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CN AND CH VARIATIONS ON THE M5 SUBGIANT BRANCH[1]

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ABSTRACT

Moderate-resolution (FWHM ≅ 3 Å) blue spectra have been obtained using the Palomar 5 m telescope for a sample of 14 subgiants and six giants in the Galactic globular cluster M5. These data have been combined with MMT spectra of subgiants to yield 3883 Å CN band strength indices for 20 stars with $M_V > +1$. A G-band (CH) index was also measured for the stars observed at Palomar. The bimodality in 3883 Å CN band strengths, seen among the more luminous giants by Smith & Norris and Langer, Kraft, & Friel, is clearly present. That large C and N abundance variations are found among such relatively unevolved stars suggests that the CN distribution found among the brighter stars is at least in part due to a preexisting variation.

A decrease in C abundance with a corresponding increase in N is seen between the subgiant branch (SGB) and red giant branch (RGB) stars, as would be expected from mixing accompanying the RGB ascent (although the differences are on the order of the size of the error bars). Similar trends have been seen in RGB stars of many other intermediate metallicity clusters, and it is suggested that two abundance altering mechanisms are responsible for the C and N abundance variations in M5—one having produced early abundance inhomogeneities on the SGB or main sequence, and the second being RGB ascent mixing.

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

1. INTRODUCTION

For most of the past two decades, the Galactic globular cluster M5 has been known to contain red giant branch (RGB) stars with anomalously strong CN bands. This was first observed by Osborn (1971) in the DDO colors of two M5 giants and confirmed later by qualitative descriptions of the 3883 and 4215 Å CN band strengths by Zinn (1977). Similar trends have been observed in 47 Tuc, NGC 6752, M3, M4, M13, NGC 3201, and many other clusters (see, e.g., the reviews by Smith 1987 and Suntzeff 1989). It is now known that M5 is typical of the moderate- to metal-rich globulars in regard to its star-to-star CN band variations, which follow a bimodal distribution (Smith & Norris 1983; hereafter S&N).

Rather than reiterate here what can already be found in the literature on this subject, the reader is directed to reviews by Smith (1987, 1989), Norris (1988), and Suntzeff (1989). To summarize a few of the observed properties of the RGB stars in CN-bimodal clusters: differences in G-band (CH) strengths usually accompany CN variations, with CN and CH often being roughly anticorrelated. It is not uncommon to find Na or Al line strengths correlated with CN band strength, although whether this is due to a non–LTE effect or an actual abundance variation has yet to be fully explored. There is a slight correlation between cluster ellipticity and the ratio of the number of CN-strong to CN-normal stars (Norris 1987), as well as a radial gradient in that ratio within 47 Tuc (Paltoglou 1991).

Among fainter stars, Suntzeff (1988) and Suntzeff & Smith (1991) have observed star-to-star anticorrelated CN and CH band differences between two NGC 6752 main-sequence (MS) stars ($M_V = +6$). Also, in 47 Tuc, CN variations have been found among MS stars at $M_V \cong +5.2$, with no indication of a difference in the spread of C and N abundances between the MS and brighter subgiant branch (SGB) stars (Briley, Hesser, & Bell 1991). Very large quantities of ^{13}C have also been found among both the CN-strong and CN-normal RGB tip stars of the bimodal clusters M4, NGC 6752, and 47 Tuc (Smith & Suntzeff 1989; Brown & Wallerstein 1989; Bell, Briley, & Smith 1990; Suntzeff & Smith 1991).

The origins of these variations remain unknown, as different observations seem to point toward different sources. The low $^{12}C/^{13}C$ ratios (of order 4–10) as well as the C versus N anticorrelations suggest that material from a zone of CN-processing (which would be N-rich/C-poor, with a very low

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$^{12}C/^{13}C$ ratio) has been circulated or mixed to the stellar surface. This is the generally accepted interpretation of the C depletions which are seen to correlate with evolutionary state on the RGBs of metal-poor clusters (see Sweigart & Mengel 1979; Bell, Dickens, & Gustafsson 1979; Carbon et al. 1982; Trefzger et al. 1983; Langer et al. 1986; Suntzeff 1989; Briley et al. 1990). However, the existence of CN variations on the MSs of NGC 6752 and 47 Tuc, as well as on the SGBs of other clusters, the Na and/or Al correlations, and the CN gradient in 47 Tuc are all very difficult to explain in terms of a mixing scenario. These observations suggest that at least some of the origins of the CN variations may be primordial. A further discussion may be found in the reviews mentioned above.

In the most recent studies of CN band strengths in M5, S&N found a bimodal distribution of CN strengths on the RGB, with many more CN-strong stars than CN-normal (a ratio of 2.6:1). A detailed examination of CH, CN, and NH in six of the brighter giants by Langer, Kraft, and Friel (1985, hereafter LKF) revealed a C versus N anticorrelation, with little variation in the total C + N abundance (after a small zero-point shift in their absolute abundance scales), as would be expected from the mixing of CN–processed material. Furthermore, Suntzeff (1989) and Suntzeff & Smith (1991) have reported anticorrelated CN and CH band variations among two faint M5 SGB stars ($M_V \cong 3$). In order to verify these results, as well as examine the abundance distributions in pre–RGB stars, spectra have been obtained for six M5 red giants and a number of SGB stars with the goal of deriving both C and N abundances, and testing for any dependence on evolutionary state.

2. OBSERVATIONS

Observations of the program stars were made on the nights of 1988 June 13–15 with the Palomar 5 m telescope, using the double spectrograph at the Cassegrain focus. A 600 lines mm^{-1} grating was used on the blue side, centered at 4000 Å, giving a dispersion of about 1.5 Å $pixel^{-1}$ on the CCD detector and a resolution of 2.8 Å FWHM (as determined from arc lines). Bias frames were taken either at the start or finish of each night, as well as sets of flats from an incandescent lamp. All observations were bracketed by arc spectra of both He + Hg and Ne + Hg for dispersion corrections. Exposure times ranged from 600 s for the brighter M5 stars to 3600 s for the dimmer.

Fourteen SGB stars (see Table 1) were randomly selected for observation from the photometry of Buonanno, Corsi, & Fusi Pecci (1981). Spectra were also taken of six bright giants observed by both S&N and LKF, for use as comparisons. The locations on the cluster color-magnitude diagram (CMD) of the program stars, as well as those from S&N, are plotted in Figure 1.

A second set of observations of six additional M5 SGB stars has also been included in the analysis. These spectra were taken at the MMT on the nights of 1984 May 4 and 5 in parallel with a study of MS turn-off stars in NGC 188 (Norris & Smith 1985). The MMT spectrograph was used with a 832 lines mm^{-1} grating in second order and either a 1″ × 3″ or a 2″ × 3″ entrance aperture, resulting in resolutions of 1.4 or 2.5 Å and wavelength coverage from 3600 to 4600 Å. Further details of the observations may be found in Norris & Smith (1985).

The apparent spread in SGB colors seen in Figure 1 is of concern. Modeling with synthetic spectra indicates that this range in $B-V$ color corresponds to over a 500 K variation in

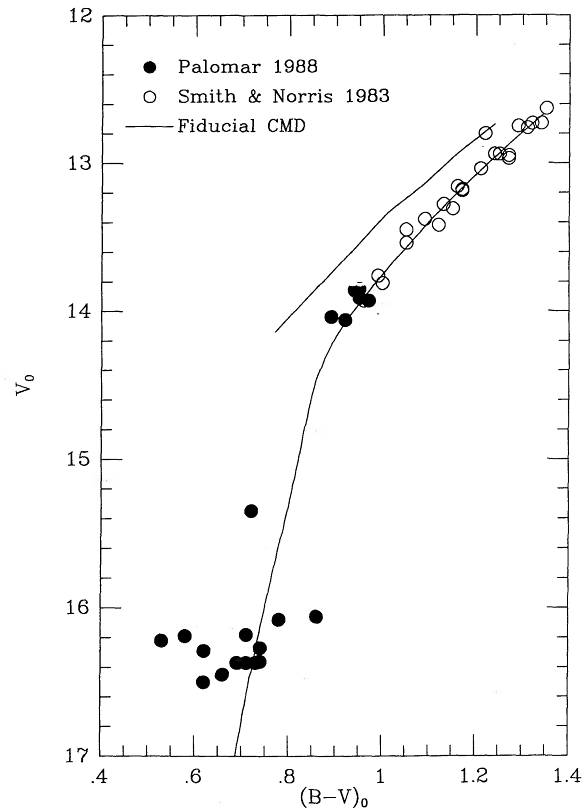

FIG. 1.—The fiducial CMD for M5 from buonanno et al. (1981) and Richer & Fahlman (1987) is plotted together with the locations of the observed stars from both S&N and the present work. Photometry for the observed stars was taken from Buonanno et al.

TABLE 1

OBSERVED STARS AND MEASURED INDICES

Star	V_0	$(B-V)_0$	CN Type	S(3839)	s_{CH}	Source
I-27 ……….	16.50	0.62	S	0.295	0.095	P
I-38 ……….	…	…	S	0.30	…	M
I-46 ……….	16.30	0.67	S	0.20	…	M
I-50 ……….	13.85	0.95	S	0.580	0.093	P
II-4 ……….	16.40	0.81	S	0.19	…	M
II-26 ……….	16.37	0.71	S	0.258	0.132	P
II-32 ……….	16.22	0.56	S	0.201	0.060	P
II-35 ……….	16.29	0.62	S	0.193	0.138	P
II-50 ……….	13.86	0.94	I	0.389	0.152	P
II-65 ……….	16.19	0.58	S	0.241	0.122	P
II-70 ……….	16.25	0.58	S	0.18	…	M
II-73 ……….	15.35	0.72	S	0.354	0.162	P
II-75 ……….	16.37	0.72	N	−0.019	0.184	P
II-77 ……….	16.23	0.66	S	0.35	…	M
III-44 ……….	16.27	0.67	S	0.29	…	M
III-45 ……….	16.36	0.74	S	0.266	0.123	P
III-52 ……….	14.04	0.89	N	0.145	0.148	P
III-54 ……….	16.32	0.76	S	0.26	…	M
III-59 ……….	13.91	0.95	S	0.526	0.111	P
III-74 ……….	16.37	0.69	…	0.275	0.118	P
III-79 ……….	16.18	0.71	N	−0.024	0.159	P
III-81 ……….	16.27	0.74	S	0.256	0.144	P, M
IV-4 ……….	14.06	0.92	N	0.158	0.153	P
IV-36 ……….	13.93	0.96	S	0.568	0.130	P
IV-76 ……….	16.45	0.66	S	0.145	0.129	P. M
IV-77 ……….	16.08	0.78	N	0.050	0.177	P. M
IV-83 ……….	16.06	0.86	S	0.191	0.100	P

NOTE.—P, spectrum obtained with Hale 5 m telescope; M, spectrum obtained with MMT; S, N, I, respectively strong, normal, intermediate CN type.

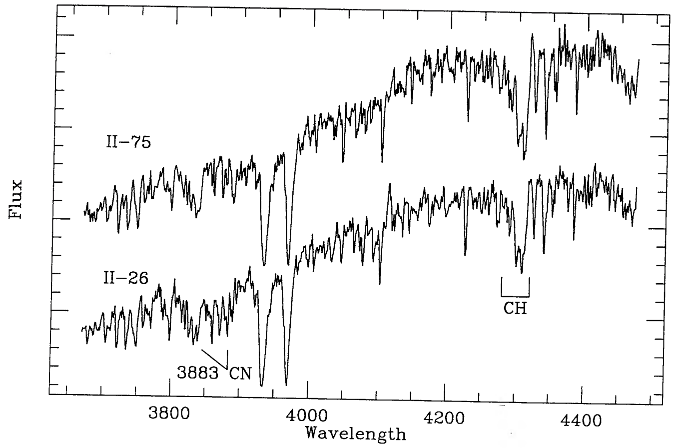

FIG. 2.—Spectra for two M5 SGB stars of similar brightness and color are plotted together. Note the differences in 3883 Å CN band strengths, which are anticorrelated with CH (G band) absorption (II-26 is CN-strong, II-76 is CN-normal).

$T_{\rm eff}$. The more recent CCD photometry of M5 by Richer & Fahlman (1987) indicates that this is largely due to scatter in the photographic photometry of Buonanno et al. However, as our program stars were not observed in this CCD study, the uncertainty in color will lend some uncertainty to the results. Since a broad spread in $B-V$ at $M_V \cong +2.2$ is not seen in the CCD based CMD of Richer & Fahlman, we adopt their mean V, $B-V$ relation for the SGB stars.

The observations were reduced using standard methods with the IRAF software package. Final spectra of two subgiants (II-76 and II-26, $M_V \cong +2$) with similar brightness and color are plotted together in Figure 2. Note that large and anticorrelated differences in both the 3883 Å CN and 4300 Å G-band strengths are evident.

Star III-74 appears to exhibit unusually strong Fe and Ca lines, as well as a substantially different continuum slope when compared to other cluster stars of similar color. Differential refraction is probably not the cause, as III-74 was not observed at an unusual hour angle. It is suggested that III-74 may not be a cluster member, but rather a more metal-rich foreground dwarf. As such, it is identified by being marked as a cross in Figures 5–8.

TABLE 2
DEFINITIONS OF INDEX BANDPASSES

Bandpass	Start Wavelength (Å)	End Wavelength (Å)
$F_{\lambda,F38}$	3846	3883
$F_{\lambda,C39}$	3883	3916
$F_{\lambda,F43}$	4280	4320
$F_{\lambda,C42}$	4220	4280

Two spectral indices, $S(3839)$ and $s_{\rm CH}$, designed to quantify the flux removed by the 3883 Å CN and 4300 Å CH (G) bands, respectively, were measured for all spectra taken during the Palomar run. The indices are defined as

$$S(3839) = -2.5 \log (F_{\lambda,F38}/F_{\lambda,C39}) ,$$

$$s_{\rm CH} = -2.5 \log (F_{\lambda,F43}/F_{\lambda,C42}) ,$$

where F_λ refers to the mean flux over the wavelength intervals specified in Table 2. The measured values of these indices are listed in Table 1.

In Figure 3, we compare the $S(3839)$ indices from the present observations and those of S&N and LKF for the six RGB stars in common. The agreement between the three studies appears to be good. A comparison with the S&N data suggests a 1 σ error of 0.04, which is typical of such studies. The line in Figure 3 is one of slope unity and zero intercept, implying that no transformation is required between the S&N $S(3839)$ indices and the Palomar indices of Table 1. The $m_{\rm CN}$ index measured by LKF has slightly different bandpasses to $S(3839)$; however, the fit in Figure 3*b* suggests that only a zero-point shift of 0.211 separates the two systems. The large difference between the two values for star II-50 (almost 0.16) appears to be due to an underestimation of the CN band strength by S&N. As noted by LKF, II-50 may be a CN-intermediate giant, a classification which is supported by the Palomar $S(3839)$ measurements.

Although both S&N and LKF used different indices for their G-band measurements [W(G) and $m_{\rm CH}$, respectively], these have been plotted in Figure 4 versus the $s_{\rm CH}$ indices of the

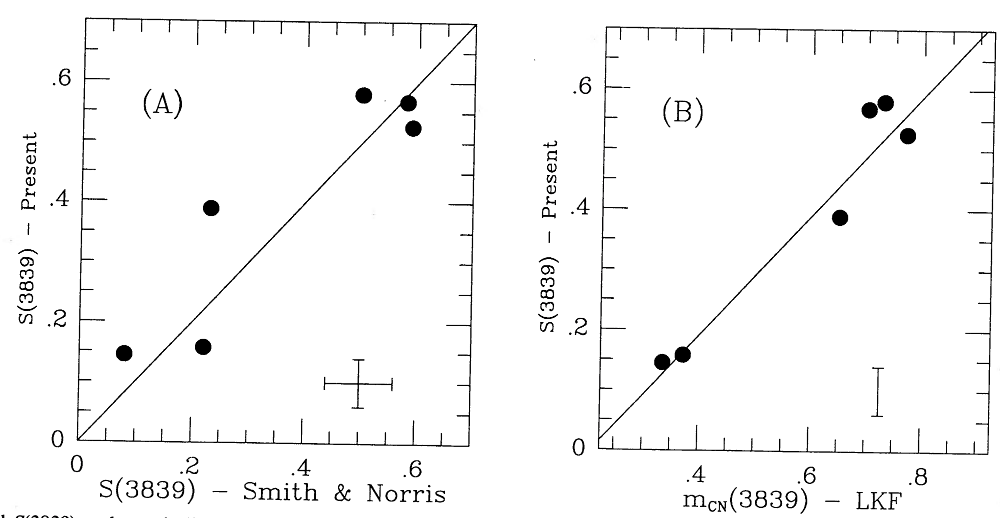

FIG. 3.—Measured $S(3839)$ and $m_{\rm CN}$ indices for six M5 RGB stars obtained from S&N, LKF, and this work are compared. The lines are of slope unity and intercept 0 for (a) and 0.211 for (b).

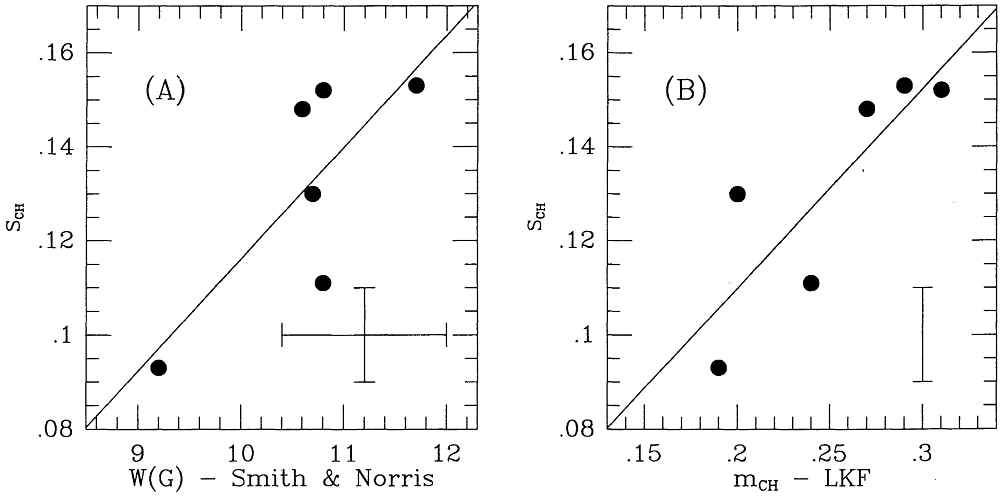

FIG. 4.—The W(G) index from S&N and the m_{CH} index from LKF have been plotted against the s_{CH} values from the present work for the same six RGB stars of Fig. 3. The lines represent the best linear fit of the data.

six stars in common. Again, the agreement is satisfactory. A 1 σ error in s_{CH} is estimated to be 0.01.

Values of S(3839) were also measured from the MMT spectra. These data, as well as those of S&N, have been combined together to produce Figure 5, where S(3839) is plotted against V_0 magnitude. The Palomar S(3839) indices are taken to be on the same system as the S&N indices on the basis of Figure 3. The MMT indices were transformed onto the Palomar system using the three stars in common (a zero-point shift of 0.087 $\pm$ 0.005) and are listed in Table 1. It is apparent from this figure that the bimodality in 3883 Å CN band strengths observed by S&N continues well onto the SGB.

Similarly, the s_{CH} indices for the stars observed at Palomar have been plotted versus V_0 in Figure 6. As with CN, there is a range in CH band strengths, with the CN-normal stars tending to have stronger CH bands than the CN-strong stars (as illustrated by the anticorrelated CN and CH features in Fig. 2).

3. ANALYSIS

3.1. *Models and Synthetic Spectra*

A considerable body of work devoted to the metallicity of M5 may be found in the literature. Values of [Fe/H] have been measured ranging from -1.01 to -1.59 using different techniques (see Table 3). For the present analysis, the Zinn & West (1984) value of -1.40 was used (although the effect of using -1.25 is explored below). Oxygen, which is particularly important in the cooler stars through CO formation, has been found to be overabundant in M5 with respect to iron by comparison with the solar ratio ([O/Fe] = $+0.33$, Pilachowski, Wallerstein, & Leep 1980; $+0.21$, Pilachowski, Sneden, & Wallerstein 1983b; and $+0.5$, Gratton 1987). A value of $+0.25$ for [O/Fe] has therefore been assumed throughout this analysis. The color excess $E(B-V)$ and observed distance modulus (m – M) have been taken to be 0.02 and 14.30, respectively, following Richer & Fahlman (1987).

A grid of flux-constant, plane-parallel model atmospheres, which take into account the effects of line blanketing and convection, were computed to represent the observed M5 CMD. The MARCS program used to compute the atmospheres is described in Gustafsson et al. (1975). The opacity distribution function (ODF) table for [A/H] = -1.40 ([A/H] being the scaled solar abundance of all metals) was computed from cubic splines between the [A/H] = 0.0, -0.5, -1.0, -2.0, and -3.0

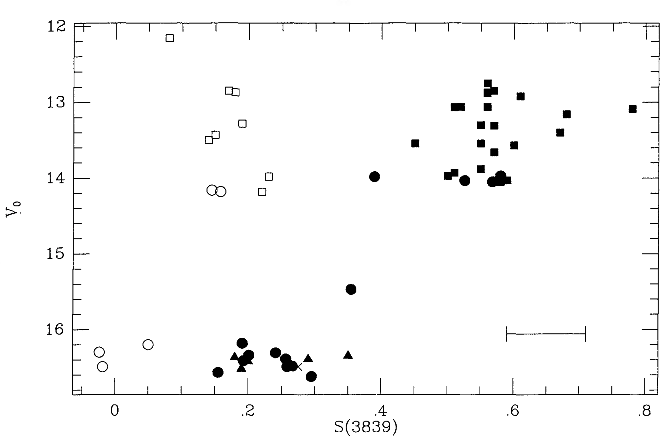

FIG. 5.—Values of S(3839) are plotted against V_0 for the RGB stars from S&N (*squares*), Palomar (*circles*), and the MMT (*triangles*). CN-strong stars are represented by filled symbols, CN-normal stars by open symbols, and the possible field star III-74 by a cross.

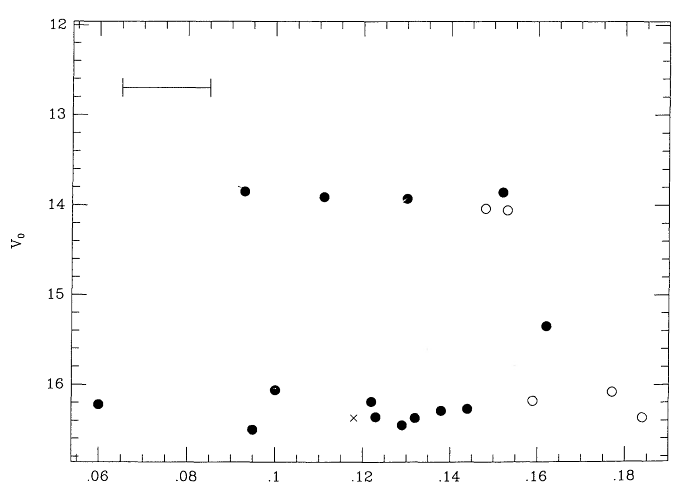

FIG. 6.—The G-band index, s_{CH}, is plotted against V_0 for stars in the Palomar sample. The symbols used are those of Fig. 5.

TABLE 3

VALUES FOR [Fe/H] FOR M5 FOUND IN THE LITERATURE

Source	[Fe/H]
Butler 1975	−1.01
Searle & Zinn 1978	−1.15
Zinn 1980	−1.59
Pilachowski, Wallerstein, & Leep 1980	−1.33
Frogel, Cohen, & Persson 1983	−1.49
Pilachowski, Sneden, & Wallerstein 1983b	−1.13
Pilachowski, Olszewski, & Odell 1983a	−1.2
Zinn & West 1984	−1.40
Langer, Kraft, & Friel 1984	−1.45
Gratton 1987	−1.4
Richer & Fahlman 1987	−1.13

ODFs. We note that there is little difference between the models computed with the splined ODF and models scaled from $[A/H] = -1.0$. The model input parameters of $T_{\rm eff}$ and surface gravity were varied until the resulting synthetic spectra, as computed from the SSG program (see Bell & Gustafsson 1978), yielded appropriate brightnesses and colors for the Richer & Fahlman fiducial M5 CMD. The B and V magnitudes were calculated using the IRCONV program (see Bell & Gustafsson 1978) to convolve the synthetic spectra with B and V response curves modified from those given by Matthews & Sandage (1963). The synthetic colors were normalized such that a model of Vega yielded colors of zero, as in Bell & Gustafsson (1989). The masses of the stars, used to find M_V, were assumed to be 0.8 $M_\odot$, and the computed bolometric corrections (BC) were adjusted so that a solar MARCS model yielded a BC of −0.07. A more detailed description of the steps in the model grid computation may be found in Briley et al. (1990). The final model parameters and their resulting colors are listed in Table 4.

For comparisons with observed data, synthetic spectra were calculated with fluxes tabulated every 0.05 Å and for a variety of C and N abundances as discussed below. These were then smoothed by a Gaussian of width 2.8 Å to match the resolution of the Palomar data. A microturbulent velocity (ξ) of 2.0 km s^{-1} was used in the equation of Doppler broadening velocity:

$$\mathrm{DBV} = \left(\frac{2kT}{m} + \xi^2\right)^{1/2} .$$

A solar ratio of $^{12}C/^{13}C = 89$ was initially chosen for the calculations. The effects of using different values of ξ and $^{12}C/^{13}C$ are explored below.

The sources of data for the atomic and molecular lines are given elsewhere (e.g., Bell & Gustafsson 1978).

Synthetic spectra were calculated from the models in Table 4, with [C/A] ranging from −0.9 to 0.0 and [N/A] ranging from −0.3 to +1.5, both in 0.3 dex steps. The standard logarithmic abundances of C, N, and O were scaled to $[A/H] = -1.40$ from the solar values of 8.62, 8.00, and 8.86 respectively. From these spectra, $S(3839)$ and $s_{\rm CH}$ indices were measured, with the results given in Tables 5 and 6.

The grids of synthetic indices were then used to translate the observed band strengths into abundances. This was accomplished by first deriving [C/A] from the observed CH bands, then using the 3883 Å CN bands to solve for [N/A]. The determination of [C/A] was similar to the method used by Briley et al. (1990). For each modeled [C/A] (i.e., 0.0, −0.3, −0.6, −0.9), a function relating $s_{\rm CH}$ to V_0 was constructed using cubic splines. The next step was then to interpolate the synthetic $s_{\rm CH}$ indices to the V_0 of each program star and compare them with the observed $s_{\rm CH}$ band strength to determine [C/A]. Once a star's [C/A] abundance was computed, a similar process was repeated for [N/A], the grid of synthetic $S(3839)$ indices being adjusted to the proper [C/A] through

TABLE 4

MODEL GRID AND RESULTING COLORS FOR THE M5 CMD WITH $[A/H] = -1.40$

$T_{\rm eff}$	$\log g$	V_0	$(B-V)_0$
4600	1.75	13.68	0.936
4725	2.00	14.31	0.890
4850	2.40	15.15	0.821
5000	2.85	16.10	0.735
5100	3.10	16.61	0.716

TABLE 5

G-BAND INDICES FOR VARIOUS C ABUNDANCES AS COMPUTED FROM MODELS WITH $[A/H] = -1.40$ AND $^{12}C/^{13}C = 89$

MODEL		$s_{\rm CH}$			
$T_{\rm eff}$	$\log g$	[C/A] = 0.0	[C/A] = −0.3	[C/A] = −0.6	[C/A] = −0.9
4600	1.75	0.184	0.154	0.116	0.076
4725	2.00	0.190	0.157	0.115	0.075
4850	2.40	0.191	0.153	0.110	0.070
5000	2.85	0.185	0.143	0.097	0.060
5100	3.10	0.178	0.133	0.088	0.054

TABLE 6

CN INDICES $S(3839)$ COMPUTED FOR DIFFERENT VALUES OF [C/A] AND [N/A] FROM THE $[A/H] = -1.40$ MODEL GRID WITH $^{12}C/^{13}C = 89$

MODEL		[N/A]						
$T_{\rm eff}$	$\log g$	−0.3	0.0	+0.3	+0.6	+0.9	+1.2	+1.5
		$S(3839)$, [C/A] = 0.0						
4600	1.75	0.044	0.174	0.332	0.506	0.683	0.850	1.005
4725	2.00	0.011	0.128	0.279	0.454	0.640	0.822	0.989
4850	2.40	−0.016	0.082	0.219	0.386	0.573	0.761	0.937
5000	2.85	−0.045	0.029	0.142	0.292	0.470	0.660	0.842
5100	3.10	−0.059	−0.001	0.094	0.228	0.395	0.582	0.766
		$S(3839)$, [C/A] = −0.3						
4600	1.75	−0.050	0.043	0.172	0.329	0.499	0.671	0.831
4725	2.00	−0.065	0.014	0.130	0.281	0.454	0.636	0.811
4850	2.40	−0.073	−0.010	0.088	0.224	0.389	0.573	0.755
5000	2.85	−0.079	−0.036	0.038	0.150	0.299	0.474	0.658
5100	3.10	−0.082	−0.048	0.010	0.104	0.237	0.402	0.584
		$S(3839)$, [C/A] = −0.6						
4600	1.75	−0.104	−0.044	0.049	0.175	0.328	0.493	0.656
4725	2.00	−0.104	−0.056	0.023	0.138	0.286	0.454	0.628
4850	2.40	−0.098	−0.062	0.000	0.097	0.231	0.393	0.568
5000	2.85	−0.091	−0.067	−0.024	0.049	0.159	0.304	0.472
5100	3.10	−0.089	−0.070	−0.037	0.021	0.114	0.244	0.403
		$S(3839)$, [C/A] = −0.9						
4600	1.75	−0.129	−0.094	−0.035	0.056	0.179	0.325	0.481
4725	2.00	−0.121	−0.094	−0.046	0.032	0.145	0.287	0.447
4850	2.40	−0.108	−0.088	−0.052	0.010	0.105	0.235	0.388
5000	2.85	−0.094	−0.081	−0.058	−0.015	0.057	0.164	0.302
5100	3.10	−0.090	−0.080	−0.061	−0.028	0.029	0.120	0.244

TABLE 7

C AND N ABUNDANCES FOR M5 STARS, AS DERIVED FROM SYNTHETIC SPECTRA

Star	[A/H] = −1.40 $^{12}C/^{13}C$ = 89		[A/H] = −1.40 $^{12}C/^{13}C$ = 4		[A/H] = −1.25 $^{12}C/^{13}C$ = 89	
	[C/A]	[N/A]	[C/A]	[N/A]	[C/A]	[N/A]
I-27	−0.56	1.23	...	...	−0.62	1.14
I-50	−0.77	1.52	−0.77	1.33	−0.71	1.42
II-26	−0.34	0.92	...	...	−0.38	0.82
II-32	−0.89	1.30	...	...	−0.93	1.21
II-35	−0.31	0.74	...	...	−0.35	0.65
II-50	−0.32	0.73	−0.31	0.59	−0.19	0.48
II-65	−0.42	0.92	...	...	−0.46	0.83
II-73	−0.22	0.79	...	...	−0.23	0.65
II-75	0.01	−0.14	...	...	−0.01	−0.22
III-45	−0.40	0.99	...	...	−0.44	0.89
III-52	−0.36	0.34	−0.35	0.26	−0.30	0.15
III-59	−0.64	1.31	−0.63	1.12	−0.58	1.16
III-74	−0.43	1.04	...	...	−0.47	0.91
III-79	−0.19	0.00	...	...	−0.21	−0.07
III-81	−0.28	0.84	...	...	−0.31	0.73
IV-4	−0.32	0.34	−0.31	0.25	−0.26	0.14
IV-36	−0.50	1.24	−0.50	1.05	−0.43	1.08
IV-76	−0.35	0.71	...	...	−0.39	0.63
IV-77	−0.07	0.13	...	...	−0.09	0.04
IV-83	−0.58	0.95	...	...	−0.63	0.87

interpolation. Note that unlike Briley et al. (1990) who used $(B-V)$ colors in their interpolation procedure, V_0 values were used in this study as they were assumed to be more accurate than the $(B-V)$ colors of Buonanno et al. (1981). The resulting C and N abundances are listed in Table 7 and plotted in Figure 7. The application of a Spearman rank correlation test to the computed [C/A] and [N/A] values shown in Figure 7 indicates that a very strong anticorrelation exists ($r_s = -0.89$ with a two-sided significance of 1.5×10^{-7}).

Unlike Brown, Wallerstein, & Oke (1990), we have not applied any corrections to the C abundances deduced from CH lines. The DDO system calculations of Tripicco & Bell (1991)

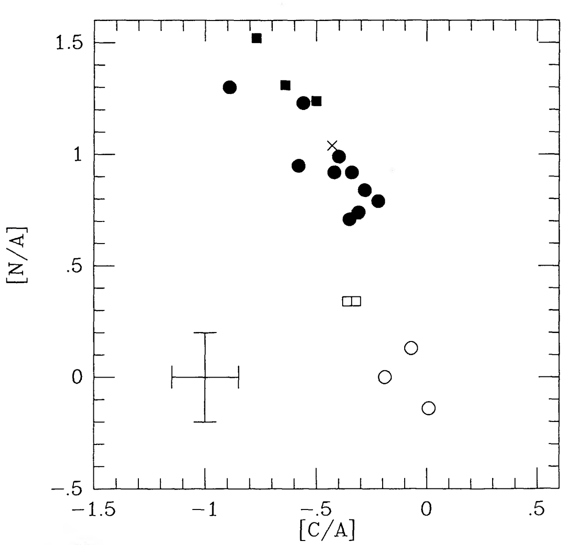

FIG. 7.—Derived [C/A] and [N/A] abundances for stars in M5, as derived from CH and CN band strengths have been plotted against each other (square markers are used for RGB stars, circles of SGB stars, and filled/unfilled for CN-strong/CN-normal, respectively). The error bars represent an error due to typical observational uncertainties.

TABLE 8

G-BAND INDICES FOR VARIOUS C ABUNDANCES AS COMPUTED FROM RGB MODELS WITH [A/H] = −1.40 AND $^{12}C/^{13}C$ = 4

Model		s_{CH}			
T_{eff}	log g	[C/A] = 0.0	[C/A] = −0.3	[C/A] = −0.6	[C/A] = −0.9
4600	1.75	0.179	0.153	0.116	0.076
4725	2.00	0.186	0.156	0.115	0.075

indicate that the programs and data which we use give CH band strengths consistent with observations of Population I giants, when the C depletion derived from spectroscopic observations of other C features is included in the calculations. Similarly, the Tripicco & Bell calculations of the 4215 Å CN bands are also consistent with observations, provided that the C depletion is accompanied by a N enhancement in the hotter Population I giants. Any errors in the derivation of the C abundance will produce errors in the N abundance when CN bands are used to derive the N values.

Some of the N abundances found in Table 7 are very high. Since the amount of free N available to form CN is reduced by N_2 formation and this depletion depends on the square of the N abundance, matching strong CN bands requires very large amounts of N.

3.2. *Sensitivity of Derived Abundances on Stellar Parameters*

In light of recent work which shows typical globular cluster giants to have $3 \leq {}^{12}C/^{13}C \leq 15$ (Brown & Wallerstein 1989; Smith & Suntzeff 1989; Bell et al. 1990; Suntzeff & Smith 1991), the grid of synthetic spectra appropriate to the brighter red giants was recalculated assuming a $^{12}C/^{13}C$ ratio of 4 (see Tables 8 and 9), and the analysis repeated. The resulting C and N abundances are listed in Table 7. Note that the cooler synthetic spectra have slightly increased 3883 Å CN absorption, due to the enhancement of ^{13}CN, while the G-band strengths remain largely unchanged. Because the CN and CH absorption is considerably weaker in the spectra of the SGB stars, the effect of a lower $^{12}C/^{13}C$ ratio on the resulting SGB abundances will be much smaller than the changes seen in Table 7

TABLE 9

CN INDICES [S(3839)] COMPUTED FOR DIFFERENT VALUES OF [C/A] AND [N/A] FROM THE [A/H] = −1.40 RGB MODEL GRID WITH $^{12}C/^{13}C$ = 4

Model		[N/A]						
T_{eff}	log g	−0.3	0.0	+0.3	+0.6	+0.9	+1.2	+1.5
				S(3839), [C/A] = 0.0				
4600	1.75	0.067	0.219	0.412	0.634	0.861	1.068	1.242
4725	2.00	0.027	0.161	0.342	0.562	0.803	1.035	1.234
				S(3839), [C/A] = −0.3				
4600	1.75	−0.041	0.065	0.216	0.406	0.624	0.845	1.044
4725	2.00	−0.058	0.030	0.164	0.343	0.560	0.796	1.020
				S(3839), [C/A] = −0.6				
4600	1.75	−0.099	−0.034	0.071	0.218	0.403	0.613	0.823
4725	2.00	−0.100	−0.048	0.039	0.170	0.346	0.556	0.781
				S(3839), [C/A] = −0.9				
4600	1.75	−0.127	−0.090	−0.026	0.077	0.219	0.396	0.593
4725	2.00	−0.119	−0.090	−0.039	0.047	0.175	0.344	0.543

TABLE 10

MODEL GRID AND RESULTING COLORS FOR THE M5 CMD WITH $[A/H] = -1.25$

T_{eff}	log g	V_0	$(B-V)_0$
4500........	1.70	13.88	0.987
4625........	1.90	14.20	0.916
4750........	2.25	14.91	0.847
4925........	2.65	15.69	0.795
5075........	3.10	16.64	0.735

for the RGB stars, and so this analysis has not been repeated for the SGB stars.

To investigate the dependence of the derived abundances on the assumed overall metallicity, a second grid of model atmospheres was computed for $[A/H] = -1.25$. The resulting model parameters are listed in Table 10, and the computed indices in Tables 11 and 12. The procedure of finding [C/A] and [N/A] was repeated and the final values are listed in Table 7.

A test of the effect of using different values of ξ was performed, by computing synthetic spectra from the 4600/1.75/−1.40 and 5100/3.00/−1.40 (T_{eff}/log g/[A/H]) models, for the abundance combinations of $[C/A] = -0.3$, $[N/A] = -0.0$, and $[C/A] = -0.6$, $[N/A] = 1.0$, and values of $\xi = 1.5$ and 2.5 km s^{-1}. The process for computing [C/A] and [N/A] (based on the $\xi = 2.0$ km s^{-1} grid) was then applied to the indices resulting from these synthetic spectra, with the results listed in Table 13.

Thus, while uncertainties in $^{12}C/^{13}C$, [A/H], and ξ appear to result in errors in [C/A] and [N/A] of 0.2 to perhaps 0.3 dex, they cannot account for the large variations seen in Figures 5, 6, and 7.

A source of uncertainty in the abundance analysis of the SGB stars derives from the photometric data. The range in $(B-V)_0$ at $V_0 \sim 16$ given by Buonanno et al. (1981) is slightly larger than 0.2 (see Fig. 1). To help explore the extent to which this would influence the results, if we had used $B-V$ instead of V in the analysis, a 5500/3.05/−1.40 model was constructed. This yielded a synthetic spectrum appropriate to a $V_0 = 16.07$, $(B-V)_0 = 0.572$ star in M5. This is very similar in brightness to the 5000/2.85/−1.40 model, which yields $V_0 = 16.10$, but has the somewhat redder color of $(B-V)_0 = 0.753$. The two models roughly represent the spread in $(B-V)_0$ seen in the Buonanno et al. photometry. With $[C/A] = -0.3$ and $[N/A] = +0.6$, the computed values of $S(3839)$ and s_{CH} are −0.061 and 0.072, respectively, for the hotter model, versus 0.150 and 0.143 for the cooler one. This difference in T_{eff} would correspond to the hotter model yielding [C/A] and [N/A] values which are 0.5 and 0.4 dex higher for a given program star, using $B-V$ in the analysis. While such errors would not result in the [C/A] versus [N/A] anticorrelation of Figure 7, they are a source of concern. To minimize the errors, the analysis used V_0 instead of $(B-V)_0$. We reiterate that the spread in $B-V$ is not seen in the CCD CMD and so we regard it as being due to observational error.

TABLE 11

G-BAND INDICES FOR VARIOUS C ABUNDANCES AS COMPUTED FROM MODELS WITH $[A/H] = -1.25$ AND $^{12}C/^{13}C = 89$

MODEL		s_{CH}			
T_{eff}	log g	$[C/A] = 0.0$	$[C/A] = -0.3$	$[C/A] = -0.6$	$[C/A] = -0.9$
4500	1.70	0.169	0.142	0.108	0.071
4625	1.90	0.182	0.152	0.115	0.076
4750	2.25	0.187	0.155	0.114	0.075
4925	2.65	0.189	0.151	0.108	0.069
5075	3.10	0.182	0.140	0.095	0.059

TABLE 12

CN INDICES [$S(3839)$] COMPUTED FOR DIFFERENT VALUES OF [C/A] AND [N/A] FROM THE $[A/H] = -1.25$ MODEL GRID WITH $^{12}C/^{13}C = 89$

MODEL		[N/A]						
T_{eff}	log g	−0.3	0.0	+0.3	+0.6	+0.9	+1.2	+1.5
		$S(3839)$, $[C/A] = 0.0$						
4500	1.70	0.098	0.242	0.403	0.569	0.729	0.877	1.013
4625	1.90	0.071	0.212	0.377	0.553	0.728	0.890	1.041
4750	2.25	0.040	0.169	0.330	0.509	0.693	0.866	1.026
4925	2.65	−0.007	0.099	0.243	0.416	0.604	0.790	0.962
5075	3.10	−0.039	0.042	0.163	0.321	0.503	0.691	0.869
		$S(3839)$, $[C/A] = -0.3$						
4500	1.70	−0.022	0.091	0.232	0.390	0.551	0.705	0.845
4625	1.90	−0.037	0.068	0.208	0.371	0.544	0.713	0.867
4750	2.25	−0.050	0.041	0.169	0.328	0.505	0.683	0.849
4925	2.65	−0.070	−0.001	0.105	0.248	0.419	0.604	0.784
5075	3.10	−0.078	−0.030	0.051	0.172	0.328	0.506	0.689
		$S(3839)$, $[C/A] = -0.6$						
4500	1.70	−0.097	−0.019	0.091	0.230	0.382	0.535	0.681
4625	1.90	−0.012	−0.031	0.073	0.210	0.369	0.534	0.695
4750	2.25	−0.098	−0.041	0.049	0.175	0.330	0.500	0.670
4925	2.65	−0.099	−0.059	0.009	0.114	0.255	0.421	0.598
5075	3.10	−0.094	−0.067	−0.019	0.062	0.180	0.332	0.503
		$S(3839)$, $[C/A] = -0.9$						
4500	1.70	−0.139	−0.089	−0.012	0.095	0.227	0.371	0.515
4625	1.90	−0.134	−0.092	−0.023	0.079	0.212	0.363	0.519
4750	2.25	−0.121	−0.088	−0.032	0.057	0.180	0.328	0.489
4925	2.65	−0.110	−0.089	−0.049	0.018	0.121	0.257	0.415
5075	3.10	−0.099	−0.084	−0.057	−0.009	0.069	0.183	0.328

3.3. *Comparison with the Langer et al. Study*

Differences in abundances measured by independent studies are not unusual, as different model atmospheres, as well as different atomic and molecular constants are often used. Indeed, the situation is made worse in the comparison between the present results and those of LKF by the use of different molecular features as well. An unfortunate drawback of using CH to derive [C/A] and then CN to find [N/A] is that any underestimation of [C/A] will cause an overestimation of

TABLE 13

THE EFFECTS OF VARYING ξ ON DERIVED ABUNDANCES

MODEL		ξ	INPUT		RESULTING		CHANGE	
T_{eff}	log g	(km s^{-1})	[C/A]	[N/A]	$S(3839)$	s_{CH}	[C/A]	[N/A]
4600	1.75	1.5	−0.3	+0.0	0.047	0.142	−0.10	−0.25
4600	1.75	2.5	−0.3	+0.0	0.037	0.168	+0.13	−0.15
4600	1.75	1.5	−0.6	+1.0	0.369	0.105	−0.08	+0.06
4600	1.75	2.5	−0.6	+1.0	0.393	0.129	+0.10	−0.08
5100	3.00	1.5	−0.3	+0.0	−0.039	0.127	−0.04	+0.09
5100	3.00	2.5	−0.3	+0.0	−0.056	0.141	+0.05	−0.10
5100	3.00	1.5	−0.6	+1.0	0.156	0.084	−0.03	+0.03
5100	3.00	2.5	−0.6	+1.0	0.153	0.094	+0.05	−0.05

TABLE 14

Derived Values of [C/A] and [N/A] for Stars in Common with Langer et al. 1985

Star	Langer et al.[a] [C/A]	Langer et al.[a] [N/A]	Present [C/A]	Present [N/A]	Difference [C/A]	Difference [N/A]
I-50	−0.94	+0.50	−0.77	+1.52	0.17	1.02
II-50	−0.46	+0.15	−0.32	+0.73	0.14	0.58
III-52	−0.42	+0.07	−0.36	+0.24	0.06	0.27
III-59	−0.59	+0.53	−0.64	+1.31	−0.05	0.78
IV-4	−0.41	+0.08	−0.32	+0.34	0.09	0.26
IV-36	−0.85	+0.48	−0.50	−1.24	0.35	0.76

[a] Values adjusted to reflect LKF's choice of 8.55 and 7.93 for the solar logarithmic C and N abundances, respectively.

[N/A]. The natural result of this is an anticorrelation in [C/A] versus [N/A]. LKF avoided this difficulty by using the 3360 Å NH bands to derive an independent [N/A]. The present results are compared with the values of LKF for both [C/A] and [N/A] in Table 14 (the values of [C/A] and [N/A] have been adjusted for their choice of 8.55 and 7.93 for the solar logarithmic abundances of C and N, respectively). While most of the determinations of [C/A] agree reasonably well (although a systematic difference of 0.2–0.4 dex in [C/A] has often been noted between the analyses of Bell et al. 1979 and Carbon et al. 1982), the values of [N/A] differ significantly, with the differences increasing with stronger CN band strengths.

A number of approaches have been taken in an attempt to understand the origins of the differences between the two sets of derived N abundances. First, synthetic m_{NH} indices were computed from the models and compared with the observed indices from LKF. Unfortunately, the synthetic m_{NH} indices were too large and lead to unreasonable values of [N/A]. Without observed spectra in the region, it is very difficult to calibrate the synthetic indices and determine the source of this problem. As another test, the LKF values of [N/A] were assumed, and the CN band strengths were then solved for [C/A] in a manner similar to the [N/A] derivation above. This resulted in C abundances several dex greater than those expected from the G-band strengths.

The absolute abundances for the six stars in common with LKF are given in Table 15, as well as the total log ϵ(C × N). To first order, the CN band strengths will be proportional to (C × N) in these stars (Smith & Bell 1986). Note that among the LKF results (C × N) tends to remain constant over the full range of CN band strengths (13.14, 13.52, 13.21 for the CN-strong, and 13.23, 13.25 for the CN-normal). The present values vary somewhat more with CN band strength (14.57, 14.49, 14.56 for the CN strong stars, and 13.80, 13.84 for the CN-normal stars), as would be expected. One simple explanation for the LKF result is that the NH bands have saturated and therefore do not adequately reflect the N abundances.

4. DISCUSSION

The present results verify the finding of Suntzeff (1989) and Suntzeff & Smith (1991): that CN and CH variations occur among M5 SGB stars. These observations, plus those of MS stars in both 47 Tuc (Hesser 1978; Briley et al. 1991) and NGC 6752 (Suntzeff 1988; Suntzeff & Smith 1991), indicate that large CN differences exist even among the relatively unevolved stars within globular clusters of high to intermediate metallicities. Indeed, any luminosity cutoff for CN variations has yet to be observed. Such findings are particularly noteworthy because they indicate that the origin of the CN variations within these globular clusters is not linked to some form of mixing which takes place during the RGB phase of evolution.

This result is to be contrasted with the findings of Bell et al. (1979), Carbon et al. (1982), Trefzger et al. (1983), Langer et al. (1986), and Briley et al. (1990), that the [C/A] abundance decreases as stars ascend the RGB in very metal poor clusters such as M92, M15, and NGC 6397. This phenomenon is most probably due to some form of mixing possibly the circulation of the lower outer envelope through a region of C → N processing as proposed by Sweigart & Mengel (1979). Stars near the RGB tip in such clusters exhibit considerable [C/A] depletions, greater than −0.7 dex (see also Bell & Dickens 1980; and Suntzeff 1989). If such extreme C depletions had been produced by the C → N processing of the envelopes of otherwise solar [C, N/A] M5 RGB stars, then a preponderance of CN weak red giants would be expected (the low C would give a very low CN abundance, as discussed by Smith, Bell, & Hesser [1989]). This is not in accord with the observations of S&N, who found that CN strong stars predominate on the upper RGB of M5.

However, an examination of Figure 8 shows that the lower RGB stars in M5 do tend toward lower [C/A] and higher [N/A] than the SGB stars, as would be expected from RGB ascent mixing. But the size of these variations are of the order the observational uncertainties, so no firm conclusion may be reached. Other clusters of similar metallicity, i.e., M3, [Fe/H] = −1.66; M13, [Fe/H] = −1.65; and NGC 6752, [Fe/H] = −1.54 (Zinn & West 1984), have been found to exhibit progressive C depletions along the RGB (Bell & Dickens 1980; Suntzeff 1981, 1989; and Suntzeff & Smith 1991), although to a smaller degree than in the [Fe/H] ≤ −2 clusters. In addition, the upper RGB and AGB stars in M3 and M13 are observed to have weak CN and CH band strengths due to their C depletions, further emphasizing the extent of the RGB ascent mixing (Norris & Zim 1977; Suntzeff 1981, 1989). Yet in the most extensively studied of the metal-rich globular clusters, 47 Tuc, such significant RGB carbon depletions have not been

TABLE 15

Derived Absolute C and N Abundances for Stars in Common with Langer et al. 1985

Star	CN Type	S(3839)	Langer et al. log ϵ(C)	Langer et al. log ϵ(N)	Langer et al. log ϵ(C × N)	Present log ϵ(C)	Present log ϵ(N)	Present log ϵ(C × N)
I-50	S	0.580	6.16	6.98	13.14	6.45	8.12	14.57
II-50	I	0.389	6.64	6.63	13.27	6.90	7.33	13.23
III-52	N	0.145	6.68	6.55	13.23	6.86	6.94	13.80
III-59	S	0.526	6.51	7.01	13.52	6.58	7.91	14.49
IV-4..............	N	0.158	6.69	6.56	13.25	6.90	6.94	13.84
IV-36	S	0.568	6.25	9.96	13.21	6.72	7.84	14.56

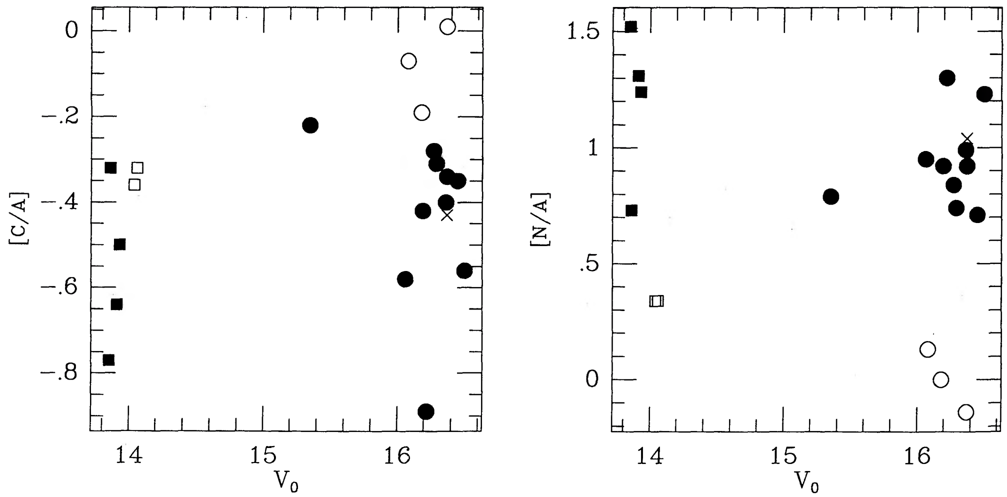

FIG. 8.—Values of $[C/A]$ and $[N/A]$ have been plotted as a function of luminosity (symbols are from Fig. 7). Note the apparently lower C abundances and higher N abundances of the RGB stars as compared to their SGB counterparts, as would be expected from RGB ascent mixing. Depletion of C is predicted to occur at roughly $V_0 = 14$ for the metal abundance of M5 (Sweigart & Mengel 1979).

observed. Dickens, Bell, & Gustafsson (1979) found a limit of $0.0 \leq [C/A] \leq -0.5$ near the RGB tip of 47 Tuc, while Bell et al. (1990) found $[C/A] = 0.0$ and -0.2 to -0.4 for two pairs of CN-normal and CN-strong RGB tip stars, respectively (assuming $\xi = 2.5$ km s^{-1} and using the CO transition probability correction of 0.2 dex in $[C/A]$ from Bell & Briley 1991). Similarly, Brown et al. (1990) derived $[C/A]$ abundances from -0.37 to -0.11 for four bright 47 Tuc RGB stars (two of which were in common with Bell et al. 1990, and assuming our solar logarithmic C abundance of 8.62 as well as their values for [Fe/H]).

These results are conveniently illustrated by Figure 14 of Bell & Dickens (1980), where the RGB tip C depletion is plotted as a function of [Fe/H] for M92, NGC 6397, M3, M13, NGC 6752, and 47 Tuc. The trend of decreasing $[C/A]$ at the RGB tip with [Fe/H] is suggestive of the Sweigart & Mengel (1979) meridional circulation models. These models predict that a zone of significant CNO processing should be located exterior to the main H burning shell in giant branch cluster stars. The size of the $C \rightarrow N$ process region, as well as the deeper and smaller $O \rightarrow N$ process region, are inversely related to the metal abundance Z. Furthermore, the molecular weight (μ) gradient, which acts to inhibit mixing, is directly related to Z in both regions. Thus, in low Z stars, the μ gradient should be insufficient to prohibit circulation through a large zone of $C \rightarrow N$ and possibly $O \rightarrow N$ processing; while in higher Z stars, not only does the larger gradient make mixing more difficult, but the $C \rightarrow N$ process zone is smaller as well. This at least qualitatively explains the Bell & Dickens (1980) result, although the start of C depletions are often observed to begin at luminosities fainter than the predictions of Sweigart & Mengel (Carbon et al. 1982; Trefzger et al. 1983; Norris & Smith 1984; Langer et al. 1986; and Briley et al. 1990).

A certain caveat to the preceding discussion is the very low $^{12}C/^{13}C$ ratios ($3 \leq {}^{12}C/^{13}C \leq 15$) observed on the 47 Tuc RGB (Brown & Wallerstein 1989; Bell et al. 1990; Brown et al. 1990), which imply that the mixing of $C \rightarrow N$ processed material into the atmosphere has occurred, despite there being apparently little change in surface $[C/A]$ (C being $^{12}C + {}^{13}C$). Very low $^{12}C/^{13}C$ ratios have also been observed in M67 upper RGB stars with, surprisingly, no appreciable decline in C/N (Gilroy & Brown 1991). Simple modeling of extreme RGB ascent mixing by Sneden, Pilachowski, & VandenBerg (1986) and VandenBerg & Smith (1988) indicates that a drop in $^{12}C/^{13}C$ will be the first observable change due to mixing, long before any decrease in C abundance becomes measurable. Should this be the case, the low 47 Tuc $^{12}C/^{13}C$ ratios may indicate that RGB mixing has occurred to some extent even within this cluster.

It is probable that two mechanisms are required to explain the CN variations observed in M5, 47 Tuc, M3, M13, and many other clusters: (1) some process which results in the CN inhomogeneities observed among the relatively unevolved MS and SGB stars and (2) RGB ascent mixing which produces a decrease in $[C/A]$ with luminosity and low RGB tip $^{12}C/^{13}C$ ratios. This conclusion was also reached for 47 Tuc, M4, NGC 6752, and M22 by Brown et al. (1990) and Suntzeff & V. Smith (1991). That $[C + N/Fe]$ is constant to less than 0.2 dex in both M3 and M13 (Suntzeff 1989) is not inconsistent with (1), as two stars leaving the MS, one with $[C/Fe] = [N/Fe] = 0.0$ and the other with $[C/Fe] = 0.0$ and $[N/Fe] = +0.6$, will have the same $[(C + N)/Fe]$ to 0.2 dex and yet appear to have very different CN band strengths. If they both reach $[C/Fe] = -1.0$ on the RGB they will be different in [N/Fe] by only 0.21 dex (assuming that C + N is held constant).

Of course, a pre–MS/SGB abundance altering mechanism has yet to be determined, and it is undoubtably not only dependent on [Fe/H]. A comparison of the observed CN band strengths as well as the derived N abundances for M3 and M13, two clusters of almost identical metallicities, reveals significant differences, despite their similar C abundances (cf. Figs. 6 and 9 of Suntzeff 1989). Also, CN-rich stars are observed to occur far less frequently in the field. The surveys of field dwarfs by Clegg, Lambert, & Tomkin (1981); Tomkin & Lambert (1984), Laird (1985); and Carbon et al. (1987) found very little scatter in [N/Fe] among stars of similar [Fe/H] over the abundance range of $-2.0 \leq [Fe/H] \leq +0.3$. Only 5% of the stars in Laird's sample appear to have high N abundances, four of which were further observed by Spite & Spite (1986) and shown not to have undergone any deep convective dredge-up. Thus the early abundance altering mechanism would seem to be much more efficient in the cluster environments. The observation by Norris (1987) that the ratio of CN-strong to CN-normal stars within a cluster is loosely related to cluster ellipticity, as well as the conclusion of Paltoglou (1991) that there is a radial gradient in this ratio within 47 Tuc, also limit the possible mechanisms, as such dependences would seem hard to produce via mixing processes.

Clearly, further investigations of CN variations among faint stars are required—not only to determine the luminosity at which the variations begin, but to provide statistics on the distribution of CN strengths as cluster stars evolve (i.e., does the ratio of CN-strong to CN-normal stars change with evolution as suggested by Hartwick & McClure 1980 and Suntzeff & Smith 1991).

5. CONCLUSIONS

From Figure 5, it has been shown that the 3883 Å CN bimodality in M5 seen in the bright giants exists well onto the SGB in accord with the findings of Suntzeff (1989). Indeed, given the observations of significant CN variations within NGC 6752 at $M_V = +6$ by Suntzeff (1989), as well as on the MS of 47 Tuc (Briley et al. 1991) and over the luminosity range of $+1 < M_V < +2$ in NGC 6752 (Norris et al. 1991; Bell, Hesser, & Cannon 1984), NGC 362 (Smith 1983), and M3 (Norris & Smith 1984), such a result is not surprising. That CN variations occur among such unevolved stars provides a significant constraint on any theory which attributes these variations to a mixing or internal circulation mechanism.

However, Figure 8 appears to suggest the possibility that the M5 RGB stars tend to have lower C and higher N abundances than their SGB counterparts. Similar results have been obtained for other intermediate metallicity clusters (M3, M13, and NGC 6752, Bell & Dickens 1980; Suntzeff 1981, 1989; and Suntzeff & Smith 1991) and are commonly attributed to RGB ascent mixing.

Thus it is suggested that two mechanisms are required to explain the CN variations in M5; one providing the early MS/SGB abundance inhomogeneities, and another to produce RGB ascent C depletions. Given the similarity between M5, M3, M13, and other intermediate metallicity clusters (in terms of the presence of low-luminosity CN variations and low RGB tip [C/A] abundances), two mechanisms are also likely required to explain the CN inhomogeneities in many globular clusters.

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REFERENCES

Bell, R. A., & Briley, M. M. 1991, AJ, 102, 763
Bell, R. A., Briley, M. M., & Smith, G. H. 1990, AJ, 100, 187
Bell, R. A., & Dickens, R. J. 1980, ApJ, 242, 657
Bell, R. A., Dickens, R. J., & Gustafsson, B. 1979, ApJ, 229, 604
Bell, R. A., & Gustafsson, B. 1978, A&AS, 34, 229
———. 1989, MNRAS, 236, 653
Bell, R. A., Hesser, J. E., & Cannon, R. D. 1984, ApJ, 283, 615
Buonanno, R., Corsi, C. E., & Fusi Pecci, F. 1981, MNRAS, 196, 435
Butler, D. 1975, ApJ, 200, 68
Briley, M. M., Bell, R. A., Hoban, S., & Dickens, R. J. 1990, ApJ, 359, 307
Briley, M. M., Hesser, J. E., & Bell, R. A. 1991, ApJ, 373, 482
Brown, J. A., & Wallerstein, G. 1989, AJ, 98, 1643
Brown, J. A., Wallerstein, G., & Oke, J. B. 1990, AJ, 100, 1561
Carbon, D. F., Barbuy, B., Kraft, R. P., Friel, E. D., & Suntzeff, N. B. 1987, PASP, 99, 335
Carbon, D. F., Langer, G. E., Butler, D., Kraft, R. P., Suntzeff, N. B., Kemper, E., Trefzger, C. F., & Romanishin, W. 1982, ApJS, 49, 207
Clegg, R. E. S., Lambert, D. L., & Tomkin, J. 1981, ApJ, 250, 262
Dickens, R. J., Bell, R. A., & Gustafsson, B. 1979, ApJ, 232, 428
Frogel, J. A., Cohen, J. G., & Persson, S. E. 1983, ApJ, 275, 773
Gilroy, K. K., & Brown, J. A. 1991, ApJ, 371, 578
Gratton, R. G. 1987, A&A, 177, 177
Gustafsson, B., Bell, R. A., Eriksson, K., & Nordlund, Å. 1975, A&A, 42, 407
Hartwick, F. D. A., & McClure, R. D. 1980, ApJ, 235, 470
Hesser, J. E. 1978, ApJ, 223, L117
Laird, J. B. 1985, ApJ, 289, 556
Langer, G. E., Kraft, R. P., Carbon, D. F., Friel, E. D., & Oke, J. B. 1986, PASP, 98, 473
Langer, G. E., Kraft, R. P., & Friel, E. D. 1985, PASP, 97, 373 (LKF)
Matthews, T. A., & Sandage, A. R. 1963, ApJ, 138, 30
Norris, J. 1987, ApJ, 313, L65
———. 1988, in IAU Symposium 126, Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies, ed. J. E. Grindlay & A. G. Davis Phillip (Dordrecht: Kluwer), 93
Norris, J., Cottrell, P. L., Freeman, K. C., & Da Costa, G. S. 1981, ApJ, 244, 205
Norris, J., & Smith, G. H. 1984, ApJ, 287, 255
———. 1985, AJ, 90, 2526
Norris, J., & Zinn, R. 1977, ApJ, 215, 74
Osborn, W. H. 1971, Observatory, 91, 223
Paltoglou, G. 1991, in preparation
Pilachowski, C. A., Olszewski, E. W., & Odell, A. 1983a, PASP, 95, 713
Pilachowski, C. A., Sneden, C., & Wallerstein, G. 1983b, ApJS, 52, 241
Pilachowski, C. A., Wallerstein, G., & Leep, E. M. 1980, ApJ, 236, 508
Richer, H. B., & Fahlman, G. G. 1987, ApJ, 316, 189
Searle, L., & Zinn, R. 1978, ApJ, 225, 357
Smith, G. H. 1983, AJ, 88, 40
———. 1987, PASP, 99, 67
———. 1989, in The Abundance Spread within Globular Clusters: Spectroscopy of Individual Stars, ed. G. Cayrel de Strobel, M. Spite, & T. Lloyd Evans (Paris: Obs. de Paris-Meudon), 63
Smith, G. H., & Bell, R. A. 1986, AJ, 91, 1121
Smith, G. H., Bell, R. A., & Hesser, J. E. 1989, ApJ, 341, 190
Smith, G. H., & Norris, J. 1983, ApJ, 264, 213 (S&N)
Smith, V. V., & Suntzeff, N. B. 1989, AJ, 97, 1699
Sneden, C., Pilachowski, C. A., & VandenBerg, D. A. 1986, ApJ, 311, 826
Spite, F., & Spite, M. 1986, A&A, 163, 140
Suntzeff, N. B. 1981, ApJS, 47, 1
———. 1989, in The Abundance Spread within Globular Clusters: Spectroscopy of Individual Stars, ed. G. Cayrel de Strobel, M. Spite, & T. Lloyd Evans (Paris: Obs. de Paris-Meudon), 71
Suntzeff, N. B., & Smith, V. V. 1991, AJ, in press
Sweigart, A. V., & Mengel, J. G. 1979, ApJ, 229, 624
Tomkin, J., & Lambert, D. L. 1984, ApJ, 279, 220
Trefzger, C. F., Carbon, D. F., Langer, G. E., Suntzeff, N. B., & Kraft, R. P. 1983, ApJ, 266, 144
Tripicco, M. J., & Bell, R. A. 1991, AJ, 102, 744
VandenBerg, D. A., & Smith, G. H. 1988, PASP, 100, 314
Zinn, R. 1977, ApJ, 218, 96
———. 1980, ApJS, 42, 19
Zinn, R., & West, M. J. 1984, ApJS, 55, 45