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VARIATIONS IN $^{12}C/^{13}C$ AS AN EXPLANATION FOR THE 3883 Å CN-BIMODALITY AMONG 47 TUCANAE SUBGIANTS

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ABSTRACT

Spectroscopic observations of subgiants in the metal-rich ([M/H] = −0.8) globular cluster 47 Tucanae have been used to measure the strengths of the CN bands located at 3883 Å and 4215 Å. A bimodal distribution is clearly seen in the 3883 Å CN band strengths, but not in the 4215 Å bands. Synthetic spectrum calculations have been used to probe the effect on both CN bands of varying the $^{12}C/^{13}C$ ratio. The sensitivity of the 3883 Å CN feature to ^{13}C relative abundance is found to be considerably higher than that of the 4215 Å band for the stars observed. Spectroscopic indices derived from these features are consequently observable probes of atmospheric $^{13}C/^{12}C$ enhancements. It is thus suggested that the bimodality observed in the 3883 Å CN band may be due in large measure to a difference in the $^{12}C/^{13}C$ ratios of the two groups.

Subject headings: clusters: globular — stars: abundances

I. INTRODUCTION

CN band strength variations are known to occur among members of a large number of metal-rich to intermediate-metallicity ($-0.5 < [M/H] < -1.6$) globular clusters. Many of these variations appear bimodal in distribution, with a population of seemingly CN-normal stars, and another population of CN-strong stars (notably 47 Tuc, Hesser, Hartwick, and McClure 1977; Hesser 1978; Norris and Freeman 1979; NGC 6752, Norris *et al.* 1981; Bell, Hesser, and Cannon 1984; M5, Smith and Norris 1983; and NGC 6934, Smith and Bell 1986; see Smith 1987 and Norris 1988 for recent reviews).

The mixing of CN-process material from the shell-burning regions of stars has long been suggested as a possible cause of the CN band strength variations (e.g., Sweigart and Mengel 1979; Smith 1987). While theories of stellar evolution seem to have difficulty describing the exact mechanism, the results of such a process are well defined. They include an increase in the atmospheric nitrogen abundance at the expense of carbon due to the nitrogen bottle-neck in the equilibrium CN-cycle. A similar abundance anomaly may occur for oxygen as well, if the mixing should reach into the oxygen-deficient, nitrogen-rich areas in ON-processed regions.

Smith, Bell, and Hesser (1989, hereafter SBH89) have discussed the 4215 Å CN band strengths of a sample of 26 giants and subgiants with $M_V > +0.5$ in 47 Tucanae. A population of CN-normal and CN-enhanced stars was identified. The surface abundances of C, N, and O needed to match the observed strengths of the band were determined. Somewhat surprisingly from the viewpoint of stellar interior theory, it was found that the enhanced CN band strengths could be explained only if either ON process material (rich in C and N, and depleted in O) had been mixed with the stellar surface material, or if a primordial nitrogen abundance enhancement existed. The former explanation is supported by the fact that 47 Tuc red giant stars with strengthened CN bands have weakened CO bands.

Following the completion of the paper by SBH89, an index dependent on the strength of the 3883 Å CN band was measured. It was noted that the cluster stars exhibit a bimodal range in a plot of this index versus V magnitude, whereas no such bimodality exists in the plot of a 4215 Å index versus V. Synthetic spectrum calculations show that this effect cannot be produced by changes in C, N, or O abundances, but can be caused by changes in the $^{12}C/^{13}C$ ratio.

II. OBSERVATIONS

The spectra analyzed in the present paper were previously discussed by SBH89, to which the reader is referred to for full details. In brief, spectra were obtained of the sample of subgiants in 47 Tucanae given in Table 1, on the nights of 1987 August 31 and September 1 and 2 with the CTIO 4 m telescope and RC spectrograph. The majority of these stars have magnitudes in the range $14.5 < V < 15.5$, or $+1.1 < M_V < +2.1$ upon adopting an apparent distance modulus to 47 Tuc of $V - M_V = 13.40$ (Hesser *et al.* 1987). Resolutions of ~2–4.5 Å (FWHM) were achieved in the spectra. All aspects of the data reduction were carried out with the IRAF software package.

A number of spectroscopic indices designed to quantify the strengths of the violet 3883 Å and 4215 Å bands have been computed from the spectra. These indices are defined as follows:

$$S(3839) = -2.5 \log (\bar{F}_{\lambda,\mathrm{CN38}}/\bar{F}_{\lambda,\mathrm{CP38}}) ,$$

$$s_{\mathrm{CN}} = -2.5 \log (\bar{F}_{\lambda,\mathrm{CN42}}/\bar{F}_{\lambda,\mathrm{CP42}}) ,$$

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TABLE 1

SPECTROSCOPIC INDICES FOR 47 TUC SUBGIANTS

Star (1)	V (2)	$(B-V)_0$ (3)	$S(3839)$ (4)	$\delta S(3839)$ (5)	s_{CN} (6)	δs_{CN} (7)
4-2082	13.96	0.95	0.194	−0.184	−0.010	−0.022
4-2106	14.10	0.96	0.593	0.234	0.224	0.215
4-2151	14.22	0.96	0.754	0.412	0.244	0.239
4-2177	14.37	0.93	0.306	−0.016	0.037	0.036
AW-1	14.585	0.918	0.273	−0.019	0.064	0.069
AW-2	14.590	0.928	0.251	−0.041	0.018	0.024
1-9038	14.615	0.901	0.582	0.294	0.123	0.129
AW-3	14.817	0.854	0.841	0.580	0.176	0.188
5-3344	14.93	0.89	0.487	0.242	0.082	0.097
AW-4	14.944	0.902	0.504	0.261	0.103	0.118
5-1528	14.98	0.85	0.556	0.317	0.115	0.131
5-1620	15.01	0.87	0.682	0.448	0.108	0.125
5-3348	15.03	0.89	0.475	0.243	0.144	0.162
5-3363	15.03	0.88	0.219	−0.013	0.012	0.030
1-9016	15.037	0.91	0.552	0.321	0.121	0.139
5-3571	15.06	0.88	0.600	0.372	0.145	0.164
5-2466	15.06	0.81	0.201	−0.027	0.028	0.047
5-3380	15.10	0.85	0.731	0.509	0.170	0.190
5-3307	15.17	0.90	0.289	0.076	0.039	0.061
5-3375	15.22	0.82	0.437	0.231	0.113	0.136
AW-5	15.379	0.832	0.248	0.064	−0.038	−0.010
5-1527	15.38	0.81	0.535	0.351	0.104	0.132
5-3310	15.38	0.87	0.484	0.300	0.055	0.083
1-9015	15.493	0.868	0.454	0.285	0.083	0.113
AW-6	15.617	0.819	0.085	−0.067	−0.053	−0.019
AW-7	15.967	0.815	0.121	0.017	−0.057	−0.013

where $\bar{F}_\lambda$ refers to the mean flux per pixel over a specified wavelength range. The wavelength ranges over which these mean fluxes $\bar{F}_\lambda$ have been computed are listed in Table 2. The indices are defined in such a way as to increase in value as the CN bands increase in strength. Values of the indices are listed in Table 1. The designations of the program stars given in column (1) of this table are explained in SBH89. Three of the 47 Tuc program stars and two flux standards were observed on more than one night, and their repeated observations were used to estimate the observational uncertainties in the $S(3839)$ measurements. The uncertainty of ~ 0.05 mag thereby estimated should be treated with caution in view of the small number of spectra from which it is derived.

III. THE CN DISTRIBUTION AMONG THE 47 TUC SUBGIANTS

The $S(3839)$ indices of the 47 Tuc subgiants are plotted versus V magnitude in Figure 1. Intrinsic variations among stars of comparable magnitudes are evident, the range in $S(3839)$ among $V \sim 15.0$ subgiants being ~ 0.55 or $\sim 11\ \sigma$. These 3883 Å CN variations are illustrated in Figure 4 of SBH89, which shows spectra of four such stars. In order to facilitate a comparison of stars having different magnitudes, the displacements of the $S(3839)$ indices have been measured relative to a straight line having the equation $S(3839) = -0.136V + 2.282$, which was chosen to provide a reasonable lower baseline to the data. These CN-excess indices, denoted as $\delta S(3839)$, are recorded in Table 1, while the baseline is shown in Figure 1. A smoothed distribution of these values, in which each data point is replaced by a Gaussian kernel with $\sigma = 0.04$, is shown in Figure 2. It is noticeably bimodal. Both Figures 1 and 2 indicate that on the basis of the 3883 Å CN band strengths, the observed 47 Tuc subgiants can be divided into a CN-rich and a CN-normal population, in a manner analogous to the brighter giants (e.g., Norris and Freeman 1979).

The behavior of the s_{CN} indices among the 47 Tuc subgiants is discussed by SBH89, who also calculated a 4215 Å CN-excess index δs_{CN}, using the baseline equation $s_{CN} = -0.028V + 0.403$. A smoothed histogram of the δs_{CN} indices is shown in Figure 2, for a kernel of $\sigma = 0.02$. Unlike the case for the 3883 Å CN band, this distribution does not reveal a clear bimodality. The two sets of indices do correlate well; however, whereas there is essentially a continuum in δs_{CN} values, there are no $\delta S(3839)$ indices in the range 0.08–0.23 (see Table 1 and Figure 2). It is this relative behavior of these two CN bands which we wish to investigate.

TABLE 2

WAVELENGTH RANGES FOR $\bar{F}_\lambda$ CALCULATIONS

Mean Flux	Wavelength Range (Å)
$\bar{F}_{\lambda,\mathrm{CN38}}$	3846–3883
$\bar{F}_{\lambda,\mathrm{CP38}}$	3883–3916
$\bar{F}_{\lambda,\mathrm{CN42}}$	4140–4220
$\bar{F}_{\lambda,\mathrm{CP42}}$	4220–4280

IV. MODELS AND SYNTHETIC SPECTRA

A series of line-blanketed, plane-parallel, flux-constant model atmospheres, which include the effects of convection, were generated using the MARCS program (Gustafsson *et al.* 1975). These models were chosen as representative of the subgiant branch of 47 Tuc ([M/H] = −0.8), following SBH89. The models used were ones which correspond to stars with V magnitudes between 14.43 and 15.22. A fourth model for $V = 13.88$ was also added to better match the range in V of the stars observed. The SSG program (Bell and Gustafsson 1978) was then used to compute grids of synthetic spectra from the

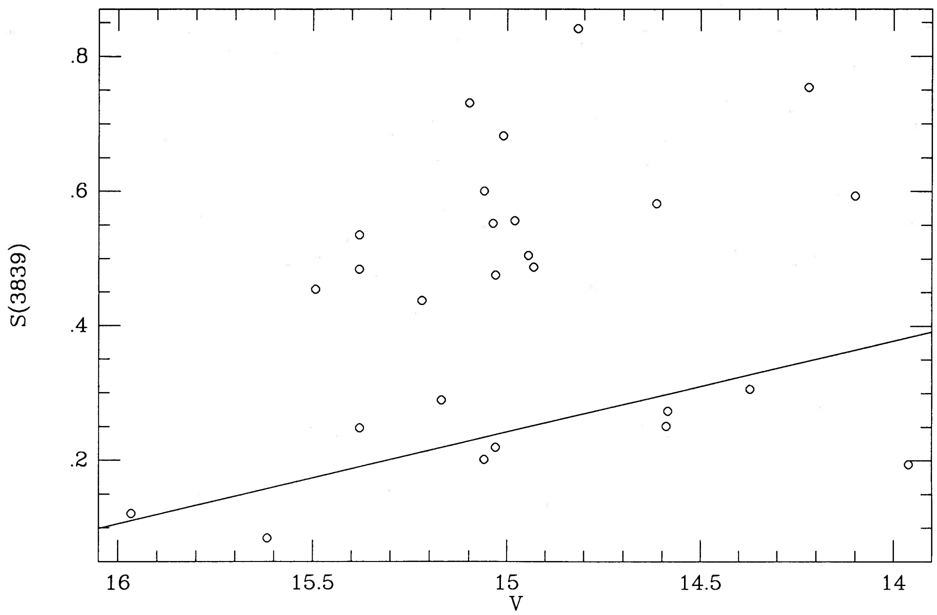

FIG. 1.—Observed values of the $S(3883)$ index vs. V magnitude are plotted for the stars listed in Table 1. The baseline $-0.136V + 2.282$ used in the $\delta S(3839)$ calculation is also shown. A bimodality in $S(3839)$ is quite evident.

models for a variety of carbon, nitrogen, and oxygen abundances, and changing $^{12}C/^{13}C$ ratios. The spectra were calculated as in SBH89, with a Doppler broadening velocity of 2.0 km s^{-1} over the range of 3000–12,000 Å, and a resolution of 0.1 Å.

The logarithmic solar C, N, and O abundances were considered to be 8.62, 8.00, and 8.86 respectively, relative to hydrogen = 12.0. These abundances were adopted as the standard ones for the cluster stars upon being scaled down by the cluster metallicity [M/H] = −0.8. Variations in CNO abundances were patterned after the groups *a*, *b*, and *c* described in SBH89. Thus, the spectra in group *a* assume no change in the relative ratios of C, N, and O, while group *b* simulates the effect of C-N processed material being mixed into the atmosphere, and group *c* reflects the addition of both C-N and O-N processed material. In all cases, the total amount of CNO elements present was kept fixed.

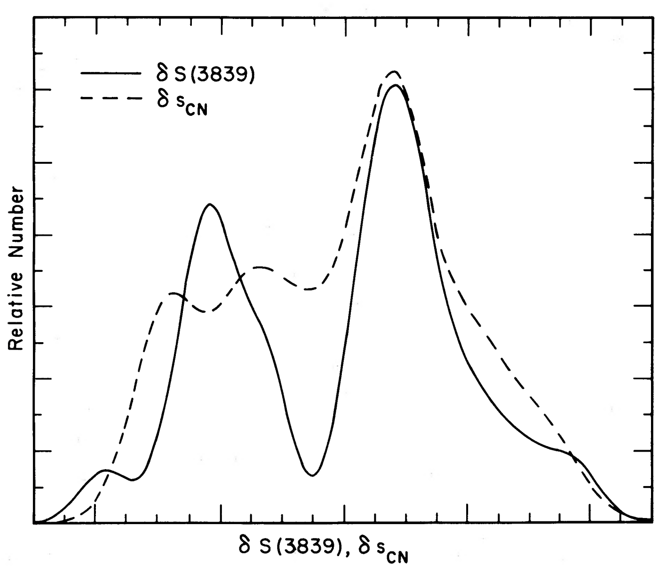

FIG. 2.—The smoothed distributions of $\delta S(3839)$ and δs_{CN} are plotted together. Each data point has been replaced by a Gaussian kernel of $\sigma = 0.04$ for $\delta S(3839)$ (*solid curve*), and a kernel of $\sigma = 0.02$ for δs_{CN} (*dashed curve*). While the 3883 Å band exhibits a bimodality, the 4215 Å band appears to have a much smoother distribution.

Spectra in groups *a*, *b*, and *c* were calculated first with a solar $^{12}C/^{13}C$ ratio of 89. A second series of spectra were also computed with a $^{12}C/^{13}C$ ratio of 10, and a third group with a characteristic equilibrium CN-burning ratio of 4. The resulting $S(3839)$ and s_{CN} indices are listed in Table 3 along with the corresponding $\delta S(3839)$ and δs_{CN} values.

Sample synthetic spectra for $T_{eff} = 4750$ K, $\log g = 2.70$, [A/H] = −0.8, $\Delta C = -0.10$, $\Delta N = +0.26$ (Δ indicating the logarithmic change in abundance with respect to the solar ratio), with $^{12}C/^{13}C = 89$ and 4 are shown in Figure 3 over the regions appropriate to the passbands of the $S(3839)$ and s_{CN} indices. Both regions have been normalized to a continuum flux of 1.0 to better emphasize the difference in response to the $^{12}C/^{13}C$ ratio. It can be seen that as the lines of the 4215 Å CN band are relatively weak, the sensitivity of this band to $^{12}C/^{13}C$ changes is low. In fact, the 4215 Å band index is sometimes reduced as the $^{12}C/^{13}C$ value is reduced, owing to the increase in strength in the CH features in the comparison band exceeding the increase in the CN lines. However, the 3883 Å CN band lines are much stronger, and much more responsive to $^{12}C/^{13}C$ variations, exhibiting substantial increases in strength with the reduction of this ratio. This is further shown in Figure 4, where the $S(3839)$ and s_{CN} indices from the $T_{eff} = 4500$ K, $\log g = 2.25$, [A/H] = −0.8 model for groups *a*, *b*, and *c* are plotted. The effect of $^{12}C/^{13}C$ on the $S(3839)$ index is pronounced. The change in $^{12}C/^{13}C$ from 89 to 4 in solar C/N/O ratio spectra results in 3883 Å CN band strength increases greater than those induced by decreasing C by −0.1 and increasing N by 0.26. Note in fact, that for a given $^{12}C/^{13}C$ value, the group *b* models with $\Delta C = -0.3$ and $\Delta N = +0.49$ exhibit less of an enhancement in $S(3839)$ than

TABLE 3

A. CN INDICES DERIVED FROM SYNTHETIC SPECTRA WITH SOLAR $^{12}C/^{13}C$

T_{eff}	Log g	ΔC	ΔN	ΔO	V	$(B-V)_0$	$S(3839)$	$\delta S(3839)$	s_{CN}	δs_{CN}
					Group *a*					
4400	2.00	−0.00	+0.00	+0.00	13.88	1.019	0.44	0.045	0.011	−0.003
4500	2.25	−0.00	+0.00	+0.00	14.43	0.967	0.42	0.100	−0.004	−0.003
4625	2.50	−0.00	+0.00	+0.00	14.88	0.910	0.38	0.122	−0.018	−0.004
4750	2.70	−0.00	+0.00	+0.00	15.22	0.859	0.32	0.108	−0.032	−0.020
					Group *b*					
4400	2.00	−0.10	+0.26	+0.00	13.88	1.016	0.49	0.095	0.049	0.035
4500	2.25	−0.10	+0.26	+0.00	14.43	0.964	0.48	0.160	0.035	0.036
4625	2.50	−0.10	+0.26	+0.00	14.88	0.907	0.45	0.192	0.020	0.034
4750	2.70	−0.10	+0.26	+0.00	15.22	0.856	0.40	0.188	0.006	0.029
4400	2.00	−0.30	+0.49	+0.00	13.88	1.005	0.47	0.075	0.061	0.047
4500	2.25	−0.30	+0.49	+0.00	14.43	0.954	0.46	0.140	0.049	0.050
4625	2.50	−0.30	+0.49	+0.00	14.88	0.897	0.44	0.182	0.038	0.052
4750	2.70	−0.30	+0.49	+0.00	15.22	0.846	0.40	0.188	0.026	0.049
					Group *c*					
4400	2.00	−0.20	+0.61	−0.10	13.88	1.021	0.65	0.255	0.136	0.122
4500	2.25	−0.20	+0.61	−0.10	14.43	0.969	0.64	0.320	0.119	0.120
4625	2.50	−0.20	+0.61	−0.10	14.88	0.912	0.62	0.362	0.101	0.115
4750	2.70	−0.20	+0.61	−0.10	15.22	0.861	0.58	0.368	0.082	0.105
4400	2.00	−0.30	+0.76	−0.20	13.88	1.021	0.70	0.305	0.169	0.155
4500	2.25	−0.30	+0.76	−0.20	14.43	0.969	0.70	0.380	0.153	0.154
4625	2.50	−0.30	+0.76	−0.20	14.88	0.912	0.67	0.412	0.134	0.148
4750	2.70	−0.30	+0.76	−0.20	15.22	0.860	0.63	0.418	0.112	0.135

B. CN INDICES DERIVED FROM SYNTHETIC SPECTRA WITH $^{12}C/^{13}C=10$

T_{eff}	Log g	ΔC	ΔN	ΔO	V	$(B-V)_0$	$S(3839)$	$\delta S(3839)$	s_{CN}	δs_{CN}
					Group *a*					
4400	2.00	−0.00	+0.00	−0.00	13.88	1.024	0.54	0.146	0.001	−0.013
4500	2.25	−0.00	+0.00	−0.00	14.43	0.972	0.51	0.190	−0.014	−0.013
4625	2.50	−0.00	+0.00	−0.00	14.88	0.914	0.46	0.202	−0.030	−0.016
4750	2.70	−0.00	+0.00	−0.00	15.22	0.863	0.39	0.178	−0.043	−0.020
					Group *b*					
4400	2.00	−0.10	+0.26	−0.00	13.88	1.020	0.61	0.216	0.046	0.032
4500	2.25	−0.10	+0.26	−0.00	14.43	0.968	0.59	0.270	0.030	0.031
4625	2.50	−0.10	+0.26	−0.00	14.88	0.911	0.55	0.292	0.013	0.027
4750	2.70	−0.10	+0.26	−0.00	15.22	0.860	0.49	0.278	−0.002	0.021
4400	2.00	−0.30	+0.49	−0.00	13.88	1.008	0.58	0.186	0.061	0.047
4500	2.25	−0.30	+0.49	−0.00	14.43	0.957	0.56	0.240	0.048	0.049
4625	2.50	−0.30	+0.49	−0.00	14.88	0.899	0.53	0.272	0.035	0.049
4750	2.70	−0.30	+0.49	−0.00	15.22	0.849	0.49	0.278	0.023	0.046
					Group *c*					
4400	2.00	−0.20	+0.61	−0.10	13.88	1.026	0.80	0.406	0.144	0.130
4500	2.25	−0.20	+0.61	−0.10	14.43	0.974	0.79	0.470	0.125	0.126
4625	2.50	−0.20	+0.61	−0.10	14.88	0.916	0.76	0.502	0.104	0.118
4750	2.70	−0.20	+0.61	−0.10	15.22	0.865	0.71	0.498	0.081	0.104
4400	2.00	−0.30	+0.76	−0.20	13.88	1.026	0.86	0.466	0.184	0.170
4500	2.25	−0.30	+0.76	−0.20	14.43	0.974	0.86	0.540	0.164	0.165
4625	2.50	−0.30	+0.76	−0.20	14.88	0.916	0.83	0.572	0.141	0.155
4750	2.70	−0.30	+0.76	−0.20	15.22	0.864	0.78	0.568	0.116	0.139

C. CN INDICES DERIVED FROM SYNTHETIC SPECTRA WITH $^{12}C/^{13}C = 4$

T_{eff}	Log g	ΔC	ΔN	ΔO	V	$(B-V)_0$	$S(3839)$	$\delta S(3839)$	s_{CN}	δs_{CN}
					Group *a*					
4400	2.00	−0.00	+0.00	−0.00	13.88	1.019	0.61	0.215	−0.002	−0.016
4500	2.25	−0.00	+0.00	−0.00	14.43	0.967	0.58	0.260	−0.020	−0.019
4625	2.50	−0.00	+0.00	−0.00	14.88	0.910	0.52	0.262	−0.037	−0.023
4750	2.70	−0.00	+0.00	−0.00	15.22	0.859	0.45	0.238	−0.052	−0.029

TABLE 3—*Continued*

T_{eff}	Log g	ΔC	ΔN	ΔO	V	$(B-V)_0$	$S(3839)$	$\delta S(3839)$	s_{CN}	δs_{CN}
					Group b					
4400...........	2.00	−0.10	+0.26	−0.00	13.88	1.016	0.68	0.285	0.045	0.031
4500...........	2.25	−0.10	+0.26	−0.00	14.43	0.964	0.66	0.340	0.027	0.028
4625...........	2.50	−0.10	+0.26	−0.00	14.88	0.907	0.62	0.362	0.009	0.023
4750...........	2.70	−0.10	+0.26	−0.00	15.22	0.856	0.55	0.338	−0.008	0.015
4400...........	2.00	−0.30	+0.49	−0.00	13.88	1.011	0.64	0.245	0.062	0.048
4500...........	2.25	−0.30	+0.49	−0.00	14.43	0.959	0.63	0.310	0.047	0.048
4625...........	2.50	−0.30	+0.49	−0.00	14.88	0.902	0.60	0.342	0.033	0.047
4750...........	2.70	−0.30	+0.49	−0.00	15.22	0.851	0.55	0.338	0.020	0.043
					Group c					
4400...........	2.00	−0.20	+0.61	−0.10	13.88	1.021	0.87	0.475	0.154	0.140
4500...........	2.25	−0.20	+0.61	−0.10	14.43	0.969	0.87	0.550	0.132	0.133
4625...........	2.50	−0.20	+0.61	−0.10	14.88	0.912	0.84	0.582	0.108	0.122
4750...........	2.70	−0.20	+0.61	−0.10	15.22	0.861	0.79	0.578	0.083	0.106
4400...........	2.00	−0.30	+0.76	−0.20	13.88	1.021	0.94	0.545	0.199	0.185
4500...........	2.25	−0.30	+0.76	−0.20	14.43	0.969	0.94	0.620	0.176	0.177
4625...........	2.50	−0.30	+0.76	−0.20	14.88	0.912	0.91	0.652	0.149	0.163
4750...........	2.70	−0.30	+0.76	−0.20	15.22	0.860	0.86	0.648	0.121	0.144

the less processed models with ΔC = −0.1 and N = +0.26. This effect has been discussed by Smith and Bell (1986) and illustrates the point that in the case of a subgiant atmosphere that has been partially processed through the CN-cycle only, the changes in the 3883 Å CN band strength are driven predominantly by the changes in the $^{12}C/^{13}C$ ratio. The changes in s_{CN} are much smaller than those in $S(3839)$, and in some instances are negative, as mentioned above.

V. DISCUSSION

It has long been proposed that the CN-rich stars in globular clusters owe their CN enhancements to the existence of deep interior mixing which has dredged up CN-processed material (see, e.g., Langer and Kraft 1984; Langer 1985; SBH89), whereas the CN-normal stars have remained relatively unmixed. We can use this assumption to interpret the behavior of the 47 Tuc subgiants in Figure 5, which shows a plot of δs_{CN}

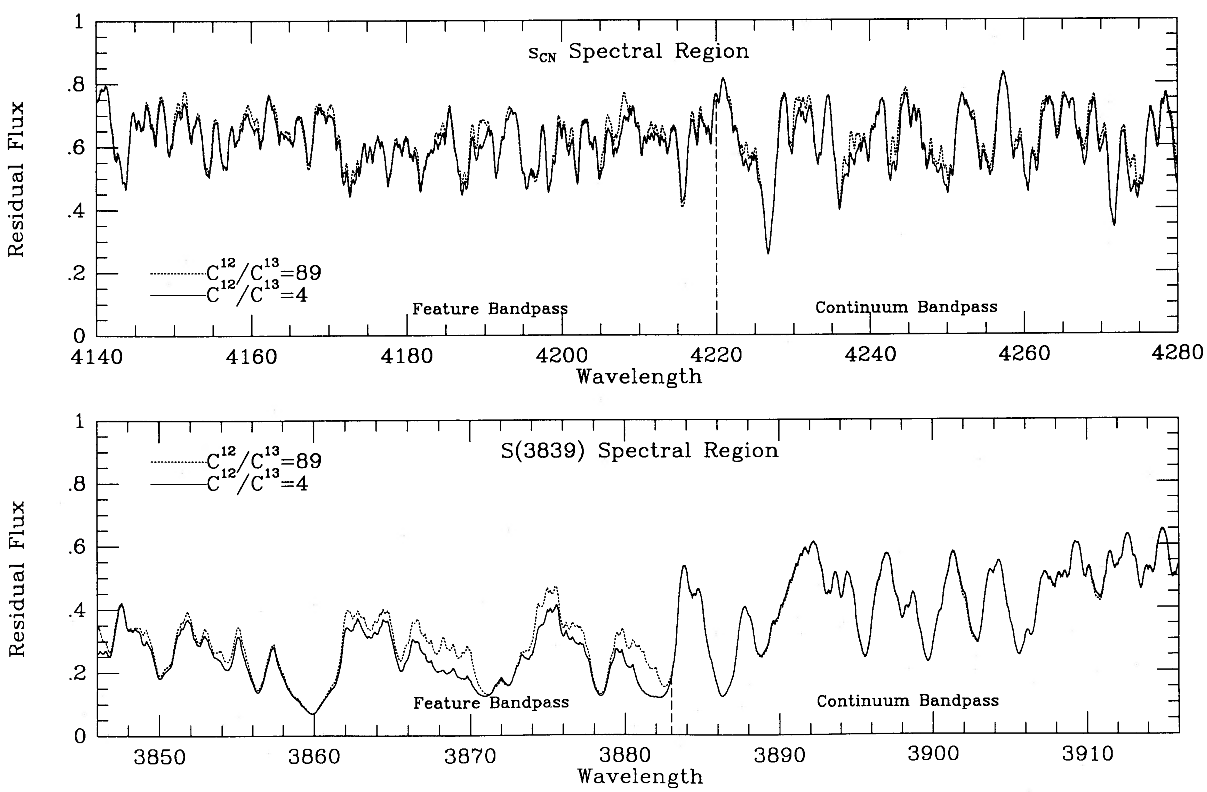

FIG. 3.—Sample synthetic spectra having (T_{eff} = 4750 K, log g = 2.70, [A/H] = −0.8, ΔC = −0.10, and ΔN = +0.26) but different $^{12}C/^{13}C$ ratios are plotted over the wavelength regions appropriate to the $S(3839)$ and s_{CN} regions. The spectra have also been normalized to a continuum flux of 1.0. There is a much greater sensitivity to $^{12}C/^{13}C$ in the 3883 Å CN band than in the 4215 Å band.

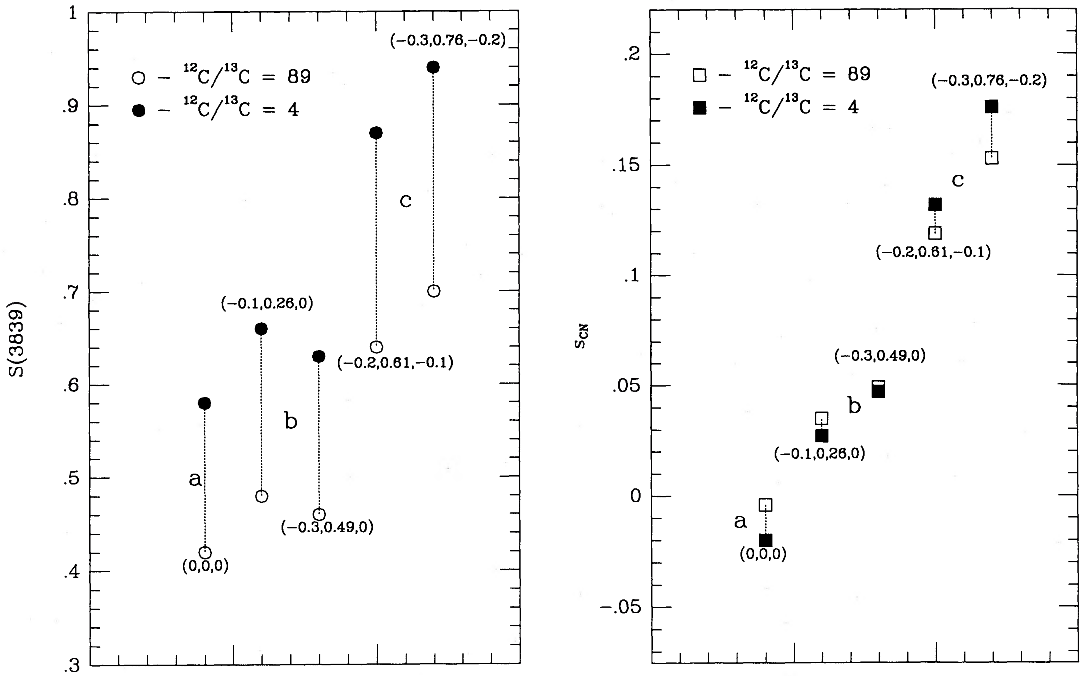

FIG. 4.—Values of both s_{CN} and $S(3839)$ as computed for the synthetic spectra from the $T_{eff} = 4500$ K, $\log g = 2.25$, and $[A/H] = -0.8$ model for groups *a*, *b*, and *c* are plotted. Open markers represent values obtained with $^{12}C/^{13}C = 89$ and filled markers indicate $^{12}C/^{13}C = 4$. The data points have been somewhat spread out along an arbitrary *X*-axis to better show the resulting shifts for various CNO abundances. Models having the same C/N/O abundances are connected by vertical lines, and their (ΔC, ΔN, ΔO) enhancements are also indicated. It can be seen that the sensitivity to $^{12}C/^{13}C$ of the $S(3839)$ index is quite high, with the changes due to varying isotope ratios rivaling those due to CNO abundance changes. The s_{CN} indices appear to be much less responsive, and for the weaker CN bands, the shift caused by decreased $^{12}C/^{13}C$ changes sign (due to CH in the comparison band as noted in the text).

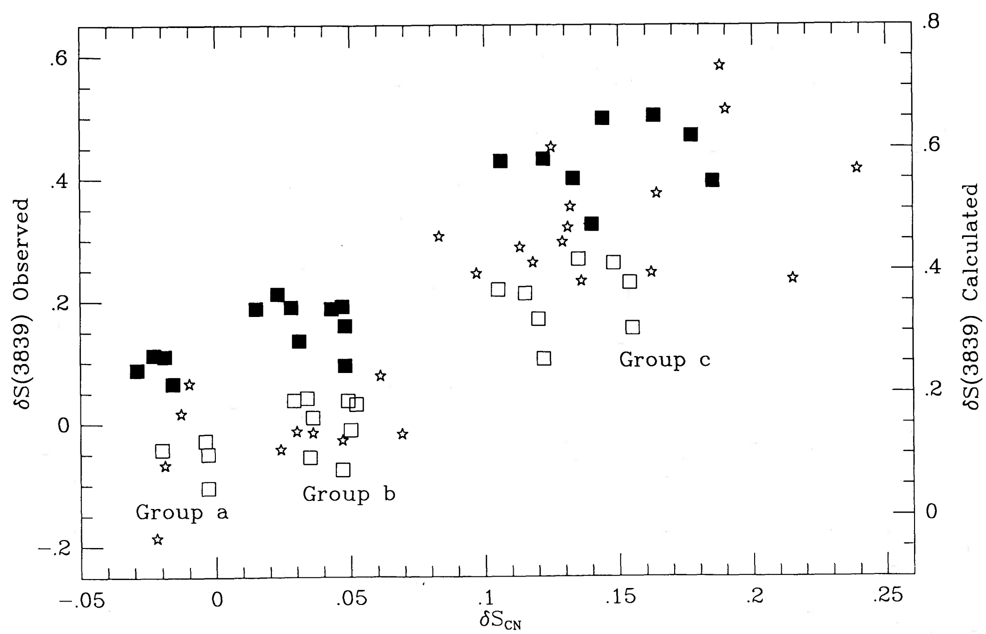

FIG. 5.—δs_{CN} is plotted vs. $\delta S(3839)$ for both the observed stars (*star-shaped markers*) in Table 1, and the synthetic spectra with $^{12}C/^{13}C = 89$ (*open squares*) and 4 (*filled squares*). The three different groups of models *a*, *b*, and *c* are indicated. As mentioned in the text, a zero point shift of 0.15 was applied to the synthetic $\delta S(3839)$ indices. Note the lack of observed stars in the range of $0.08 < \delta S(3839) < 0.23$. While the CN-normal stars (*lower left*) cluster around the $^{12}C/^{13}C = 89$ points, there is a tendency for the CN-strong stars to group somewhat higher, toward the $^{12}C/^{13}C = 4$ results. This would imply that the CN-rich members have lower $^{12}C^{13}C$ ratios than do their CN-normal counterparts.

versus $\delta S(3839)$ for both the observed stars and the synthetic spectra. Note that although the model $\delta S(3839)$ indices were measured relative to the same baseline as the observed indices, a zero point shift of 0.15 has been applied to the synthetic values as plotted in Figure 5. As there is usually difficulty in matching zero points of indices in wavelength regions where the stellar flux is varying rapidly with wavelength such a shift should not be cause for alarm. The relative behavior of the bands to $^{12}C/^{13}C$ variations remains unchanged.

It can be seen from Figure 5 that a significant change in the CN abundance is required to reproduce the range in δs_{CN} and $\delta S(3839)$ observed. The spread is in fact so great, that oxygen depletion needs to also be considered (group *c*). Such a depletion would indicate mixing of not only CN-process material, but ON-process material as well. ON-process material mixing, in addition to supplying additional C and N, causes an oxygen depletion which frees up carbon that otherwise would be tied up in CO. Thus the relative amount of CN in the atmosphere is increased.

As a result of CN-process material mixing, the CN-rich stars might also be expected to have $^{12}C/^{13}C$ ratios close to that characteristic of CN-cycle equilibrium burning (VandenBerg and Smith 1988). This would then result in large and sharp differences in the $^{12}C/^{13}C$ ratios between the CN-normal and CN-rich populations. Given the 3883 Å CN band's sensitivity to ^{13}C and the 4215 Å band's insensitivity discussed above, this would then result in an observed bimodality in the 3883 Å CN band, with no bimodality in the 4215 Å band. This would also have a pronounced effect on the δs_{CN} versus $\delta S(3839)$ diagram. Stars with low δs_{CN}, $\delta S(3839)$ strengths would be expected to have high $^{12}C/^{13}C$ ratios, as little mixing is assumed to have taken place. Stars with larger δs_{CN}, $\delta S(3839)$ values, which are assumed to have undergone extensive mixing, would be anticipated to have lower ^{12}C to ^{13}C ratios, and hence be displaced upward on the diagram. In Figure 5, the stars in the lower left corner would form one population (CN and $^{12}C/^{13}C$ normal), while the stars in the upper right would form another population (CN and $^{13}C/^{12}C$ enhanced). This is indeed very similar to the pattern of $\delta S(3839)$, δs_{CN} indices observed on the 47 Tuc subgiant branch, as is shown by the comparison between the models and the observations in Figure 5. Note, however, as mentioned above, the large s_{CN} indices of the CN-rich stars require the presence of ON-processed material regardless of the $^{12}C/^{13}C$ ratio. The conclusions of SBH89 in this regard remain unaltered.

IV. CONCLUSIONS

It may be anticipated that some form of deep mixing process, presumed to have dredged up CN and ON-process material in the CN rich stars of 47 Tuc, also causes a corresponding decrease in the surface $^{12}C/^{13}C$ ratio. This is a possible explanation for the observed 3883 Å CN bimodality among 47 Tuc subgiants, which is absent in the 4215 Å band, as evidenced by the gap in $\delta S(3839)$ seen in the δs_{CN} versus $\delta S(3839)$ diagram. If this is indeed the case, the 3883 Å CN bimodality seen in 47 Tuc, and possibly other clusters as well, is largely the consequence of a bimodal distribution of $^{12}C/^{13}C$ in addition to C and N abundance variations. It should be mentioned that further synthetic spectrum calculations have shown that for the brighter giants of 47 Tuc ($V < 14$), the increased strength of the 4215 Å CN band cause the s_{CN} index to become much more sensitive to these effects as well.

One caveat is necessary to conclude this discussion. In a strict sense, we have demonstrated only that the existence of a $S(3839)$ bimodality among 47 Tuc subgiants can be explained by invoking the presence of CNO-processed material at the surfaces of the CN-rich stars. The assumption of interior mixing within the CN-rich stars themselves is the most natural explanation for these results. Yet there are problems with current stellar interior models in reproducing this behavior, as has been discussed by SBH89 (see also Hesser 1978; Hesser and Bell 1980; Bell, Hesser, and Cannon 1983; Cottrell and Da Costa 1981; Da Costa and Demarque 1982; VandenBerg and Smith 1988).

Finally, it has not escaped our attention that the variations in the $^{12}C/^{13}C$ ratio will affect any discussion of CO band strength. The comments by SBH89 on the weakening of CO bands which accompany the mixing of CNO-processed material must be expanded to include $^{12}C/^{13}C$ variations. Table 3 of SBH89 gives an illustration of the changes which are to be expected. This point will be discussed further in a following paper.

Regardless of these uncertainties, however, it has been demonstrated in the present paper that the sensitivity of the 3883 Å CN band to differences in the carbon isotope ratios among stars of the observed portion of the 47 Tuc subgiant branch must be taken into account in C and N abundance analyses.

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