THE ASTROPHYSICAL JOURNAL, 244: 205–220, 1981 February 15

THE ABUNDANCE SPREAD IN THE GIANTS OF NGC 6752

JOHN NORRIS, P. L. COTTRELL, AND K. C. FREEMAN
Mount Stromlo and Siding Spring Observatories, Research School of Physical Sciences, Australian National University
AND
G. S. DA COSTA
Mount Wilson and Las Campanas Observatories, Carnegie Institution of Washington
Received 1980 January 31; accepted 1980 April 21

ABSTRACT

A spectroscopic survey has been performed of 69 stars on or near the giant branches of the metal-poor globular cluster NGC 6752. Our basic results are: (i) There is a large range in the strength of the violet cyanogen bands on the red giant branch, with the available evidence strongly suggesting that the distribution is bimodal. (ii) The cyanogen variations on the giant branch appear to be accompanied by an anticorrelated variation in the abundance of the CH molecule. Spectrum synthesis analysis of a (CN strong)/(CN weak) pair of stars for which relatively high resolution data are available shows that there is a variation of $\Delta[\mathrm{N/A}] \sim +0.9$, and $\Delta[\mathrm{C/A}] \sim -0.3$, indicative of the CN cycle. (iii) On the red giant branch there are variations in the strength of the lines of Al I which correlate positively with the cyanogen variations. The size of the variations is consistent with the hypothesis that the same phenomenon has occurred in NGC 6752 and ω Centauri, but to a much smaller extent in the former. (iv) On the asymptotic giant branch (AGB), the features of CH are weaker than on the red giant branch at the same color or magnitude, and there are no examples of stars in the strong CN group. Spectrum synthesis suggests that the behavior of the CH features is consistent, on the average, with the effective temperature and gravities of the AGB stars, but that the absence of strong CN stars cannot be explained in this way. We set an upper limit of $\Delta[\mathrm{C/H}] \sim 0.3$ to the possible range of carbon on the AGB at $\log L/L_{\odot} \sim 2.3$, and between this group and stars of similar color on the red giant branch. (v) Most of the stars on the anomalously low luminosity end of the AGB are not members of NGC 6752. Two stars, (CS 41 and CS 44), however, deserve further study, since they could be examples of partially mixed stars.

No definitive statement can be made concerning the origin of the abundance anomalies. If mixing is responsible, the data require this process to have operated in stars on the giant branch at a luminosity of $\log L/L_{\odot} \sim 1.6$ (the level of the horizonatal branch), and that at least half the stars have mixed. The Al I variations are difficult to explain as the result of mixing. If, on the other hand, the variations are primordial, it is difficult to envisage a succession of stellar generations which can lead to the two observed, roughly equal, populations in which the nitrogen strong, Al I strong group is deficient in carbon by a factor of roughly 2. One somewhat ad hoc primordial model which is consistent with the observations is that proton NGC 6752 was made up of two cells of different chemical histories which merged to leave the cluster as we see it today.

We consider two hypotheses which are consistent with the present observations and the existence of the well known gap on the horizontal branch of NGC 6752. In the first we suggest that, when star formation ceased in the cluster, there were two groups of stars having not only the observed carbon and nitrogen properties, but also a difference in helium abundance, $\Delta Y \sim 0.05$, in the sense that the nitrogen strong group has enhanced helium. This difference in helium leads to a mass difference of $\sim 0.07\ M_{\odot}$ at the main sequence turnoff, which, together with our current knowledge of horizontal branch morphology, provides an explanation of both the gap on the horizontal branch and the lack of CN strong stars on the AGB. (The high helium, high CN group does not ascend the giant branch for a second time.) The second hypothesis supposes that mixing is responsible for the abundance anomalies, and that this process is associated with greater mass loss, leading to two mass groups on the horizontal branch. (Here, too, the CN strong, low mass group does not ascend the giant branch for a second time.)

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

I. INTRODUCTION

It has become clear in recent years that globular clusters are chemically inhomogeneous. The prime example of this phenomenon is ω Cen, in which both the light elements (C and N) and the heavy elements (Ca, Sr, Ba) exhibit large (1 dex) variations (Bell and Dickens 1974; Freeman and Rodgers 1975; Dickens and Bell 1976). For the majority of giants in this cluster there also appears to be a strong correlation between the enhancement of CN and that of the heavy elements (Norris 1979; Norris, Freeman, and Seitzer 1980). For all other Galactic globular clusters, however, this is not the case; while cyanogen and G-band (CH) variations are widespread (see Hesser, Hartwick, and McClure 1977; Norris and Zinn 1977), there exists little substantial evidence for heavy element variations. Although Cohen (1978) has reported a scatter in the abundance of the gas from which M3 formed (0.1–0.4 dex), several other investigators have set stringent upper limits ($\sim$0.2 dex) to the possible range of heavy elements in a number of clusters (Sandage and Katem 1977; Norris and Zinn 1977; Searle and Zinn 1978). One would like to understand this apparent difference between ω Cen and the other globular cluster: an answer to this problem could throw light on the origin of the inhomogeneities.

A second problem concerns the anomalous abundances inferred for the light elements in globular clusters. As noted by McClure and Norris (1977), the weak-G-band effect is most prominent in very metal deficient clusters ($[\mathrm{Fe/H}] \lesssim -1.5$), while CN anomalies (generally based on the blue CN band at $\sim$4200 Å) are most common in the metal rich clusters ($[\mathrm{Fe/H}] \gtrsim -1.3$). Since this is to some extent a selection effect, studies are necessary, similar to that of Zinn (1977) in M5 and Norris and Freeman (cf. Norris 1978) in 47 Tuc, which seek correlations between these two phenomena.

The present paper seeks to address these and other problems through an investigation of the metal deficient ($[\mathrm{Fe/H}] \sim -1.4$; see § II*b*) globular cluster NGC 6752. This cluster has a narrow giant branch, a conspicuous asymptotic giant branch (AGB), and a very blue horizontal branch (Cannon and Stobie 1973; Wesselink 1974; Cannon and Lee 1973, 1978 [see Lee 1976]; Carney 1979). Early in the investigation it became clear that the giants in this system possess a considerable range in cyanogen abundance. This being the case, an effort has been made to throw light on several related questions: First, what is the distribution of cyanogen abundance on the giant branch? These data could set constraints on the mechanism leading to the observed cyanogen spread. Second, is there any correlation between the behavior of cyanogen and that of the CH molecule? In particular, is there any anticorrelation between CN and CH as has been suggested for 47 Tuc (Norris 1978; Norris and Cottrell 1979) and as might be expected if CN processing plays a role in producing the anomalies? Third, is there any evidence for heavy element variations accompanying those seen in CN? If not, what is the upper limit to such variations?

The color-magnitude diagram of NGC 6752 possesses two further interesting features. First, as is implicit in the work of Cannon and Lee (1973) and as demonstrated by Newell and Sadler (1978), there is a marked dichotomoy in the temperature distribution of the blue-horizontal-branch (BHB) stars. According to Newell and Sadler there are no stars in the range $4.28 \leq \log T_{\mathrm{eff}} \leq 4.37$, while both sides of this gap are well populated. The question then arises: Do the abundance anomalies seen on the giant branch correlate with this BHB anomaly? The second interesting feature is found in the color-magnitude diagram of probable members presented by Cannon and Stobie (1973, Fig. 1). In their diagram one sees a fairly well defined AGB which stretches *below* the level of the horizontal branch defined by the blue stars. If their seven stars below the horizontal branch are cluster members, they cannot be explained by standard stellar evolution theory (the AGB always occurs at higher luminosity than the horizontal branch [see Sweigart and Gross 1976]), and some radical departures seem indicated. The question here is: Are these stars indeed cluster members?

In order to investigate these questions, observational material has been obtained for some 69 stars on the giant and asymptotic giant branches of NGC 6752. The data are presented in § II, while in § III the question of cluster membership is considered. In § IV we demonstrate that on the giant branch there is a bimodal distribution of cyanogen, that there appears to be a correlation between the strengths of cyanogen and aluminium, and that there is evidence for an anticorrelation between CN and CH. On the AGB, on the other hand, CN and CH both appear weak. In the final section (§ V) we use spectrum synthesis techniques to derive estimates of the ranges of nitrogen and carbon required by the observations, and discuss the implications of our results. Spectrum synthesis analyses of giants in NGC 6752 have also been performed by Mallia (1977, 1978), and by Da Costa and Cottrell (1980).

II. OBSERVATIONS

The sample of 69 stars lies on or near the giant branches of NGC 6752 and has been chosen from the work of Cannon and Stobie (1973, Tables 1 and 2) and Cannon and Lee (1978) with the proviso that objects thought to be field stars on the basis of *UBV* data have been excluded. The sample is defined in Table 1, where columns (1)–(4) give the identification and *UBV* photometry from Cannon and Stobie (1973) and Cannon

1981ApJ...244..205N

TABLE 1

Observational Data for 69 Stars in the Field of NGC 6752

Star* (1)	V (2)	B-V (3)	U-B (4)	R-I (5)	S3839 (6)	A(Ca) (7)	$W_G(1)$ (8)	$W_G(2)$ (9)	v_r km/s (10)	$n^†$ (11)	C4548 (12)	C4245 (13)	C4142 (14)	C3842 (15)	C3538 (16)	$n^§$ (17)	Symbol‡ (18)	Member** (19)
CS 1	12.39	0.88	0.47		0.09	0.299	4.8			1000							△	Y3
CS 3	11.50	1.25	1.08	0.50	0.49	0.421	7.1	7.9	M	1012	*1.313*	*0.866*	*0.176*	*-0.229*		3	●	Y123
CS 8	14.06	0.79	0.27		-0.13	0.300	7.3			1000							○	Y3
CS 9	12.37	1.03	0.70	0.44	0.55	0.416	7.1	8.6	M	1100	*1.226*	*0.761*	*0.145*	*-0.453*		4	●	Y123
CS 10	13.46	0.59	0.03	0.22	-0.16	0.320	5.7			1000	1.028	0.590		-0.824	0.888	3	...	N1
CS 41	14.22	0.65	0.09		0.03	0.358	7.1		-50	1100							△	Y23
CS 42	13.97	0.56	0.02		-0.22	0.284	5.1			1000	0.983	0.533		-0.823	0.982	3	...	N1
CS 44	13.52	0.72	0.09		-0.09	0.329	4.9			1000	1.074	0.562		-0.824	1.048	2	△	Y13
CS 47	14.16	0.58	0.02		0.01	0.295	6.2			1000	0.999	0.570		-0.830	0.918	2	...	N1
CS 48	12.61	0.83	0.34		0.10	0.316	5.4		-59	1100							△	Y23
CS 49	13.76	0.62	0.06		-0.14	0.325	7.4			1000	0.984	0.606		-0.808	0.899	3	...	N1
CS 102	14.11	0.67	0.10		...	...	...		5	0100							...	N2
CS 105	13.76	0.83	0.27	0.42	0.34	0.342	7.2		-34	1100							●	Y23
CS 106	13.60	0.86	0.34	0.38	0.31	0.337	6.3			1000							●	Y3
CS 107	12.34	1.09	0.64		0.17	0.398	8.2		M	2010							○	Y23
CS 112	12.70	0.78	0.29		0.07	0.347	5.1			1000							△	Y3
CS 114	13.61	0.83	0.28	0.38	-0.17	0.322	6.5	8.4	-34	1101							○	Y23
CS 115	13.55	0.87	0.44	0.37	0.22	0.357	7.9			1000							●	Y3
CS 118	12.18	1.07	0.80	0.44	0.50	0.443	5.9		M	1010	*1.250*	*0.754*	*0.161*	*-0.370*		3	●	Y123
CS 119	13.00	0.93	0.51	0.42	0.37	0.370	6.8			1000	*1.184*	*0.709*	*0.071*	*-0.600*		4	●	Y13
CS 121	13.47	0.85	0.45	0.39	0.23	0.359	6.8			1000							●	Y3
CS 122	12.73	1.00	0.53	0.43	0.11	0.351	9.2	10.0	M	2100	*1.201*	*0.770*	*0.029*	*-0.636*		4	○	Y123
CS 123	12.20	1.07	0.68	0.45	0.36	0.406	7.7	9.5	M	1610	*1.227*	*0.806*	*0.098*	*-0.470*		3	●	Y123
CS 124	13.22	0.86	0.42		0.37	0.361	8.0:			1000							●	Y3
CS 125	12.16	1.08	0.72	0.46	0.53	0.437	6.5	7.9	M	1110	*1.238*	*0.759*	*0.156*	*-0.394*		4	●	Y123
CS 126	11.30	1.30	1.13		0.24	0.410	7.1		M	1010							○	Y23
CS 128	13.73	0.85	0.42		0.33	0.338	6.7			1000							●	Y3
CS 133	14.66	0.61	0.00		...	...	...		+50	0100							...	N2
CS 135	11.44	1.15	0.86	0.50	0.32	0.378	5.5			1000	*1.294*	*0.793*	*0.153*	*-0.338*		3	△	Y13
CS 136	12.78	0.81	0.32	0.38	-0.12	0.331	5.6	5.1	-57	1102	*1.142*	*0.616*	*0.075*	*-0.750*		3	△	Y123
CS 137	14.26	0.80	0.32		0.19	0.322	5.1			1000							●	Y3
CS 140	13.75	0.65	0.05		-0.13	0.307	6.8			1000	1.026	0.631		-0.820	0.875	3	...	N1
A 2	12.58	0.86	0.38		0.00	0.322	6.1			1000							△	Y3
A 3	12.02	1.09	0.74		0.14	0.412	7.5	9.8	-22	2300							○	Y23
A 8	12.03	1.12	0.79	0.45	0.56	0.453	6.6	9.0	-28	2300							●	Y23
A 9	11.30	1.20	0.88		0.15	0.401	6.9			1000							△	Y3
A 10	12.77	0.76	0.24	0.37	0.09	0.306	4.1			1000							△	Y3
A 12	11.25	1.35	1.26	0.54	0.31	0.454	7.5	10.9	M	1110	*1.375*	*0.967*	*0.180*	*-0.113*		1	○	Y123
A 29	11.85	1.14	0.89	0.48	0.58	0.417	7.2		M	1010							●	Y23
A 30	12.18	1.06	0.65	0.41	0.12	0.414	8.0	9.5	M	1013							○	Y23
A 31	10.80	1.60	1.66	0.63	0.31:	0.454	6.2		M	1010							○	Y23
A 33	12.28	1.02	0.65	0.42	0.41	0.403	5.8			2000							●	Y3
A 36	11.59	1.16	0.72		0.20	0.391	7.4			2000							○	Y3
A 45	11.57	1.23	1.10	0.50	0.48	0.447	6.8		M	1010							●	Y23
A 46	12.84	0.84	0.25		-0.03	0.341	6.7			1000							△	Y3
A 48	13.05	0.94	0.51		0.30	0.364	7.7	7.6	M	1101							●	Y23
A 59	10.90	1.59	1.78	0.62	0.36:	0.506	8.4		M	1010						2	○	Y123
A 61	11.71	1.13	0.97		0.10	0.379	6.2			2000							○	Y3
A 63	12.75	0.77	0.14		0.07	0.331	5.1			1000							△	Y3
A 68	12.02	1.11	0.79		0.65	0.430	6.4	6.7	M	2100							●	Y23
CL 10	13.57	0.80			0.33	0.352		6.4	M	0001							●	Y2
CL 25	13.18	0.87			-0.04	0.362		8.9	M	0002							○	Y2
CL 57	13.45	0.82			0.33	0.360		6.2	M	0001							●	Y2
CL 61	13.50	0.81			0.35	0.345		5.3	M	0001							●	Y2
CL 79	13.42	0.84			0.34	0.366		6.6	M	0002							●	Y2
CL 119	13.36	0.84			0.34	0.361		7.0	M	0002							●	Y2
CL 139††	12.78	0.90			0.39	0.364		7.4	M	0102							●	Y2
CL 140	13.26	0.85			0.03	0.352		8.4	M	0101							○	Y2
CL 166	12.95	0.86			0.40	0.388		5.6	M	0102							●	Y2
CL 173	13.08	0.86			0.33	0.370		7.5	M	0001							●	Y2
CL 194	13.20	0.85			0.33	0.368		7.6	M	0001							●	Y2
CL 1003	12.37	1.01			0.27	0.401		8.5	M	0100							●	Y2
CL 1005	13.01	0.91			-0.01	0.366		10.0	M	0100							○	Y2
CL 1015	11.88	1.17			0.25	0.423		9.8	M	0520							○	Y2
CL 1048	12.22	1.10			0.76	0.453		13.5	M	0100							...	see § III
CL 1066	11.53	1.22			0.19	0.444		10.0	M	0110							○	Y2
CL 1071	12.69	0.97			0.11	0.385		9.2	M	0100							○	Y2
CL 1089	11.08	1.33			0.23	0.456		10.4	M	0110							○	Y2
CL 1131	12.88	0.89			0.34	0.367		7.8	M	0100							●	Y2
s.e.											0.013	0.014		0.014	0.018			

*CS ≡ Cannon and Stobie (1973); A ≡ Alcaino (1972); CL ≡ Cannon and Lee (1978).

†Four digit positional code giving number of observations obtained with (1) 1.9m telescope, (2) AAT in blue spectral region, (3) AAT in green spectral region, and (4) du Pont telescope.

‡Number of observations.

§Circles and triangles represent red giant branch and AGB stars respectively. Open and closed symbols indicate CN strong and CN weak objects.

**Y(N) indicates membership (non-membership) according to DDO colors (1), radial velocity (2), or UBV colors (3).

††CL 139 ≡ CS 111.

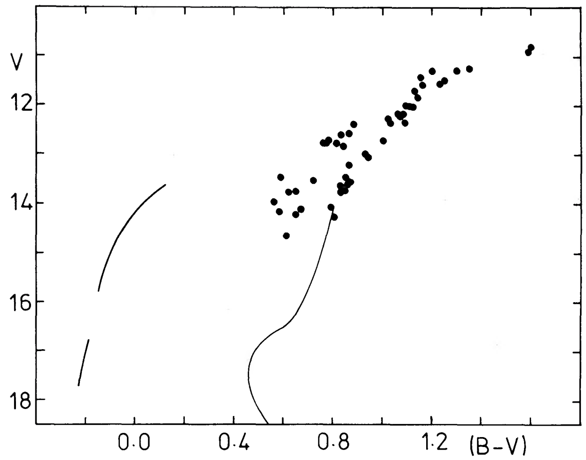

FIG. 1.—The color-magnitude diagram of NGC 6752. Dots represent the photelectric measures of Cannon and Stobie (1973), while the horizontal branch, lower giant branch, and main sequence are shown schematically following Cannon and Lee (1978; see also Lee 1976).

and Lee (1978). Column (5) of the table lists $(R-I)_K$ based on the data of Eggen (1972*a*, *b*) and Bessell and Norris (1980). The color-magnitude diagram of the 50 stars taken from Cannon and Stobie is shown in Figure 1. (This selection was dictated by a desire to present a homogeneous sample based on only photoelectric measurements.) Of particular interest in this diagram is the morphology of the asymptotic giant branch. The clump of stars at $V \sim 12.6$ and $B-V \sim 0.8$ is not unlike that found in several other clusters. The nine other stars, however, stretching from $(V, B-V) \sim (13.5, 0.65)$ to (14.6, 0.6) (below the level of the horizontal branch), form an "anomalous" AGB, in that no such feature is seen in other clusters, and in that, according to standard stellar evolution computations, the AGB is always brighter than the horizontal branch.

a) *Spectroscopy*

Some 137 spectra of these 69 objects have been obtained using spectrographs at the Cassegrain foci of the 1.9 m telescope at Mount Stromlo, the 2.5 m du Pont telescope at Las Campanas Observatory, and the 3.9 m Anglo Australian Telescope (AAT) at Siding Spring Mountain. Table 2 gives a brief description of the nature of the material obtained. At Mount Stromlo the spectra were obtained throughout 1974–1977 with Carnegie image tubes. The effect of the bright sky was minimized by using a small entrance slit ($\sim 3-7 \times 2$) arcsec^2, while widening (to 0.5 mm on the plate) was effected by using an oscillating quartz block below the slit. Observations made with the AAT employed the Royal Greenwich Observatory (RGO) spectrograph/Image Photon Counting System (IPCS) while those made with the du Pont Telescope used the Cassegrain spectrograph/Shectman Photon Counting Image Intensifier System. These data were obtained during 1977 and 1978. In both cases star and nearby sky regions, chosen to be free of contamination, were observed simultaneously and enabled the effects of cluster and night sky background to be removed. The signal-to-noise ratio in a resolution element was ~9 at λ3900 Å.

Two stars, A3 and A8, have been observed at higher resolution with the AAT and RGO spectrograph/IPCS combination. These observations were made to investigate in more detail peculiarities seen on the low-resolution spectra and will be presented later in the paper where appropriate (§ V).

Details of the number of spectra obtained for individual objects may be determined from the code given in column (11) of Table 1.

From this material three parameters have been measured. The first is a cyanogen index, $S(3839)$, which compares the intensity in the violet CN band at ~λ3883 with that in the nearby continuum. Specifically

$$S(3839) = -2.5 \log \int_{3846}^{3883} I_\lambda \, d\lambda \Big/ \int_{3883}^{3916} I_\lambda \, d\lambda ,$$

where I_λ is the intensity derived from the spectra and the terminology, $S(3839)$, parallels that used for colors on the DDO photometric system. It should be noted that no attempt was made to measure a similar index based on the blue (λ4216) cyanogen band; for a large proportion of our sample this feature is not seen. The second index measures the absorption in the region of the Ca II H and K lines. Defining the mean intensity in a wavelength range λ_1 to λ_2 as

$$\bar{I}(\lambda_1, \lambda_2) = \int_{\lambda_2}^{\lambda_1} I_\lambda \, d\lambda / (\lambda_2 - \lambda_1),$$

we measure the calcium index $A(\mathrm{Ca}) = 1. - 2.\bar{I}(3916, 3985)/[\bar{I}(3883, 3916) + \bar{I}(3985, 4018)]$, which is a measure of the mean absorption in the region of Ca II H and K, compared to the "continuum" on either side. The advantage of this index over an equivalent width measurement is that it gives an entirely objective method of determining the position of the "continuum." Finally, we have measured the strength of the G band at 4300 Å. Because of the strength of several other features in this region (including the night sky feature at λ4358 on the Stromlo spectra) we have not attempted to determine a mean absorption similar to that defined above, but have measured the "equivalent width" of the G band in the wavelength range 4290–4320 Å. Because three sets of equipment have been employed in this investigation we now briefly discuss our efforts to being all of the data onto the same system.

TABLE 2

SPECTROSCOPIC MATERIAL

Group	Telescope (m)	Spectral Range (Å)	Resolution (FWHM) (Å)	No. of Stars	Comments
1........	1.9	3700–4600	3.7	48	
2........	3.9	3700–4600	1.0	27	14 stars in common with 1
3........	2.5	3700–4600	1.0	16	5 in common with 1, 6 in common with 2
4........	3.9	4750–5750	1.2	14	For radial velocity only

i) *The Cyanogen Index S(3839)*

In the first instance observations of the 48 stars obtained at Mount Stromlo have been used to determine $S(3839)$. Nine stars in common with the Stromlo and AAT samples were then used to transform between these two systems. (The values given in this paper are on the natural system of the AAT spectra.[1] This has been done to facilitate comparison of the present results with those of other clusters [in particular ω Cen] currently under way with that telescope.) Data on an additional 11 objects were thus obtained from the AAT material. Finally the Las Campanas material was transformed using eight stars in common between it and the other data, yielding a further eight objects. Our results are given in column (6) of Table 1; we estimate that they are accurate to ~0.045 mag, based on objects in the Stromlo sample for which multiple observations are available, and on the mean deviations from the transformations discussed above.

ii) *The Calcium Index A* (Ca)

Exactly the same procedure has been applied here as for $S(3839)$. Forty-eight, eleven, and eight values have been derived from the Stromlo, AAT, and Las Campanas spectra, respectively, with the values again being on the natural system of the AAT. The results are given in column (7) of Table 1. We estimate that they should be accurate to 0.025.

iii) *The* CH *Index* W_G

Since the measurement of equivalent width requires a knowledge of the continuum level, such a measurement is not strictly possible for the cool stars and the low resolution with which we are working. If, however, one objectively seeks to establish a pseudocontinuum for a set of spectra having the same resolution, one should be able to establish a homogeneous set of measurements within which meaningful comparison can be made. We adopt this procedure. Our data divide naturally into two resolution groupings. We have Stromlo specta of 48 objects with resolution 3.7 Å, and spectra of some 32 objects taken with the du Pont and Anglo Australian Telescopes with resolution ~1 Å, with some overlap between the two groups. We choose to treat these groups independently, and hope to convince the reader (in § IV*b*) that a systematic anticorrelation exists between CH and CN in the objects in both groups, and is hence unquestionably real. On the lower resolution data we have based the continuum level on regions of the spectrum near 4250–4280 and 4320–4340 Å. An example of this procedure, and the actual area measured, may be seen in Figure 3 of Norris and Zinn (1977) in their investigation of the giant in NGC 6397. Our values of G-band strength, which we designate $W_G(1)$, are given in column (8) of Table 1. The standard deviation of these data is 0.6 Å. For the higher resolution material we adopted as the continuum level the mean intensity determined from a 3 Å region centered on 4320 Å. Our results, $W_G(2)$, are given in column (9) of Table 1. For the four stars in common to the AAT and du Pont samples there is a mean difference of 0.2 Å and a mean absolute difference of 0.7 Å. The latter quantity compares well with the standard deviation of 0.5 Å obtained from objects having repeated observations. Examination of Table 1 shows that $W_G(2)$ is systematically larger than $W_G(1)$ by 1.4 Å, a result which is readily understood in terms of the higher resolution of the former sample. If this difference is removed, the standard deviation of the differences between the two samples is 1.1 Å, which may be compared with the 0.9 Å expected from our error estimates for each sample.

b) *Photometry*

DDO intermediate-band photometry has been obtained for several of the apparently anomalous AGB stars in an effort to throw light on their cluster membership. These measurements were made with the 1 m telescope on Siding Spring Mountain and a 1P21 pulse-counting single channel photometer. The equatorial standards of McClure (1976) were also observed to standardize the results. The data are presented in columns (12)–(17) of Table 1, where the column headings are self-explanatory. Also included in the table (in

---

[1] For completeness we note that we used the 25 cm camera and the 1200B grating (blaze to collimator) with central wavelength 4100 A.

italics) are the results of Bessell and Norris (1980) for a number of giants observed in an independent program. The mean standard errors for the *present* measurements are given in the final row of the table.

It is perhaps appropriate at this point to note that these DDO data lead to an estimate of the heavy element content of NGC 6752. Following the precepts of Osborn (1971), one finds $[Fe/H]\sim-1.4$, while a determination calibrated by the newer abundances of Cohen (1978, 1979) for M3, M13, M15, and M92 yields $[Fe/H]=-1.6$ (Bessell and Norris 1980). These may be compared with a value of $[Fe/H]=-1.2$ which one obtains from $(B-V)_{0,g}=0.81$ (Cannon 1974) and the calibration of Butler (1975). Throughout this paper we shall adopt $[Fe/H]=-1.4$ which should be accurate to within a factor of 2.

III. CLUSTER MEMBERSHIP

The DDO data in Table 1 are presented in Figure 2. Since metal deficient stars occupy a characteristic position (relative to Population I stars) in these diagrams, they provide a powerful test for cluster membership (Norris and Zinn 1977; Hesser, Hartwick, and McClure 1977). In the $[C_0(4548), C_0(4245)]$- and $[C_0(3842), C_0(4548)]$-planes in Figures 2*a* and 2*b* most stars fall well above the Population I sequences as is typical of metal deficient Population II giants: They are almost certainly cluster members. There are, however, five stars in Figures 2*a*, 2*b*, and 2*c* which have the characteristics of Population I dwarfs. These are CS 10, 42, 47, 49, and 140, all of which lie on the "anomalous" AGB referred to previously. It seems likely that these are not members.

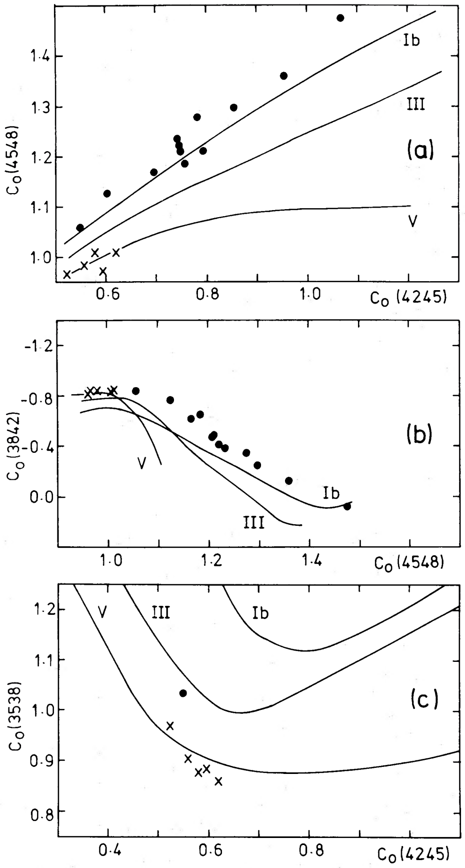

FIG. 2.—The NGC 6752 sample in the (*a*) $[C_0(4548), C_0(4245)]$-plane, (*b*) $[C_0(3842), C_0(4548)]$-plane, and (*c*) $[C_0(3538), C_0(4245)]$-plane. The Population I sequences are shown for comparison and come from Osborn (1971) for (*a*) and (*b*), and are based on the data of McClure (1976) for (*c*). The zero subscript indicates that the colors have been corrected for a reddening $E(B-V)=0.05$ following Osborn (1971). The suggested nonmembers CS 10, 42, 47, 49 and 140 are shown as crosses.

The radial velocity of NGC 6752 is -39 km s^{-1} (Kinman 1959) with a central velocity dispersion of 6 km s^{-1} (Peterson and King 1975). While this velocity is not too different from that of many Population I field stars, radial velocity estimates may be useful in removing some nonmembers. In view, however, of errors $\sim$20 km s^{-1} obtained in other projects when using the Cassegrain spectrograph of the 1.9 m telescope, no attempt has been made to check cluster membership by determining velocities from the Stromlo spectra. Velocities have been measured from the digital spectra obtained with the AAT and the du Pont telescope by using cross-correlation techniques (see Da Costa *et al.* 1977). Estimates of radial velocity are given in column (10) of Table 1, where we distinguish two classes of information. First, most stars have been observed as part of a radial velocity program undertaken by Da Costa and Freeman. For these stars we tabulate M (member) or NM (nonmember); actual velocities will be given in a later paper. A star's velocity is regarded as consistent with cluster membership if it lies within 20 km s^{-1} of the cluster velocity. Second, velocities are given for stars specifically observed on the AAT for the present program. We estimate that the standard deviation of these data is $\sim$10 km s^{-1}. Most of the stars for which we have data appear to have velocities consistent with membership. Of the three "anomalous" AGB stars, CS 102 and 133 appear not to be members, while CS 41, with $v_r=-50$ km s^{-1}, could belong to the cluster.

There are nine stars in Table 1 which lie on the "anomalous" AGB of Cannon and Stobie (1973). The data presented above show that seven of these are most likely field stars. Two, CS 41 and 44, have a radial velocity or DDO photometry (respectively) consistent with cluster membership. Although further work is clearly needed on these objects, the implications of their membership will be discussed in § V*a*.

From the radial velocity and DDO material, consistency checks on cluster membership are possible for 52 stars. All 26 red giants and "normal" AGB stars for which *UBV* measures are available in this sample have ultraviolet excesses consistent with cluster membership. There remain 17 stars, all red giants or AGB stars, for which velocities and DDO data are not available, but which have *UBV* colors consistent with membership. They also have weak-lined spectra similar to other giants in the cluster. We shall regard them as cluster members.

One star deserves special mention. CL 1048 has a radial velocity consistent with membership, but a strong-lined spectrum similar to giants of the same color in 47 Tuc. It also lies on the giant branch of the cluster. Were it as metal rich as its spectrum suggests, it should be displaced redward. This star clearly deserves further study. At present, however, we shall exclude it from further discussion, and await confirmation of membership.

Our final assessment of cluster membership is given in column (19) of Table 1. These data are based on consideration of DDO data, radial velocities, and *UBV* measures as explained in the footnote to the table.

IV. THE CHEMICAL INHOMOGENEITY OF NGC 6752

a) *Cyanogen*

As mentioned in § I, there is a large range in cyanogen strength in the present sample. This is shown in Figure 3, where $S(3839)$ is plotted versus V and $B-V$. Two types of symbols have been used: circles represent stars on the giant branch (which at high luminosities will include both single- and double-shell burning objects) while triangles represent AGB stars. Note that we class CS 135 and A9, which fall just to the blue of the giant branch (at $V \sim 12$) as AGB stars. Objects which we believe to be field stars have not been included. As may be seen from the figure, the range in $S(3839)$ (at a given V or $B-V$) is ~0.3–0.4 mag and is much larger than our observational error, 0.045 mag. On closer inspection two facts emerge. First, there is little scatter in $S(3839)$ on the asymptotic giant branch. Second, there appers to be a dichotomy in $S(3839)$ on the giant branch. We use Figure 3*a* to *define* two groups of CN strength: the filled symbols represent a CN strong group; the open symbols, a CN weak group. (CL 1003, which falls between the two groups, is represented by a half-filled circle.) The symbols used in Figure 3 are given in column (18) of Table 1 and will be used in all subsequent figures in this paper. To illustrate the behavior of CN in the giants, an average has been taken of the Stromlo spectra of the four CN weak and the six CN strong stars in the range $1.06 \leq B-V \leq 1.14$. (Seven and eight spectra were available for the two groups, respectively.) The results are compared in Figure 4, where the CN enhancement is clearly seen. The reader will also notice a slight positive correlation between the behavior of cyanogen and the absorption in the region of the Ca II H and K lines. We shall return to this point

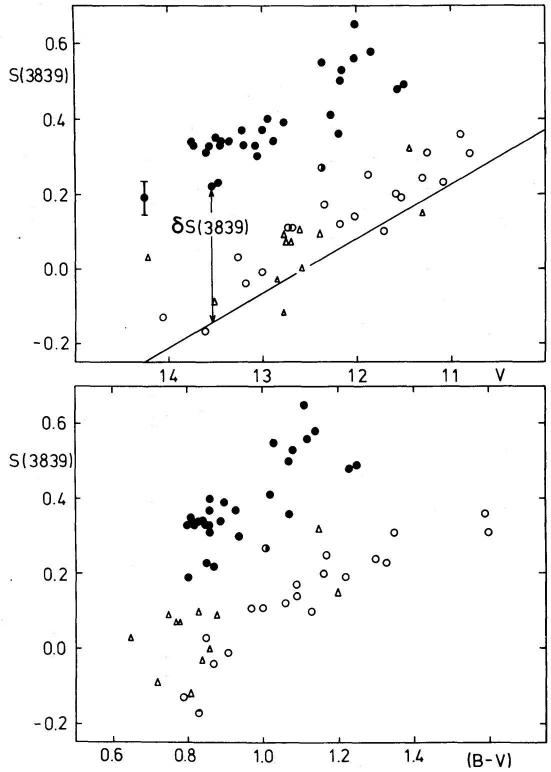

FIG. 3.—The dependence of $S(3839)$ on V and $B-V$ for members of NGC 6752. The circles and triangles represent red giant branch and asymptotic giant branch stars, respectively. The upper diagram is used to define CN strong and CN weak groups within the cluster by filled and open symbols. (The half-filled symbol is an intermediate case.) In the upper panel the line represents an assumed minimum value for $S(3839)$ at any V magnitude, relative to which the cyanogen excess $\delta S(3839)$ is measured. A typical error bar is also shown.

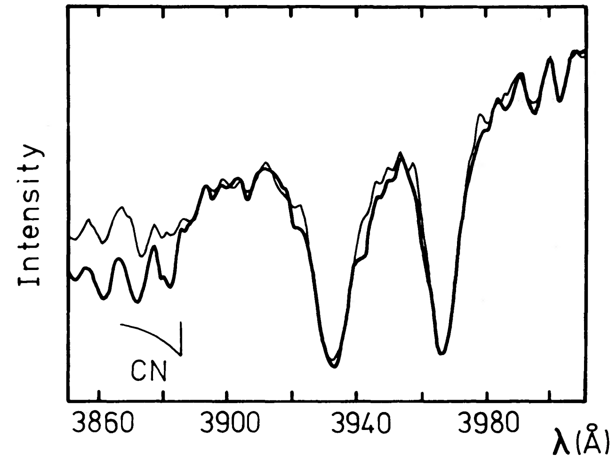

FIG. 4.—The average spectra of 4 CN weak (*thin line*) and 6 CN strong (*thick line*) red giants in the color range $1.06 \leq B-V \leq 1.14$, for which Stromlo data are available. The difference in CN is clearly seen, together with slightly enhanced absorption in the region of Ca II H and K in the CN strong group.

in § IV*c*. The behavior of CN at somewhat bluer colors ($B-V \sim 0.85$) is illustrated in Da Costa and Cottrell (1980).

In order to discuss the distribution of cyanogen on the giant branch, one must allow for the variation in $S(3839)$ with position in the color-magnitude diagram. We assume that the lower envelope to the distribution of points in Figure 3*a* represents the minimum value of $S(3839)$ at any V magnitude on the giant branch, and define a parameter $\delta S(3839)$, shown in Figure 3*a*, which measures the displacement of any observed point above this line. [The lower envelope in the figure has the equation $S(3839) = -0.146V + 1.832$.] The parameter $\delta S(3839)$ is then adopted as a measure of the CN abundance. Clearly, if the violet CN band increases in strength at different rates as a function of abundance and position on the giant branch, $\delta S(3839)$ will not be a unique CN abundance indicator. The implicit assumption made here is that over the range $11 \lesssim V \lesssim 14$, the effect is not too serious. Some encouragement for this assumption is given by noting that, if $\delta S(3839)$ were not a good abundance indicator, any dichotomy in the distribution would tend to be removed. We note also at this point that the spectrum synthesis calculations to be discussed in § V show that the assumption is a reasonable one.

Figure 5 shows the generalized histogram of $\delta S(3839)$ (cf. Searle 1977) of the 49 red giants in Table 1, where the half-width of the Gaussian kernel used in generating the distribution has been set equal to 0.045 mag, the estimated standard deviation of the observations. Here the bimodal nature of the distribution is apparent, with a separation between the peaks of ~ 0.35 mag. The question now arises as to the reality of the phenomenon. What is the probability that such bimodality results by chance from a more smoothly behaved distribution? Since we have no model against which to compare our observations, this is a difficult question to answer. To make progress, let us assume that the parent population is Gaussian, centered on $\delta S(3839) = 0.295$ with dispersion $\sigma = 0.187$, which are the values defined by the sample of 49 giants. The Kolmorgorov-Smirnov one-sample test (cf. Siegel 1956) shows that the hypothesis that the sample is drawn from such a population is rejected at the ten percent confidence level. It is also interesting to note that Norris and Freeman (1979) have reported a similar phenomenon in 47 Tuc, based on the behavior of the CN bands at λ4216.

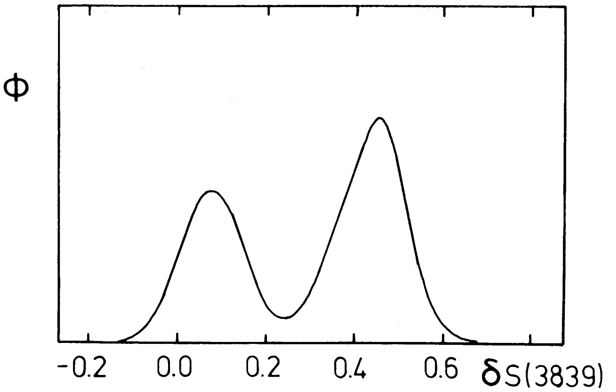

FIG. 5.—The generalized histogram of $\delta S(3839)$ for 49 red giant branch stars. Each star is represented by a Gaussian of dispersion 0.045 mag, the estimated error of measurement. Note the bimodal nature of the distribution.

b) *The G Band*

Figures 6*a* and 6*b* show the dependence of the G-band strengths, $W_G(1)$, measured from the lower resolution spectra, as a function of V and $B-V$. As noted previously, CN strong objects are represented by filled symbols. Here one sees a relatively large spread in G-band strength, without any striking correlation with CN. One statement, however, may be made. At comparable brightness or color, the AGB stars have weaker G bands than those in stars on the giant branch.

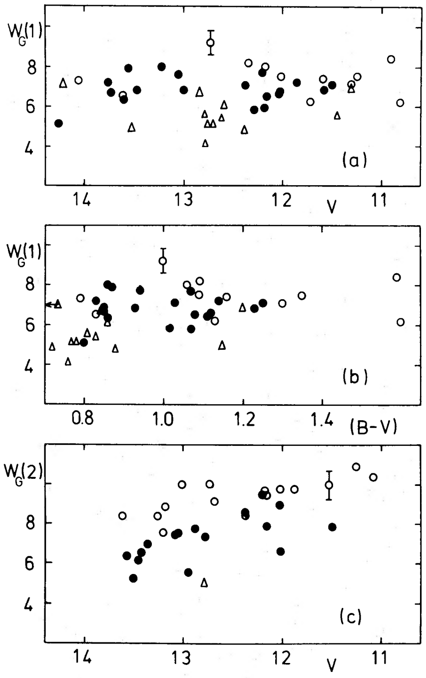

FIG. 6.—The behavior of the G-band strength. (*a*) and (*b*) show $W_G(1)$ (measured from Stromlo spectra) as a function of V and $B-V$, respectively, while (*c*) shows $W_G(2)$ (measured from AAT and Du Pont telescopes spectra) as a function of V. Circles and triangles denote stars on the red giant branch and AGB respectively, while open and filled symbols refer to CN weak and CN strong objects as defined in Fig. 3. Typical error bars are also shown. Note that the AGB stars have both weak CN and somewhat weaker G-bands than giants of similar color or magnitude. On the giant branch there is an anticorrelation between CH and CN.

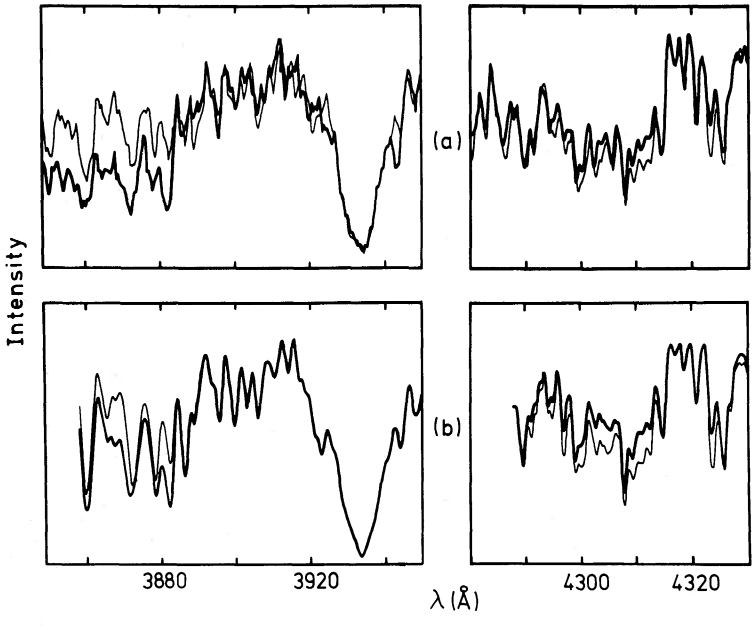

FIG. 7.—(*a*) The upper panel compares the spectra of the CN strong star A8 (*thick line*) with those of the CN weak star A3 (*thin line*) in the region of the violet CN band, and the G band of CH. This shows the important result that the CN strong star has a weaker G band. Note that the colors and magnitudes of the stars differ by only $|\Delta V|=0.01$ and $|\Delta(B-V)|=0.03$. (*b*) The lower panel shows synthetic spectra for two models chosen to represent A3 and A8. Both have $T_{\rm eff}=4400$, $\log g=1.2$, and $[A/H]=-1.4$ but have different carbon and nitrogen abundances. A3 is represented by $[C/A]=-0.1$, $[N/A]=-0.6$ (*thin line*), while A8 is represented by $[C/A]=-0.4$, $[N/A]=+0.3$ (*thick line*). See discussion in § V*b*.

This is a result first found by Zinn (1973) in M92, and also reported in M15, M13, and NGC 6397 by Norris and Zinn (1977). The present results in NGC 6752 (Figs. 3 and 6) are, however, more restrictive. *Both* CH *and* CN *appear relatively weak on the asymptotic giant branch*. It should also be noted that the same conclusion is implicit in the investigation of M5 by Zinn (1977).

The behavior of the G band on the giant branch is not so clear. At $V\sim12$ there is some indication of an anticorrelation of CH and CN. This suspicion is strengthened by the behavior of $W_G(2)$, the G-band strength measured from the higher resolution spectra, as is shown in Figure 6*c*. Here the anticorrelation of G-band strength and CN is clearly seen. We have also investigated this phenomenon at somewhat higher resolution using the AAT. Figure 7*a* shows slightly smoothed spectra of two stars, A3 (CN weak) and A8 (CN strong), which lie close together on the giant branch ($\Delta V=0.01$, $\Delta B-V=0.03$) and hence have very similar temperatures and gravities. As is clear in the figure, *the star with the stronger* CN *has slightly weaker* CH. This is seen not only in the G band itself, but also in the feature at λ4323, which comprises a blend of a number of CH lines. (It should be noted that the G-band region in each of the stars was observed on each of two nights, and that on both occasions the same behavior was obtained.) *We suggest that the anticorrelation of* CN *and* CH *is a general feature on the giant branch of NGC* 6752 *in the range* $-2\lesssim M_V\lesssim+1$.

c) *The Heavier Elements*

As may be seen in Figures 4 and 7, any variation in the absorption in the region of the H and K lines accompanying the cyanogen differences is small, though there is some indication of a positive correlation. In Figure 8 the dependence of A(Ca), the mean absorption in the region of Ca II H and K, is plotted against $B-V$ for the red giants in Table 1. In this larger body of data there also appears to exist a small positive correlation of A(Ca) with cyanogen. If one computes a least squares line of best fit to these data in the range $0.75\leq B-V\leq 1.35$ and determines the mean deviation from the line for the CN weak and CN strong groups, one finds $+0.006\pm0.003$ (s.e.) and -0.012 ± 0.004 (s.e.), respectively. The difference[2] between the two groups is thus significant at the 3.5 σ level. Inspection of the higher resolution spectra, however, shows that most, if not all, of this variation results not from differences in the calcium line strengths but rather from differences in the strength of the Al I resonance lines λλ3944 and

---

[2] If one adopts the tentative calibration of absorption in the region of H and K as a function of metal abundance reported by Norris (1979) for Population II red giants, this difference corresponds to a range in heavy element abundance $\Delta[A/H]=0.12$.

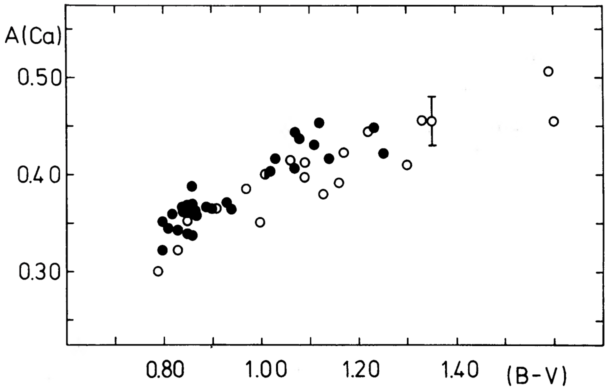

FIG. 8.—The dependence of the mean absorption in the region of Ca II H and K as a function of $B-V$ for the red giants (*circles*) and AGB stars (*triangles*) in NGC 6752. The absorption increases upward. As before, filled and open symbols represent CN strong and CN weak stars, respectively. A typical error bar is also shown. Note the positive correlation between A(Ca) and cyanogen strength.

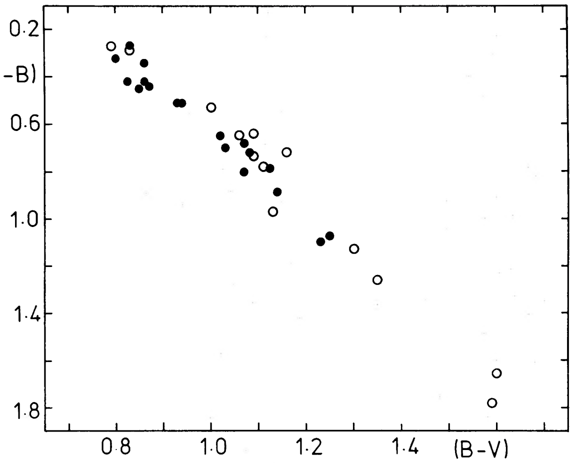

FIG. 10.—The red giants of NGC 6752 in the two-color diagram. At constant $B-V$ the CN strong stars (*filled circle*) have larger $U-B$ values (on average) then do the CN weak stars (*open circle*).

3961. This is illustrated in Figure 9, where the spectrum of the CN weak star CL 25 is compared with that of the CN strong star CL 166. (Both stars have $V \sim 13$ and $B-V \sim 0.86$.) A similar effect has been noticed in ω Centauri, where Ca and Al both appear to be enhanced in the CN strong stars, with the effect in Al being quite striking (Norris and Smith 1980).

The question then arises as to whether we are seeing the same phenomenon in NGC 6752 and ω Cen, but to a much smaller extent in the former. In an investigation of 100 giants in ω Cen, Norris (1979) found a strong correlation between cyanogen and A(Ca), with $\delta S(3839)$ and δA(Ca) varying by 1.2 mag and 0.15, respectively.[3] Inspection of his Figure 4 shows that the smaller ranges found here for NGC 6752 are not inconsistent with the hypothesis that the variations in cyanogen and the absorption in the region of H and K share a common origin, but are much less marked in NGC 6752.

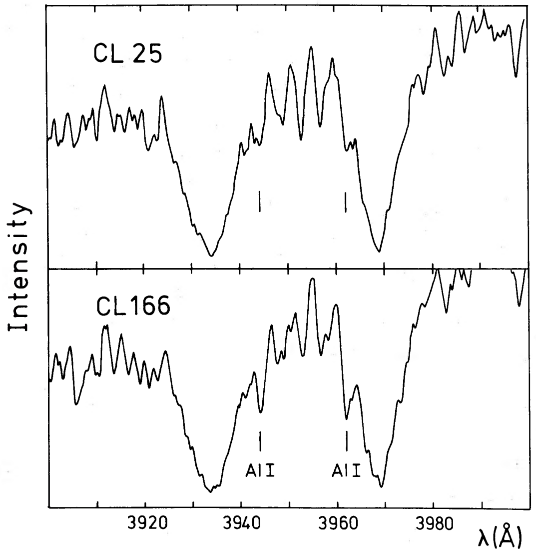

FIG. 9.—Comparison of spectra of the CN weak star CL 25 ($V=13.18$, $B-V=0.87$) with that of the CN strong star CL 166 ($V=12.95$, $B-V=0.86$) in the vicinity of the Ca II H and K lines. Note the the Al I lines at λλ3944 and 3961 are enhanced in the CN strong star.

Apart from variations of the features of CN, CH, and Al I, the data available show no clear evidence for variations of others elements. In particular the Mg *b* lines, Ca I λ4226, Sr II λ4077, and Ba II λ4554 appear similar in stars lying nearby in the color-magnitude diagram. Work is currently under way to obtain higher resolution material, together with information at longer wavelengths in an effort to obtain more definitive information on this problem.

d) *The* ($U-B$, $B-V$)*-Diagram of NGC* 6752

The two-color diagram of the red giants is shown in Figure 10, where the data are those of Cannon and Stobie (1973). Here too one sees some evidence for a separation of the weak and strong CN groups, the mean difference being $\Delta(U-B) \sim 0.05-0.10$ at constant $B-V$. This effect has also been noted by Hartwick and McClure (1980) in their analysis of *UBV* data of the giants in 47 Tuc. Since $U-B$ is substantially affected by both cyanogen (cf. Oinas 1975 [Table 5]) and heavy elements, the results in Figure 10 cannot be used as independent evidence for a heavy element variation; they do, however, provide support for an abundance spread on the giant branch.

---

[3] Norris (1979) actually gives two parameters, CN and Ca, which closely approximate our $S(3839)$ and A(Ca), respectively.

1981ApJ...244..205N

V. ANALYSIS AND DISCUSSION

There are several observational constraints which any explanation of the evolutionary history of NGC 6752 must satisfy: (i) There is a large range in CN strength on the giant branch, with the available evidence suggesting that the distribution is bimodal. (ii) On the giant branch there are small G-band variations which anticorrelate with the cyanogen variations. (iii) There appears to be a small range in the absorption in the region of Ca II H and K which positively correlates with the cyanogen variations. The size of the effect is much smaller than, but in the same proportion as, that observed in ω Cen. The Al I lines appear to be stronger in the red giants having strong cyanogen. (iv) Both CH and CN are weak on the asymptotic giant branch, with CH being weaker than on the giant branch at the same magnitude or color. (v) There is some suggestion that there is an anomalous AGB which reaches down to or below the level of the horizontal branch. (vi) The distribution of stars on the horizontal branch is also bimodal.

a) *The* (*luminosity*, *temperature*)-*Plane*

The theoretical H-R diagram for the brighter part of NGC 6752 is shown in Figure 11, where, as in Figure 1, we have included only stars with photoelectric colors. For convenience the temperature parameter $\theta_{\rm eff}^2 = (5040/T_{\rm eff})^2$ has been adopted as the abscissa. In transforming from Figure 1 to Figure 11, a distance modulus of $(m-M)_{\rm app} = 13.35$ and reddening $E(B-V) = 0.05$ were adopted following Newell and Sadler (1978), together with the $[(R-I)_{\rm K}, T_{\rm eff}]$-relation of Dickens and Bell (1976) and the bolometric corrections tabulated by Norris (1974, Table 3). Since not all stars have $(R-I)_{\rm K}$, it was decided to transform all stars through the $[(B-V), (R-I)_{\rm K}]$ relation defined by the observations in Table 1. [We adopt $(R-I)_{\rm K} = 0.337\ (B-V) + 0.088$ for $1.0 \leq B-V \leq 1.6$, and $(R-I)_{\rm K} = 0.290\ (B-V) + 0.135$ for $0.75 \leq B-V \leq 1.0$. We have also used the latter relation for the hottest two stars, CS 41 and CS 44, which requires some extrapolation. We believe, however, that the uncertainty involved will not affect the following discussion.] Also shown in the figure is the schematic position of the blue horizontal branch inferred from work of Newell and Sadler (1978) and Cannon and Lee (1973, 1978) together with that of the Cepheid variable $V1$ (Lee 1976). Here we adopted the $[(B-V)_0, \theta_{\rm eff}]$-relation of Newell, Rodgers and Searle (1969).

These data may be compared with the post helium flash computations of Gingold (1976) which are shown for $Y = 0.30$, $Z = 0.001$, and $M_{\rm core} = 0.475\ M_\odot$, values which are probably quite appropriate to NGC 6752. While other explanations may be suggested, the observations on the blue horizontal branch are consistent with a bimodal (total) mass distribution with one group having $M \sim 0.48-0.50\ M_\odot$ and the second having $M \sim 0.55-0.60\ M_\odot$ (cf. Newell and Sadler 1978). The normal AGB stars, $(\log L/L_\odot, \theta_{\rm eff}^2) \sim (2.3, 1.05)$, are readily explained as the progeny of 0.55 $M_\odot$ stars. The two remaining "anomalous" AGB stars are problematic. CS 41, which lies at $(\log L/L_\odot, \theta_{\rm eff}^2) \sim (1.6, 0.94)$, cannot be identified with any of the normal evolutionary phases of a Population II star: it is too faint to be in the helium core burning or double shell source phases associated with the horizontal branch and asymptotic giant branch. Since it lies $\Delta(B-V) = 0.15$ to the blue of a relatively narrow giant branch, it would need to be $\Delta[\mathrm{Fe/H}] = 1.0$ (cf. Butler 1975) more metal deficient than the remainder of the cluster if it is on its first ascent of the giant branch. This seems most unlikely.

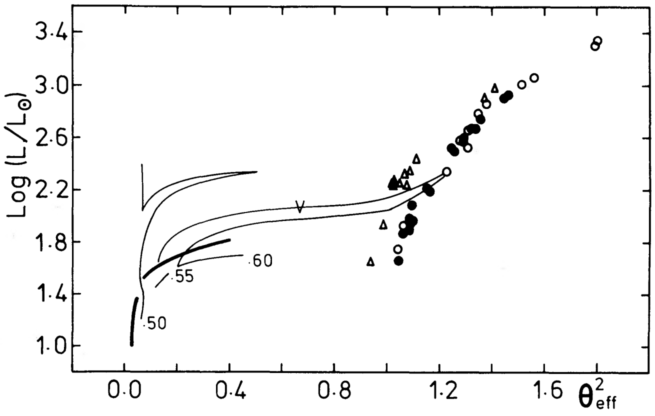

FIG. 11.—The $(\log L/L_\odot, \theta_{\rm eff}^2)$-diagram for NGC 6752. The abscissa $\theta_{\rm eff}^2 = (5040/T_{\rm eff})^2$ has been chosen for convenience to allow the giant and horizontal branch regions equal prominence. The circles and triangles are as defined in Fig. 3, while the V represents Variable 1 (Lee 1976). The bimodal horizontal branch distribution is shown schematically by thick lines following Newell and Sadler (1978), while the thin lines are the evolutionary tracks of Gingold (1976) for $M_{\rm core} = 0.475\ M_\odot$, $Y = 0.30$, $Z = 0.001$, and total masses of 0.50, 0.55, and 0.60 $M_\odot$.

One possible explanation is that we are observing the composite spectrum of a red giant and a horizontal branch star. Closer examination of the cluster membership and nature of this star is clearly warranted. Its radial velocity should be more accurately measured, and photometry should be obtained over a wide wavelength region. If it is indeed a cluster member, and is not multiple, then it may offer support for the existence of partially mixed stars similar to the models of Rood (1970) and Smith and Demarque (1978). A similar, but less extreme, problem exists for the second "anomalous" AGB star CS 44 with $(\log L/L_\odot,\ \theta^2_{\rm eff})\sim(1.9,\ 0.98)$. This star lies $\Delta\log L/L_\odot\sim0.13$ above the level defined by the coolest BHB stars, while the models in Figure 11 suggest that the AGB stars in this cluster should fall at least $\Delta\log L/L_\odot\sim0.3$ above the horizontal branch. This star also deserves further study.

b) *Abundance Anomalies on the Red Giant Branch*

i) *Analysis*

We have used the spectrum synthesis techniques of Cottrell (1978; see also Cottrell and Norris 1978) to estimate the range in carbon and nitrogen indicated by the present observations. We refer the reader also to the paper of Da Costa and Cottrell (1980) for an independent analysis of carbon and nitrogen abundances of two giants in this cluster. In the present computations we adopt (i) the model atmospheres of Bell *et al.* (1975), (ii) $[{\rm A/H}]=-1.4$ for all elements heavier than nitrogen (cf. § II*b*) (note the implicit assumption that $[{\rm O/A}]=0$), and (iii) a microturbulent velocity of 2 km s^{-1}. In Figure 7*b* we show our results for A3 (CN weak) and A8 (CN strong), for both of which we adopt $T_{\rm eff}=4400$ and $\log g=1.2$ (computed using the precepts of § V*a*). We find a good representation for the G band and the CN bands can be obtained for A3 with $[{\rm C/A}]=-0.1$ and $[{\rm N/A}]=-0.6$ and for A8 with $[{\rm C/A}]=-0.4$ and $[{\rm N/A}]=+0.3$. Differentially we have $\Delta[{\rm C/A}]=[{\rm C/A}]_{\rm A8}-[{\rm C/A}]_{\rm A3}=-0.3$ and $\Delta[{\rm N/A}]=[{\rm N/A}]_{\rm A8}-[{\rm N/A}]_{\rm A3}=+0.9$. These results are similar to those obtained by Da Costa and Cottrell (1980). We refer the reader to their paper for a discussion of the relatively high [N/A] obtained for the CN weak stars, and its implications for the origin of nitrogen in Population II objects. Here we wish to emphasize the differential determinations of carbon and nitrogen abundances and their anticorrelation.

We have also computed the quantity

$$\Delta m=-2.5\log\int_{3856}^{3883}F_\lambda\,d\lambda\Big/\int_{3883}^{3916}F_\lambda\,d\lambda$$

as a function of nitrogen abundance for two models appropriate to the giant branch of NGC 6752. Specifically we chose $(T_{\rm eff},\ \log g,\ [{\rm A/H}])=(4400,\ 1.2,\ -1.4)$ and $(4850,\ 2.1,\ -1.4)$. The first is representative of stars such as A3 and A8 (at $V=12$), while the second represents stars lower on the giant branch (at $V\sim13.5-14.0$). In all cases $[{\rm C/A}]=0.0$. Our results are shown in Figure 12. It is interesting to compare these results with the range in $S(3839)$ of $\sim0.3-0.4$ mag seen in Figure 3 in order to derive a second estimate of the range in nitrogen abundance. The reader will notice that the wavelength range of our computations (λλ3856–3916) is slightly smaller than that used in our observed parameter (λλ3846–3916). We have repeated a subset of our measurements, redefining $S(3839)$ over the smaller interval, and find that the range in $S(3839)$ remains unchanged. We may therefore use Figure 12 to obtain an estimate of the range in nitrogen necessary to explain the observed range in $S(3839)$, on the assumption that it alone is responsible for the variation. Assuming a "mean" nitrogen abundance of $[{\rm N/A}]=-0.1$ to -0.6, we find a range $\Delta[{\rm N/A}]\sim+0.6$ to $+0.8$. (If carbon varies in anticorrelation with nitrogen, this value will be an underestimate.) Figure 12 also shows that the assumption in § IV*a* that $S(3839)$ changes by about the same amount for a given cyanogen abundance change is a reasonable one for the bulk of the stars in our sample.

Taken in its entirety, the above analysis suggests that a range in nitrogen of ~1.0 dex exists on the giant branch of NGC 6752, accompanied by an anticorrelated range in carbon of ~0.3 dex.

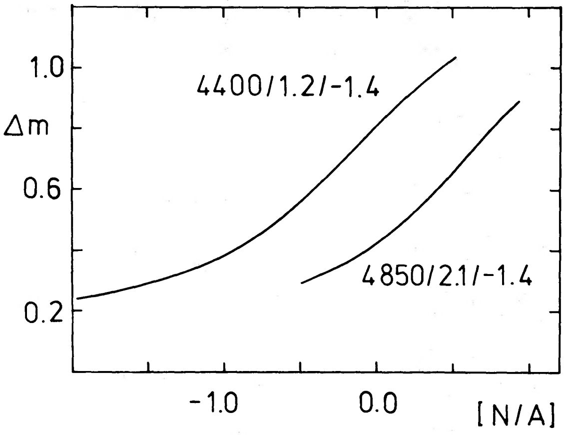

FIG. 12.—The dependence of

$$M=-2.5\log\int_{3856}^{3883}F_\lambda\,d\lambda\Big/\int_{3883}^{3916}F_\lambda\,d\lambda$$

on nitrogen abundance for models with $T_{\rm eff}/\log g/[A/H]=4400/1.2/-1.4$, and $4850/2.1/-1.4$ which were chosen to represent the red giants in NGC 6752 at $V\sim12$ and 13.5–14, respectively.

ii) *Discussion*

The question now arises as to the origin of the anomalies. The anticorrelation of carbon and nitrogen is suggestive of processing in the CN cycle. Sweigart and Mengel (1979) have shown that if red giants in globular clusters are rotating sufficiently rapidly, meridional circulation can mix CNO processed material into the envelopes of these low-mass stars above some critical luminosity, which is dependent on metal abundance. For a mass $M = 0.7\ M_{\odot}$, and abundances $Y = 0.25$, $Z = 0.001$, they predict mixing only above $\log L/L_{\odot} \sim 2.0$, which may be compared with our lower limit of $\log L/L_{\odot} \sim 1.6$ (a value at which the CN spread still exists). The difference does not seem so great, however, as to rule out the hypothesis, based on the present data. Further observations, lower on the giant branch, should be made in an effort to settle the question in this cluster. Sufficient data exist in other clusters, in particular NGC 104 and NGC 6397, to cast serious doubts on the hypothesis of Sweigart and Mengel. In NGC 104 Hesser (1978, Fig. 2) finds cyanogen variations at $\log L/L_{\odot} \sim 0.8$, while in NGC 6397 Norris and Zinn (1977, § IV*a*, Fig. 3) report carbon variations at $\log L/L_{\odot} \sim 1.9$. The predicted luminosities below which the products of mixing should not be seen in these two clusters are $\log L/L_{\odot} \sim 1.6$ and 2.2, respectively, where we adopt $[\mathrm{A/H}]_{47\ \mathrm{tuc}} = -0.5$, $[\mathrm{A/H}]_{\mathrm{NGC}\ 6397} = -2.0$. *If meridional mixing is responsible for carbon and nitrogen anomalies seen in globular cluster giants, it seems likely that it first occurs at lower luminosity than suggested by the computations of Sweigart and Mengel (1979).* The reader is referred to § IV*d* of their paper where they discuss this possibility.

Variations in the N/C ratio might also be expected from events which occurred during the formation of the cluster. According to Lamb, Iben, and Howard (1976) N/C is enhanced by a factor 5 in the envelopes of 15 and 25 $M_{\odot}$ stars, while the possibility of even greater enhancements exists in the envelope of intermediate mass stars, depending on the uncertain treatment of convection in the outer layers of these stars (Iben 1975, 1976).

A second important fact is that more than half of the giants in our sample are CN strong. If meridional-circulation–induced mixing is responsible for their peculiarity, then the majority of stars in NGC 6752 are rapid rotators. If partial mixing at the helium flash (followed by a second ascent of the giant branch) as considered by Rood (1970) and by Smith and Demarque (1978) is responsible, then one almost surely requires that roughly *all* stars mix. Whatever mixing mechanism may be postulated, the present results establish that it must be a very efficient process in NGC 6752.

If, on the other hand, the abundance anomalies are primordial to the cluster, the large fraction of CN strong stars places constraints on the production mechanism. There are two cases. In the case of a number of generations of stars in which subsequent generations are enriched by earlier nucleosynthesis, one requires that the second generation (the CN strong stars) contain as many low-mass objects as the first. The second possibility, which derives from a suggestion of Searle (1977), is that NGC 6752 formed from the merging of two cells of material which had somewhat different enrichment histories. The present results merely require that the two cells had about the same mass. Of the possibilities considered in this and the preceding paragraph, this condition is clearly the least stringent.

The third important constraint is the variation in absorption in the region of the Ca II H and K lines (Figs, 4, 7, 8, and 9). Although the Al I lines are clearly stronger in the CN strong group, no other heavy element in the range λλ3800–5200 seems to share this behavior. In particular Ca I λ4226 (already on the square root part of the curve of growth) shows no variations, although the ionization potential of Ca and Al are similar, and both the above Al lines and the Ca line have the same low-excitation potential. While it may be argued that the atmospheric structure of the giants we are considering depends to some extent on the abundances of the CNO group (Gustafsson *et al.* 1975), it seem unlikely that only the aluminium lines would be affected by these changes. Consequently, although the construction of appropriate model atmospheres is clearly essential to resolve this problem, it is difficult to see how mixing can explain these variations. If there are real aluminium abundance variations in NGC 6752, they must be primordial. There are problems here too, however. While further work is necessary to fully appreciate the behavior of aluminium in relation to the other heavy elements, the variations in carbon, if primordial, are difficult to understand. We have shown above that the CN strong group of giants appears roughly equal in number to the CN weak group but is deficient by a factor of approximately 2 in carbon. If we postulate enrichment by a series of generations of which the CN strong group comes last, then the process is required to produce a population of stars equal in number (at $M \sim M_{\odot}$) to that of the earlier generations, but in which half of the carbon has been processed. It is beyond the scope of the present work to say if such a scheme could occur in a proto–globular cluster. It does seem, however, a rather stringent requirement. The second case discussed previously of merging calls of different chemical histories does not suffer from this problem. One is then faced, however, with the problem of the production of two cells of the observed abundances.

We may summarize our discussion as follows. The anticorrelation of C and N on the giant branch of NGC 6752 is consistent with processing in the CN cycle. The bimodal distribution of cyanogen shows that if this has resulted from mixing in individual stars then this process is very efficient in NGC 6752. If, on the other hand, the distribution is primordial to the cluster, it places severe constraints on its production by successive generations of stars. It is not a problem if two cells of roughly equal mass merged to form the cluster. The enhanced Al I lines in the CN strong stars is difficult to explain as the result of mixing, and seems to require primordial effects. In counterpoint the depletion of carbon in the CN strong stars is difficult to explain as a primordial effect, except once again in the (somewhat ad hoc) context of two merging clouds of different chemical histories.

c) Abundance Anomalies on the AGB

The first distinctive feature of our observations on the AGB (where we refer to the group of stars with $\log L/L_\odot \gtrsim 2.2$) is that the G band is weaker, on average, than that found in the giant branch stars of similar $B-V$ or V. If in Figure 6*a*, for example, we consider the eight red giant branch stars and the five AGB stars in the range $0.80 \leq B-V \leq 0.90$, the mean G band strengths are 6.8 ± 0.3 Å and 5.7 ± 0.3 Å, respectively. We have attempted to use spectrum synthesis of the G band to understand this result in terms of changes in effective temperature and gravity. The major difference between the two groups is that the AGB stars have lower gravity. We estimate a difference $\Delta \log g \sim 0.5$. (In the relation $\Delta \log g = \Delta \log M - \Delta \log L + 4\Delta \log T_{\rm eff}$, we adopt $\Delta \log L = 0.35$, $\Delta \log T_{\rm eff} \sim 0.0$, and assume a change in mass from 0.75 to 0.55 $M_\odot$ to derive $\Delta \log M = -0.13$ during evolution from giant branch to AGB.) The calculations of Bell and Gustafsson (1978) show that for this gravity difference the AGB stars will be ~40 K hotter than the giants of the same color. We have accordingly computed G-band strengths for two models appropriate to the parameters of our two groups of stars. For the red giants we adopt $T_{\rm eff} = 4850$, $\log g = 2.1$; and for the AGB stars, $T_{\rm eff} = 4890$, $\log g = 1.6$. In both cases $[{\rm A/H}] = -1.4$ for all elements, including carbon. To compute G-band strengths similar to our $W_{\rm G}(1)$ we first convolved our spectra with a Gaussian of half-width 3.7 Å. We adopted the continuum level, however, in the vicinity of λ4316 since our calculations extend blueward to only λ4286. This will lead to slightly higher values of the computed G-band strengths. The resulting values are 7.8 and 6.6 Å for the red giants and AGB stars, respectively, in good agreement with the observed mean difference between the two groups. The important conclusion results, therefore, that on average there is no need to invoke a difference in carbon abundance between the two sets of stars. It is also interesting to note that in this region of atmospheric parameters the G band is quite sensitive to changes in carbon abundance. On the AGB, for example, at $T_{\rm eff} = 4850$, $\log g = 1.6$, and $[{\rm A/H}] = -1.4$ a change from [C/A] from 0.0 to -0.3 causes a change in the G-band strength from 6.6 to 4.7 Å. Comparison of these results with the range of values on the AGB seen in Figure 6 suggests that $\Delta[{\rm C/A}] \sim 0.3$ provides a reasonable upper limit to the range in carbon abundance for this group of stars. Finally, if one were to seek an upper limit to a possible systematic carbon abundance difference between giant branch and AGB stars at $T_{\rm eff} \sim 4850$ by adopting a difference in G-band strength of ~3 Å (which seems rather generous), the above calculations show that $\Delta[{\rm C/A}] \sim 0.3$ gives a reasonable value to that upper limit.

The behavior of the CN bands in the AGB stars is, on the other hand, quite difficult to understand. As may be seen in Figure 3, not one of the AGB stars studied here has enhanced CN. Yet on the giant branch there are more strong CN stars than CN weak ones. If we restrict ourselves to stars with $B-V \geq 0.80$, we can rule out the possibility of effective temperature being responsible for the difference, since strong CN stars exist at the same colors (temperatures) as do the AGB stars. Since the AGB stars have higher luminosity than the red giants of similar temperature, and since CN shows a positive luminosity effect, we can rule out differences in gravity as the cause. To produce a CN weak AGB star from a CN strong giant branch star, we are then left with the possibility of reducing carbon and/or nitrogen. Now comes the dilemma. We have argued above that a reasonable upper limit to the carbon depletion is ~0.3 dex, and there is no reasonable way of reducing the abundance of nitrogen on the giant branch. To make matters worse, any postulated carbon processing will produce nitrogen, offsetting the effect of carbon depletion. In view of the importance of this result, an investigation of CN in the AGB stars at somewhat higher resolution seems warranted.

Since the AGB stars have spent a long period on the blue horizontal branch, where spectral peculiarities are believed to originate, perhaps by diffusive processes (see Greenstein and Sargent 1974), it may be suggested that the nitrogen deficiency is set up during this phase. We believe, however, that such a suggestion is at present too ad hoc to be accepted. Little information exists on the behavior of nitrogen in Ap stars, and one would expect that atmospheric abundance anomalies would be destroyed by the convection which exists in the outer layers of AGB stars. A second possibility, which we shall discuss in § V*d*, is that not all stars presently on the red giant branch (in particular the CN strong ones) will reach the asymptotic giant branch.

There is one further possibly important effect in the CN data on the giant branch. Inspection of Figure 3 shows an apparent decrease in the ratio of CN strong to CN weak stars with increasing luminosity. To the extent that a sizable fraction of the stars above $V \sim 12.4$ may be AGB stars, which appear to be CN weak, this result may be consistent with our previous discussion. We were surprised, however, to find no stars with enhanced CN bands among the five brightest stars in the cluster. (We must add the caveat that our spectra of the two coolest stars are not well exposed in the region of the violet CN bands, having been optimized for the region at λ4300.) Abundance analyses of this group of bright giants at higher resolution could throw important light on this effect.

d) *The Gap on the Horizontal Branch*

As mentioned earlier, there is a gap on the horizontal branch of NGC 6752 stretching from $\log T_{\mathrm{eff}}=4.28$ to 4.37. This led Newell and Sadler (1978) to infer the existence of "a multimodal distribution of the physical, or chemical, parameters that determine the position of BHB stars in the HR and two-color diagrams." We, on the other hand, have found a bimodal distribution of CN strength on the giant branch. The two results are surely suggestive of a common cause, possibly related to the chemical parameters in the cluster.[4] While we are unable to propose a definitive explanation, we conclude by submitting two possibilities for consideration.

i) *Primordial Helium Abundance Differences* ($\Delta Y \sim 0.05$)

We suppose that NGC 6752 contains two groups of stars. They may be successive generations, or they may have developed independently with different chemical histories before coming into dynamical equilibrium. The first group is represented by the CN weak stars in the cluster; the second, by the group of CN strong red giants. We envisage that star formation was complete within a few hundred million years; that is, on a time scale very much shorter than the age of the cluster. We *postulate* that the CN strong group has an abundance of helium higher by $\Delta Y=0.05$ than that with weak CN. The consequence of such a difference is that the CN strong group will at the present time have a lower mass at the main sequence turnoff. If we adopt an age and metal abundance for both groups of 13×10^9 years and $Z=0.001$, and helium abundances of $Y=0.25$ and 0.30 for the CN weak and strong groups, the corresponding masses at the turnoff are 0.81 and 0.74 $M_{\odot}$, respectively[5] (Ciardullo and Demarque 1977). (A factor of 2 difference in Z has a small effect on this result, increasing the difference by $\sim0.01\ M_{\odot}$.) If one assumes that both groups experience similar amounts of mass loss as they ascend the giant branch, they will arrive on the horizontal branch with a mass difference of $\sim0.07\ M_{\odot}$. In the present case, suitable values of the total masses are 0.50 and 0.57 $M_{\odot}$ (cf. Newell and Sadler 1978). The CN strong group will populate the blue end of the horizontal branch, there will be a gap, and the second group will occupy the redder end of the horizontal branch. Because of the difference in form of the evolutionary tracks of stars having masses ~0.50 and 0.57 (cf. our Fig. 11, and Sweigart and Gross 1976), subsequent evolution on and away from the horizontal branch will not bring the groups together again in the H-R diagram. If all stars had masses either 0.50 or 0.57 $M_{\odot}$ and the parameters (Y, Z, core mass)$=$(0.30, 0.001, 0.475) there would be a gap on the horizontal branch of $\Delta\log T_{\mathrm{eff}}=0.19$ (twice the size given by Newell and Sadler). This difference in morphology of the evolutionary tracks has a further interesting consequence. The low mass, high helium, high CN group will not ascend the giant branch again; the envelope masses are too small. Here then is a possible explanation for the lack of CN strong objects on the AGB.

In changing the helium abundance by $\Delta Y=0.05$ we should also consider concomitant changes in a star's evolutionary history. A change $\Delta Y=+0.05$ will change the core mass of the star at the helium flash by $\Delta M_c=-0.01$, and consequently alter the position the star initially occupies on the horizontal branch by $\Delta\log T_{\mathrm{eff}}\sim-0.07$ (at $\log T_{\mathrm{eff}}\sim4.3$). This will be offset to some extent by the higher envelope helium abundance which moves the star hotter on the giant branch; at $\log T_{\mathrm{eff}}\sim 4.3$, $\Delta Y=0.05$ causes a change $\Delta\log T_{\mathrm{eff}}\sim+0.02$. If the increase in helium is accompanied by an increase in the abundance of the heavy elements by, say, a factor 2, the star's position on the horizontal branch would change by $\Delta\log T_{\mathrm{eff}}\sim-0.01$ at $\log T_{\mathrm{eff}}\sim4.3$. (The foregoing estimates are based on the papers of Sweigart and Gross 1976, 1978.) The net change of these effects is $\Delta\log T_{\mathrm{eff}}\sim-0.06$ which tends to reduce the size of the gap, $\Delta\log T_{\mathrm{eff}}=0.19$, suggested in the previous paragraph. The gap will, however, remain.

A further decrease in the size of the gap will be caused by any dispersion in total mass, or by core rotation in each of the groups (cf. Renzini 1977). Without realistic estimates of the size of such dispersions, however, little progress can be made in estimating their effects. The basic question raised by our hypothesis is whether or not a variation of $\Delta Y\sim0.05$ can reasonably be expected between two groups of stars in a globular cluster. This range is not too differ-

---

[4] It has been suggested to us by R. Zinn that the ratio of stars in the two horizontal branch groups does not appear to be the same as that between the two CN groups, which would argue against seeking a common origin for the two phenomena. We believe, however, that this does not necessarily follow. First, there are important selection effects in the existing color-magnitude diagrams, in that the two horizontal branch groups have not been taken from the same area of sky (cf. Lee 1976, Carney 1979). Second, and more important, the possibility exists that if two mass groups exist on the giant branch, not all stars in the lower mass group may reach the horizontal branch. If the mass on the giant branch becomes sufficiently small, there will be no helium flash and the star will become a white dwarf on a short time scale (cf. Damarque and Mengel 1971).

[5] The age spread necessary to produce such a mass difference is $\sim5\times10^9$ years (cf. Ciardullo and Demarque 1977).

ent from that suggested by Iben and Truran (1978) for stars of Population I abundance, and observed by Nissen (1976) between clusters and associations of Population I. Since, however, we are dealing with a somewhat different set of initial conditions, we must leave the decision on this matter to others.

ii) *Correlated Mixing and Mass Loss*

The second possibility is that the chemical bimodality on the giant branch results from mixing and that those stars which mix (the CN strong group) lose more mass (by $\Delta M \sim 0.07\ M_\odot$) prior to their arrival at the horizontal branch. This is intuitively what one might expect since mixing would presumably be a rather turbulent process. As before, this would be consistent with the lack of CN strong stars on the AGB, since the lower mass group probably does not ascend the giant branch a second time.

This hypothesis has one possibly observable consequence. If the CN strong group is losing mass at a faster rate, and if Hα emission in globular cluster giants is a measure of mass loss (Cohen 1976; Mallia and Pagel 1978), one might expect to find stronger emission in this group of stars. Cacciari and Freeman (1980) have instituted a search for Hα emission in several globular clusters, including NGC 6752. A preliminary analysis of their data for 14 giants in NGC 6752, however, shows no evidence for emission except at the giant branch tip (A31 and A59), and hence offers little support for the hypothesis.

It is a pleasure to thank the Director and staff of the Anglo Australian Observatory for the use of their facilities, and Mr. A. J. Pickles who assisted in the reduction of some of the material. P. L. C. wishes to acknowledge the support of an Australian National University Postgraduate Award during this work, while G. D. C. wishes to thank the Carnegie Institution of Washington for the award of a Carnegie Postdoctoral Fellowship.

REFERENCES

Alcaino, G. 1972, *Astr. Ap.*, **16**, 220.
Bell, R. A., and Dickens, R. J. 1974, *M.N.R.A.S.*, **166**, 89.
Bell, R. A., Eriksson, K., Gustafsson, B., and Nordlund, Å. 1975, *Astr. Ap. Suppl.*, **23**, 37.
Bell, R. A., and Gustafsson, B. 1978, *Astr. Ap. Suppl.*, **34**, 229.
Bessell, M. S., and Norris, J. 1980, in preparation.
Butler, D. 1975, *Pub. A.S.P.*, **87**, 559.
Cacciari, C., and Freeman, K. C. 1980, in preparation.
Cannon, R. D. 1974, *M.N.R.A.S.*, **167**, 551.
Cannon, R. D., and Lee, S.-W. 1973, paper presented at Frascati meeting on Population II evolution.
______. 1978, private communication.
Cannon, R. D., and Stobie, R. S. 1973, *M.N.R.A.S.*, **162**, 227.
Carney, B. W. 1979, *A.J.*, **84**, 515.
Ciardullo, R. D. and Demarque, P. 1977, *Yale Trans.*, Vol. **33**.
Cohen, J. 1976, *Ap. J.* (*Letters*), **203**, L127.
______. 1978, *Ap. J.*, **223**, 487.
______. 1979, *Ap. J.*, **231**, 751.
Cottrell, P. L. 1978, Ph. D. thesis, Australian National University.
Cottrell, P. L., and Norris, J. 1978, *Ap. J.*, **221**, 893.
Da Costa, G. S., and Cottrell, P. L. 1980, *Ap. J.* (*Letters*), **236**, L83.
Da Costa, G. S., Freeman, K. C., Kalnajs, A. J., Rodgers, A. W., and Stapinski, T. E. 1977, *A.J.*, **82**, 810.
Demarque, P., and Mengel, J. G. 1971, *Ap. J.*, **164**, 317.
Dickens, R. J., and Bell, R. A. 1976, *Ap. J.*, **207**, 506.
Eggen, O. J. 1972*a*, *Ap. J.*, **172**, 639.
______. 1972*b*, *Ap. J.* (*Letters*), **178**, L109.
Freeman, K. C., and Rodgers, A. W. 1975, *Ap. J.* (*Letters*), **201**, L71.
Gingold, R. A., 1976, *Ap. J.*, **204**, 116.
Greenstein, J. L., and Sargent, A. I. 1974, *Ap. J. Suppl.*, **28**, 157.
Gustafsson, B., Bell, R. A., Eriksson, K., and Nordlund, Å. 1975, *Astr. Ap.*, **42**, 407.
Hartwick, F. D. A., and McClure, R. D. 1980, *Ap. J.*, **235**, 470.
Hesser, J. E. 1978, *Ap. J.* (*Letters*), **223**, L117.
Hesser, J. E., Harwick, F. D. A., and McClure, R. D. 1977, *Ap. J. Suppl.*, **33**, 471.
Iben, I., Jr. 1975, *Ap. J.*, **196**, 525.
______. 1976, *Ap. J.*, **208**, 165.
Iben, I., Jr., and Truran, J. W. 1978, *Ap. J.*, **220**, 980.
Kinman, T. D. 1959, *M.N.R.A.S.*, **119**, 157.
Lamb, S. A., Iben, I., Jr., and Howard, W. M. 1976, *Ap. J.*, **207**, 209.
Lee, S.-W. 1976, Ph.D. thesis, Australian National University.
Mallia, E. A. 1977, *Astr. Ap.*, **60**, 195.
______. 1978, *Astr. Ap.*, **70**, 115.
Mallia, E. A., and Pagel, B. E. J. 1978, *M.N.R.A.S.*, **184**, 55P.
McClure, R. D. 1976, *A.J.*, **81**, 182.
McClure, R. D., and Norris, J. 1977, *Ap. J.* (*Letters*), **217**, L101.
Newell, E. B., Rodgers, A. W., and Searle, L. 1969, *Ap. J.*, **158**, 699.
Newell, E. B., and Sadler, E. 1978, *Ap. J.*, **221**, 825.
Nissen, P. E. 1976, *Astr. Ap.*, **50**, 343.
Norris, J. 1974, *Ap. J.*, **194**, 109.
______. 1978, in *IAU Symposium 80*, *The HR Diagram*, ed. A. G. D. Philip and D. S. Hayes (Dordrecht:Reidel), p. 195.
______. 1979, Proceedings of Nato Conference on Globular Clusters held at Cambrindge (1978 August).
Norris, J., and Cottrell, P. L. 1979, *Ap. J.* (*Letters*), **229**, L69.
Norris, J., and Freeman, K. C. 1979, *Ap. J.* (*Letters*), **230**, L179.
Norris, J., Freeman, K. C., and Seitzer, P. 1980, in preparation.
Norris, J., and Smith, G. 1980, in preparation.
Norris, J., and Zinn, R. 1977, *Ap. J.*, **215**, 74.
Oinas, V. 1975, *Ap. J. Suppl.*, **27**, 405.
Osborn, W. 1971, Ph.D. thesis, Yale University.
Peterson, C. J., and King, I. R. 1975, *A.J.*, **80**, 427.
Renzini, A. 1977, in *Advanced Stages in Stellar Evolution*, ed. P. Bouvier and A. Maeder (Geneva Observatory), p. 151.
Rood, R. T. 1970, *Ap. J.*, **162**, 939.
Sandage, A., and Katem, B. 1977, *Ap. J.*, **215**, 62.
Searle, L. 1977, in *The Evolution of Galaxies and Stellar Populations*, ed. B. M. Tinsley and R. B. Larson (New Haven: Yale University Observatory), p. 219.
Searle, L., and Zinn, R. 1978, *Ap. J.*, **225**, 357.
Siegel, S. 1956, *Nonparametric Statistics for Behavioral Sciences* (Tokyo: McGraw-Hill Kogakusku).
Smith, J., and Demarque, P. 1978, preprint.
Sweigart, A. V., and Gross, P. 1976, *Ap. J. Suppl.*, **32**, 367.
______. 1978, *Ap. J. Suppl.*, **36**, 405.
Sweigart, A. V., and Mengel, J. G. 1979, *Ap. J.*, **229**, 624.
Wesselink, A. J. 1974, *M.N.R.A.S.*, **168**, 345.
Zinn, R. 1973, *Ap. J.*, **182**, 183.
______. 1977, *Ap. J.*, **218**, 96.

P. L. Cottrell: Department of Astronomy, California Institute of Technology, Pasadena, CA 91125

G. S. Da Costa: Yale University Observatory, Box 2023 Yale Station, New Haven, CT 06520

K. C. Freeman and J. Norris: Mount Stromlo and Siding Spring Observatories, Private Bag, Woden. P.O. ACT 2606, Australia