 0.494 | 001 | |
| 2605 ....... | 12.50 | 1.22 | 0.36 | 11.7 | 0.487 | 010 | AGB |
| 2608 ....... | 12.87 | 1.22 | 0.15 | 12.8 | 0.499 | 002 | |
| 2616 ....... | 13.21 | 1.19 | 0.10 | 12.0 | 0.467 | 001 | |
| 2617 ....... | 13.31 | 1.14 | 0.10 | 12.8 | 0.457 | 001 | |
| 2618 ....... | 12.54 | 1.34 | 0.15 | 12.3 | 0.506 | 002 | |
| 2737 ....... | 13.51 | 1.13 | 0.07 | 11.0 | 0.491 | 010 | |
| 2739 ....... | 13.22 | 1.18 | 0.22 | 12.2 | 0.480 | 100 | |
| 3207 ....... | 13.05 | 1.22 | 0.17 | 12.9 | 0.490 | 100 | |
| 3305 ....... | 13.05 | 1.20 | 0.17 | 12.6 | 0.508 | 100 | |
| 3407 ....... | 12.96 | 1.23 | 0.25 | 11.9 | 0.489 | 101 | |
| 3410 ....... | 13.18 | 1.17 | 0.22 | 12.7 | 0.484 | 201 | |
| 3501 ....... | 12.13 | 1.47 | 0.27 | 12.3 | 0.542 | 001 | |
| 3516 ....... | 13.20 | 1.18 | 0.10 | 8.2 | 0.399 | 101 | Field |
| 3622 ....... | 12.60 | 1.30 | 0.15 | 12.6 | 0.512 | 002 | |
| 4312 ....... | 12.70 | 1.30 | 0.13 | 12.2 | 0.512 | 100 | |
| 4418 ....... | 12.16 | 1.46 | 0.17 | 12.2 | 0.539 | 001 | |
| 4503 ....... | 12.39 | 1.22 | 0.13 | 12.5 | 0.473 | 010 | AGB |
| 4509 ....... | 12.99 | 1.21 | 0.30 | 11.7 | 0.468 | 101 | |
| 4602 ....... | 13.07 | 1.19 | 0.24 | 12.2 | 0.498 | 001 | |
| 4626 ....... | 13.27 | 1.17 | 0.25 | 10.9 | 0.469 | 001 | |
| 4628 ....... | 12.53 | 1.31 | 0.17 | 12.6 | 0.511 | 001 | |
| 4636 ....... | 13.30 | 1.17 | 0.28 | 10.5 | 0.470 | 001 | |
| 5309 ....... | 12.20 | 1.49 | 0.21 | 12.8 | 0.538 | 002 | |
| 5312 ....... | 12.18 | 1.49 | 0.29 | 12.0 | 0.558 | 002 | |
| 5406 ....... | 12.81 | 1.30 | 0.15 | 13.1 | 0.488 | 101 | |
| 5422 ....... | 12.47 | 1.40 | 0.27 | 12.0 | 0.527 | 001 | |
| 5427 ....... | 12.93 | 1.22 | 0.17 | 12.5 | 0.479 | 101 | |
| 5601 ....... | 12.88 | 1.25 | 0.14 | 12.0 | 0.506 | 002 | |
| 5627 ....... | 12.48 | 1.29 | 0.18 | 12.8 | 0.492 | 020 | AGB |
| 6408 ....... | 12.81 | 1.29 | 0.13 | 12.4 | 0.490 | 101 | |
| 6418 ....... | 13.41 | 1.08 | 0.24 | 12.1 | 0.461 | 001 | |
| 6501 ....... | 13.72 | 1.06 | 0.08 | 11.2 | 0.476 | 010 | |
| 6519 ....... | 12.81 | 1.27 | 0.13 | 12.0 | 0.507 | 101 | |
| 6524 ....... | 13.08 | 1.21 | 0.24 | 13.8 | 0.460 | 101 | Field |
| 6614 ....... | 13.70 | 1.09 | 0.30 | 12.0 | 0.473 | 010 | |
| 6616 ....... | 13.36 | 1.17 | 0.21 | 11.7 | 0.461 | 001 | |
| 6636 ....... | 13.05 | 1.19 | 0.15 | 12.4 | 0.480 | 001 | |
| 6711 ....... | 13.34 | 1.17 | 0.21 | 11.6 | 0.452 | 100 | Field |
| 6728 ....... | 12.78 | 1.27 | 0.16 | 12.2 | 0.506 | 100 | |
| 6740 ....... | 13.37 | 1.15 | 0.34 | 12.4 | 0.498 | 100 | |
| 6728 ....... | 12.47 | 1.30 | 0.33 | 9.6 | 0.488 | 010 | AGB |
| 7103 ....... | 13.28 | 1.14 | 0.18 | 12.5 | 0.478 | 100 | |

TABLE 1—*Continued*

| Star (1) | $V$ (2) | $B-V$ (3) | $C4142$ (4) | $W$(G) (5) | $A$(Ca) (6) | $n$[a] (7) | Comment (8) |
|---|---|---|---|---|---|---|---|
| 7220 ....... | 12.53 | 1.27 | 0.32 | 11.6 | 0.491 | *04 | AGB |
| 7326 ....... | 13.00 | 1.12 | 0.32 | 11.2 | 0.444 | 100 | AGB |
| 7629 ....... | 13.37 | 1.14 | 0.27 | 11.3 | 0.474 | 001 | |
| 8406 ....... | 12.37 | 1.43 | 0.17 | 11.1 | 0.500 | 020 | Field |
| 8517 ....... | 12.62 | 1.29 | 0.17 | 12.4 | 0.497 | *05 | |
| 8602 ....... | 12.84 | 1.25 | 0.13 | 12.4 | 0.499 | 002 | |
| 8614 ....... | 13.48 | 1.11 | 0.10 | 11.7 | 0.472 | 002 | |
| 8640 ....... | 12.56 | 1.28 | 0.15 | 12.6 | 0.514 | 001 | AGB |
| 8644 ....... | 13.14 | 1.22 | 0.13 | 12.8 | 0.490 | 001 | |
| D672 ...... | 12.66 | 1.30 | 0.19 | 12.6 | 0.503 | 100 | |
| F22 ........ | 13.40 | 1.15 | 0.12 | 10.3 | ... | 100 | |
| F54 ........ | 12.35 | 1.32 | 0.33 | 11.0 | ... | 204 | AGB |
| F55 ........ | 13.13 | 1.20 | 0.25 | 12.2 | ... | 101 | |
| F125 ...... | 12.38 | 1.35 | 0.30 | 11.6 | ... | 200 | |
| F140 ...... | 13.38 | 1.20 | 0.38 | 11.5 | ... | 100 | |
| F162 ...... | 12.14 | 1.49 | 0.31 | 12.2 | ... | 003 | |
| F194 ...... | 13.43 | 1.13 | 0.27 | 10.9 | ... | 100 | |
| F201 ...... | 13.13 | 1.14 | 0.27 | 10.8 | ... | 100 | |
| F204 ...... | 13.32 | 1.00 | 0.14 | 10.1 | ... | 001 | AGB |
| F210 ...... | 13.30 | 1.18 | 0.15 | 12.4 | ... | 100 | |
| F215 ...... | 13.28 | 1.13 | 0.13 | 12.2 | ... | 101 | |
| F239 ...... | 13.50 | 1.12 | 0.27 | 11.4 | ... | 100 | |
| F263 ...... | 13.29 | 1.19 | 0.19 | 11.2 | ... | 100 | |
| F266 ...... | 13.44 | 1.11 | 0.29 | 10.5 | ... | 100 | |
| F274 ...... | 12.61 | 1.19 | 0.34 | 12.4 | ... | 001 | AGB |
| F278 ...... | 12.95 | 1.19 | 0.32 | 9.8 | ... | 101 | |
| F296 ...... | 13.45 | 1.16 | 0.24 | 11.8 | ... | 100 | |
| F306 ...... | 13.39 | 1.16 | 0.27 | 11.8 | ... | 101 | |
| F307 ...... | 12.40 | 1.26 | 0.35 | 11.0 | ... | 100 | AGB |
| F314 ...... | 12.91 | 1.24 | 0.16 | 12.8 | ... | 101 | |
| F327 ...... | 13.50 | 1.07 | 0.07 | 11.8 | ... | 100 | |
| F364 ...... | 13.47 | 1.13 | 0.25 | 11.2 | ... | 100 | |
| F379 ...... | 12.91 | 1.17 | 0.26 | 10.1 | ... | 102 | AGB |
| F382 ...... | 13.02 | 1.16 | 0.27 | 10.7 | ... | 100 | |
| F413 ...... | 13.20 | 1.17 | 0.30 | 11.1 | ... | 100 | |
| F438 ...... | 12.13 | 1.40 | 0.22 | 12.9 | ... | 001 | |
| F445 ...... | 13.05 | 1.20 | 0.23 | 11.6 | ... | 100 | |
| F449 ...... | 12.18 | 1.39 | 0.32 | 12.6 | ... | 001 | |
| F453 ...... | 13.33 | 1.04 | 0.25 | 11.8 | ... | 001 | AGB |
| F472 ...... | 13.22 | 1.10 | 0.28 | 12.1 | ... | 002 | AGB |
| F490 ...... | 12.08 | 1.44 | 0.31 | 11.9 | ... | 001 | |
| F526 ...... | 13.54 | 1.17 | 0.25 | 11.7 | ... | 001 | |
| F540 ...... | 12.47 | 1.31 | 0.33 | 10.6 | ... | 200 | AGB |
| F547 ...... | 13.49 | 1.07 | 0.18 | 12.0 | ... | 100 | |
| F548 ...... | 12.65 | 1.23 | 0.19 | 10.8 | ... | 101 | AGB |
| F568 ...... | 13.28 | 1.13 | 0.18 | 11.7 | ... | 100 | |
| F569 ...... | 13.33 | 1.14 | 0.12 | 12.2 | ... | 001 | |
| F574 ...... | 13.37 | 1.12 | 0.12 | 12.0 | ... | 100 | |
| F588 ...... | 12.34 | 1.37 | 0.27 | 11.0 | ... | 200 | |
| F589 ...... | 12.88 | 1.20 | 0.18 | 12.2 | ... | 100 | |

[a] Positional code giving number of observations obtained using (1) AAT in 1978, (2) AAT in 1981–1982, and (3) du Pont telescope. An asterisk denotes more than nine observations.

+ 0.018, with a root-mean-square departure of 0.018. All of the du Pont data were placed on the AAT system using this relation.

Our G band results, $C(4142)$ and $A$(Ca) values, and other relevant data are presented in Table 1. Columns (1)–(3) contain identification, $V$, and $(B-V)$, respectively, and have been taken from Lee (1977) for the first 71 rows, and from Chun and Freeman (1978) thereafter. Column (4) contains the DDO cyanogen index $C(4142)$ from Norris and Freeman (1979) and the present work; columns (5) and (6) give $W$(G) (in angstroms) and $A$(Ca), respectively; and column (7) contains a code for the number of observations reported here. In the final column we note stars which appear to lie on the AGB, based on the division between AGB and RGB suggested by Hartwick and McClure (1980; see our Fig. 1). We exclude these stars from our analysis. Also noted in the final column of the table are several stars which, based on the discussion in § III*a*, may be nonmembers of the cluster.

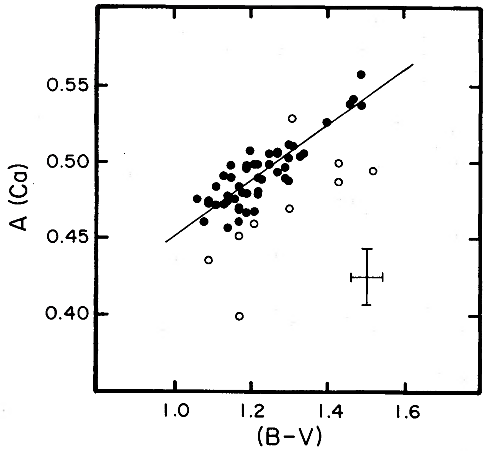


FIG. 3.—The dependence of $A$(Ca) on $(B-V)$ for stars more than 3′ from the center of 47 Tuc.

### III. ANALYSIS

#### *a*) *Cluster Membership*

The question of cluster membership in 47 Tuc is difficult to assess. Since the cluster has a radial velocity of $-14$ km s$^{-1}$ (Webbink 1981), this parameter provides only a weak criterion for the removal of field stars, and apart from one star, L3516, which has the huge radial velocity of $+425$ km s$^{-1}$ relative to 47 Tuc (and hence deserves further study in its own right) we have made no effort to utilize this test. As an alternative approach we have attempted to use the $A$(Ca) values in column (6) of Table 1 to remove nonmembers from our RGB sample. Figure 3 shows the data (excluding AGB stars) as a function of $(B-V)$, where most stars fall on a well-defined locus. Assuming that 47 Tuc is chemically homogeneous with respect to calcium, as has been found from high-dispersion spectroscopic analysis (Cottrell and Da Costa 1981), we proceeded as follows. First, a least squares line was fitted through the data in Figure 3. We then rejected, as possible field stars, all objects which fell more than 0.02 from the line. We then repeated the exercise on the new sample to remove further possible nonmembers. Our final least squares line is given in the figure, where we show as open circles those objects which we identify as possible field stars.[1] The reader will note that we have been somewhat severe in our exclusion of possible nonmembers. We have done this purposely in an effort to have a sample as free from contamination as practicable. Upon removal of these nine possible field stars, which are identified in column (8) of Table 1, we are left with a sample of 82 RGB stars for further analysis.

[1] A referee has suggested that the present discussion would be improved by identifying the population of the rejected stars. We have, however, insufficient information to do so. Since they have low velocities relative to 47 Tuc it seems most likely that they are foreground Population I or disk objects. Because we have no information on the loci of such stars in the [$A$(Ca), $(B-V)$]-plane, we are unable to estimate if the postulated nonmembers do indeed belong to such categories. (Nor may the answer be readily seen from simple model atmosphere arguments. Consider the case of a foreground dwarf. At constant $(B-V)$ and [Fe/H], on the one hand, such an object would be hotter than a 47 Tuc giant [Bell and Gustafsson 1978] and hence probably have a lower value of $A$(Ca). This effect will be offset, on the other hand, by the fact that most Population I and disk dwarfs have higher abundances than 47 Tuc. Without detailed calculations one is thus unable to determine the position of such stars in the [$A$(Ca), $(B-V)$]-plane.)

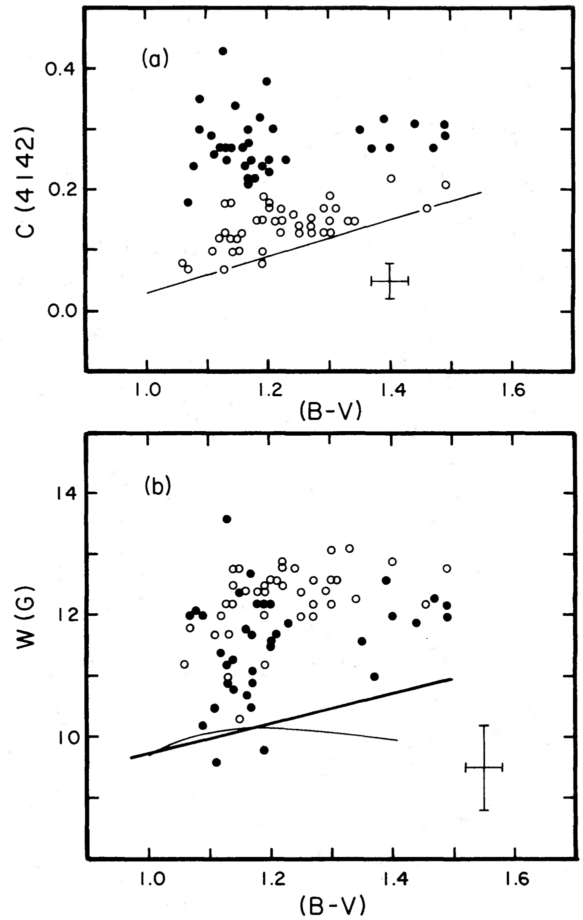


FIG. 4.—(*a*) The dependence of $C$(4142) on $(B-V)$. Filled and open symbols define CN-strong and CN-weak groups in this diagram. (*b*) The dependence of the G band strength $W$(G) on $(B-V)$. The symbols are the same as in the [$C$(4142), $(B-V)$]-diagram. The thick line represents an empirical baseline to the data, while the thin one shows a theoretical constant carbon abundance line for stars on the RGB of 47 Tuc. See text for discussion.

#### *b*) *C*(*4142*) *and W*(G) *versus* $(B-V)$

We wish to ascertain whether there is an anticorrelation between the G band strength (CH) and the cyanogen index $C$(4142) on the RGB of 47 Tuc. Figure 4*a* shows $C$(4142) as a function of $(B-V)$.[2] There as a slow increase in $C$(4142) as one moves up the giant branch, together with a decrease in the range in $C$(4142) (see also Fig. 1 of Norris and Freeman 1979). In what follows we shall need a quantitative measure of the cyanogen excess. We define this as the parameter, $\delta C(4142)$, the height a star falls above the baseline in Figure 4*a*, given by the equation $C_0 = 0.304\ (B-V) - 0.275$. We also arbitrarily define CN-strong and CN-weak groups in Figure 4*a* by filled and open circles, respectively.

[2] The reader may note that in our previous papers we have usually used the $V$ magnitude as independent variable. Because of the tight relationship between $V$ and $(B-V)$, either quantity could be used here. We adopt $(B-V)$ because of the approximately linear relationship between it and effective temperature for the present range of values.

Figure 4*b* gives the G band data in the [$W$(G), $(B-V)$]-plane. The filled and open symbols are the same as in Figure 4*a*. Given the error of measurement relative to the range in G band strength, and the possible contamination of the sample by some field stars, the interpretation of Figure 4*b* is not straightforward. The best that can be said is that there is some evidence for an anticorrelation in the data, but there are several objects for which this is certainly not true. The situation is also probably oversimplified by the arbitrary cut between CN-strong and CN-weak groups made in Figure 4*a*. We now proceed to look for a correlation between cyanogen excess $\delta C(4142)$ and a G band excess $\delta W$(G), which we now define.

In view of the fact that the G band strength varies as one moves along the giant branch we must first define a baseline with respect to which $\delta W$(G) can be measured. We consider two cases. First, it appears empirically that there exists a lower envelope to the data in Figure 4*b* which increases with increasing $(B-V)$. As a first approximation we adopt the empirical baseline shown by the thick line [which has the equation $W(\mathrm{G})_0 = 2.50\ (B-V) + 7.2$)] in the figure and measure $\delta W$(G) relative to this line. As a second approach we show as a thin line in the figure the run of $W$(G) determined from synthetic spectra computed with the code developed at MSSO by Cottrell (Cottrell and Norris 1978) to simulate as closely as possible the observed G band strength. (Details are as described in Norris and Freeman 1983. Here we set [A/H] = $-1.0$, [C/A] = 0.0, and [O/A] = 0.6. We also adopt the theoretical giant branch locus for 47 Tuc given by Dickens, Bell, and Gustafsson 1979 in the range 4000–4750 K, and the relation between $T_{\mathrm{eff}}$ and $(B-V)$ deduced from Frogel, Cohen, and Persson 1981.) There are two points that seem worth making about this locus. First, it lies below most of the data. This suggests that the adopted oxygen abundance may be too high, and that in the calculations, therefore, too much carbon is locked up in CO.[3] The second point, and the essential one for our purposes, is that in the temperature range for which the locus is shown—4000–4750 K—there is little change in G band strength. The same result, between $T_{\mathrm{eff}}$ = 4000–4500 K, may also be seen in Figure 9 of Dickens, Bell, and Gustafsson (1979). In this second case, therefore, we measure $\delta W$(G) relative to a baseline of 10 Å. We shall refer to the two baselines as the sloping and flat baseline cases in what follows. Inspection of the figure shows that there will be a systematic difference in $\delta W$(G) between the redder and bluer stars in our sample depending on which baseline we adopt. We shall see, however, that our essential result is independent of the choice of baseline.

### *c*) $\delta C(4142)$ *versus* $\delta W$(G)

The dependence of $\delta C(4142)$ on $\delta W$(G) for the RGB stars in Table 1 is shown for three groupings in Figure 5. As before filled and open circles refer to CN-strong and CN-weak objects, respectively. On the left we give the results obtained by adopting a sloping baseline for $W$(G), while on the right the data are shown on the assumption of a flat baseline. To investigate the possible role of effective temperature dependent phenomena on our result [and that of the adopted baseline for $W$(G)] we divide the sample into two groups at $(B-V) = 1.20$. In the topmost of the three panels (labeled [*a*]) we show the 34 objects with $(B-V) > 1.2$, while in the middle panel (labeled [*b*]) we show the data for the 48 stars with $(B-V) \leq 1.2$. The bottom panel (labeled [*c*]) contains the complete sample.

Figure 5 contains the essential result of our investigation. *Regardless of the baseline adopted for the measurement of the CH excess, there is a clear anticorrelation between* $\delta C(4142)$ *and* $\delta W$(G). One star, L2528 at [$\delta C(4142)$, $\delta W$(G)] $\sim$ (0.3, 3.7), stands clear of the general relationship. We are unable to say whether this is a field star superposed on the cluster, or an actual member with abnormally strong CN and CH. In either case it clearly represents a different phenomenon from that of the remainder of the sample, and while it deserves further study, we have ignored it in our analysis. The lines shown in Figure 5 are least squares fits to the data excluding this object. It is of some interest to ascertain the statistical significance of the result seen in the figure. The Kendall rank correlation coefficient test shows that for the sloping baseline case the hypothesis that there is an anticorrelation is accepted at the 0.05, $3 \times 10^{-4}$, and $2 \times 10^{-5}$ significance levels for the samples (*a*), (*b*), and (*c*), respectively. In the case of the flat baseline the confidence levels are 0.05, $3 \times 10^{-4}$, and $3 \times 10^{-7}$, respectively. One may conclude therefore, in the less favorable case of the sloping baseline, that for the total sample our result is significant at the $2 \times 10^{-5}$ level. (Had we included L2528 in our analysis, this value would drop to $1 \times 10^{-4}$.)

## IV. DISCUSSION

Our basic result then is that we see a significant anticorrelation between CN and CH on the RGB in 47 Tuc. There is also an anticorrelation between CN and CH on the red horizontal branch (RGB) of this cluster (Norris and Freeman 1982). We may reach two conclusions from these results. First, we may say with some confidence that the process responsible for the anticorrelation has operated at or lower on the giant branch than $M_v = 0.0$. Second, there is no need from the data to invoke a mixing process which becomes more marked with increasing evolutionary phase. For the giants hotter than $(B-V) = 1.2$ the mean G band strength covers a range of $\sim$1.2 Å in passing from the CN-strong to the CN-weak objects (see Fig. 5*b*). Our spectrum synthesis calculations show that this can be explained by a change in carbon abundance of $\sim$0.25 dex, similar to the values of $\sim$0.3 found by Norris and Freeman (1982) for a CN-strong, CN-weak pair of stars on the RHG of this cluster, and 0.2 by Norris and Cottrell (1979) for such a pair on the AGB.

It would of course be interesting to ascertain how far down the giant branch the anticorrelation of CN and CH extends. Clearly, if the effect is primordial, it should also exist at the cluster turnoff. It is therefore interesting to note that Bell, Hesser, and Cannon (1983, Fig. 3) show spectra of the CN-weak, CN-strong turnoff pair 1-9004 and 3-2153 which show just this effect. They note: "The G band in 3-2153 [the CN-strong star] appears to be weaker than in 1-9004. This may be indicative of a carbon abundance difference of about a factor of 2" (our comment is in brackets). They

[3] A referee has noted that this effect might also be explained if our adopted value of [Fe/H] is too low and a value of, say, $-0.8$ were more applicable. This is, however, not the case since the G band strength is relatively insensitive to overall abundance changes. Such behavior results from the fact that both the band opacity (due to CH) and the continuous opacity (due to $H^-$) increase linearly with increasing overall abundance (all other parameters being constant).

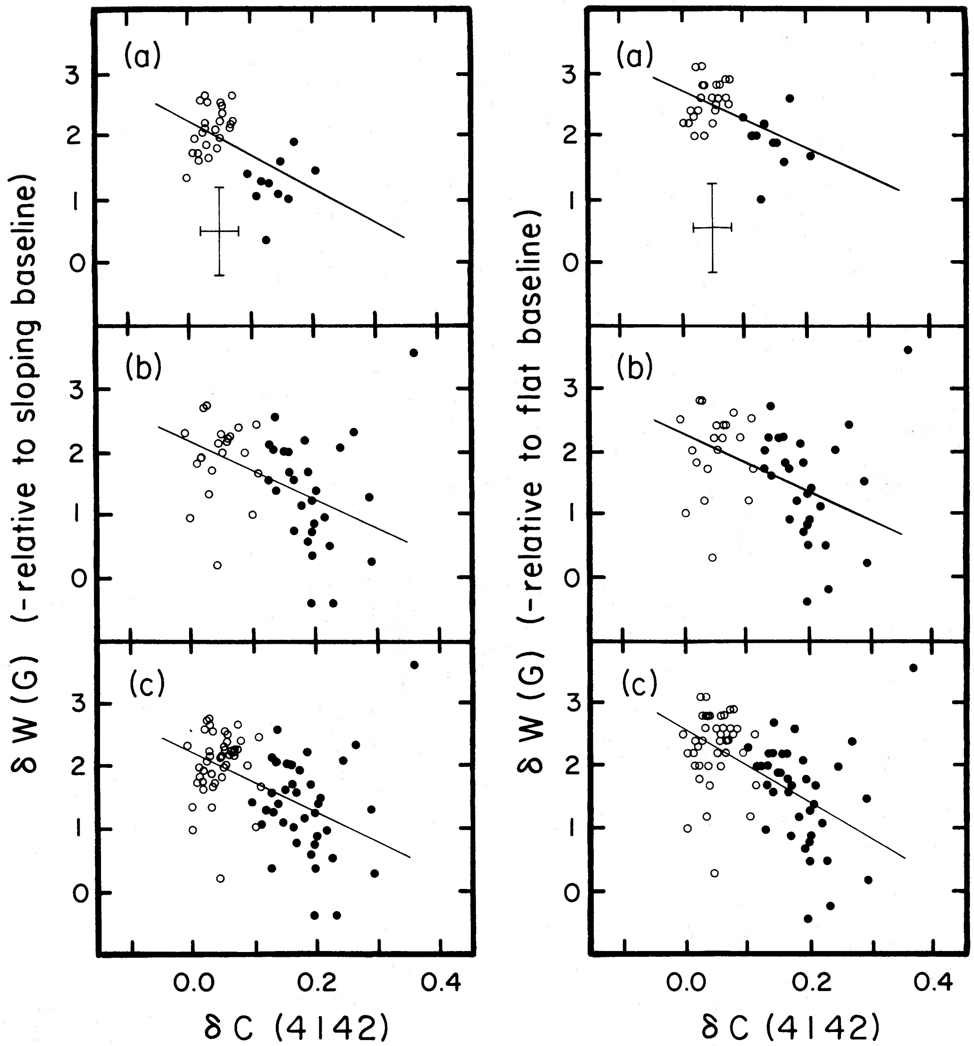


FIG. 5.—The dependence of $\delta C(4142)$ on $\delta W(\mathrm{G})$ for RGB stars with (*a*) $(B-V) > 1.2$, (*b*) $(B-V) \leq 1.2$, and (*c*) all colors. On the left $\delta W(\mathrm{G})$ has been measured relative to the sloping baseline in Fig. 4*b*, while on the right it was measured relative to the flat baseline. Note the anticorrelation between the two parameters. The filled and open symbols refer to the CN-strong and CN-weak objects as defined in Fig. 4.

caution also, however, that this could result from a small difference in temperature between the two stars, but the available colors do not support such a difference. Clearly the data are not inconsistent with the existence of an anticorrelation between CN and CH even at the turnoff of 47 Tuc.

There thus appear to be broad correlations in the abundance patterns in 47 Tuc. While individual stars may deviate to some extent from the overall trends we believe that the following general description, based on the references cited in the Introduction, the present work, and those given below, gives the behavior of the bulk of the material.

1. There is a large range in the strengths of the CN bands at all evolutionary phases observed.

2. There is reason to believe that the cyanogen distribution is bimodal, and that the proportion of CN-strong objects increases towards cluster center.

3. There is an anticorrelation between CN and CH and of CN and CO (Frogel, Cohen, and Persson 1981). These are most readily understood in terms of an anticorrelation between the abundances of C and N. At the extremes of the variations, differences of $\sim 0.9$ dex in N are accompanied by differences of $\sim -0.2$ to $-0.3$ dex in C.

4. There is a *positive* correlation between the behavior of CN and Na. The range of 0.9 dex for N is accompanied by a range of $\sim 0.4$ dex in the abundance of Na (Cottrell and Da Costa 1981).

Most of these results are consistent with a primordial origin of the abundance patterns. *The* C/N *anticorrelation is not.* At least we are unable to devise a plausible primordial explanation which incorporates this result. It has been argued elsewhere (Smith and Norris 1982) that it is very difficult to produce a second generation (the CN-strong population), containing almost half of the cluster mass, which is depleted by 0.2–0.3 dex in carbon relative to the earlier generations (the CN-weak population). We refer the reader to that work for details. More recently D'Antona, Gratton, and Chieffi (1982) and Renzini (1982) have advocated the hypothesis that accretion of N, Na rich material expelled from higher mass stars onto some of the lower mass stars we observe today may explain the abundance patterns seen in clusters such as 47 Tuc. Such a process, for any reasonable mass function, cannot cause a depletion in carbon of 0.2 to 0.3 dex. (Since the accreted material will be mixed throughout the convective envelope of the observed giants, this involves depleting carbon over roughly half the stellar mass—the extent of the convective envelope at its deepest penetration. A depletion of 0.3 dex implies, for accreting material containing zero carbon, an accreted mass equal to that of the convective envelope at its deepest extent. Only if mixing of accreted material throughout the envelope is prevented by some agency such as strong magnetic fields can this objection be overcome.)[4]

We believe that the C/N anticorrelation, which exists not only in this cluster but also in NGC 6752 (Norris *et al.* 1981), provides a basic stumbling block to the acceptance of existing primordial scenarios for the origin of the observed abundance patterns of C, N, Na, and Al in the more normal globular clusters. We hope that our emphasis of this problem will stimulate discussion of possible modifications to these hypotheses to take into account the anticorrelation.

[4] Bell *et al.* (1981) have considered the case of more recent accretion of the nitrogen-rich ejecta from lower mass stars onto main sequence objects. The above arguments apply to this scenario as well, and here, too, the observed carbon/nitrogen anticorrelation cannot be explained.

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