1984ApJ...283..615B

THE ASTROPHYSICAL JOURNAL, 283:615–625, 1984 August 15
© 1984. The American Astronomical Society. All rights reserved. Printed in U.S.A.

SPECTROSCOPY OVER A RANGE OF 5 MAGNITUDES IN NGC 6752

R. A. BELL[1]
Division of Astronomical Sciences, National Science Foundation
JAMES E. HESSER[1]
Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics
AND
R. D. CANNON[1]
Royal Observatory, Edinburgh
Received 1983 November 7; accepted 1984 March 1

ABSTRACT

SIT vidicon spectra with 3–4 Å resolution have been obtained with the CTIO 4 meter telescope for 26 stars in the southern globular cluster NGC 6752 (C1906−60). The stars observed range in brightness from the main-sequence turnoff to the tip of the giant branch and are the first spectra of upper-main-sequence stars obtained in a low-metallicity globular cluster. Interpretation of the spectra has been facilitated by comparison with an extensive grid of synthetic spectra calculated for the purpose. The overall cluster abundance is found to be [M/H] ∼ −1.5. No evidence is found for star-to-star abundance differences of any elements other than C and N, and the spectra suggest that the observed $B-V$ width of the color-magnitude diagram at faint levels is due largely, if not entirely, to observational scatter rather than to real (metal-abundance induced) temperature variations. Varying amounts of carbon depletion are inferred for brighter, as well as fainter, giants, and nitrogen enhancements $\gtrsim 3$ are inferred for the brightest giants. A range of CN strengths is observed among the faintest giants, but the sample is too small to assess whether or not the bimodal nature of the distribution seen in bright giants persists to $M_v \sim +2.0$–3.0. Observed and computed spectral indices due to Ca, CN, CH, and Fe agree well at all M_v after allowing for zero point shifts. This is the first time that spectral observations made with the same equipment for a number of globular cluster stars ranging from the tip of the giant branch to the main-sequence turnoff have been compared with model calculations.

Subject headings: clusters: globular — spectrophotometry — stars: abundances

I. INTRODUCTION

NGC 6752 (C1906−60, $\alpha_{1950} = 19^h06^m.4$, $\delta_{1950} = -60°4'$, $l = 336.°5$, $b = -25.°6$) is a nearby, metal-deficient globular cluster whose color-magnitude (C-M) diagram is characterized by a narrow giant branch, a pronounced asymptotic giant branch (AGB), and a very blue horizontal branch (BHB). These features are seen, for example, in the C-M diagrams by Cannon and Stobie (1973), Carney (1979), and Alcaino and Liller (1980). The BHB extends to exceptionally high temperatures and shows an unusual dichotomy, with a detached group of extreme BHB stars appearing at the level of the main-sequence turnoff in the (V, $B-V$) C-M diagram. These stars are most clearly seen in the C-M diagram obtained by Cannon and Lee (see Cannon 1981*a*), and Caloi *et al.* (1984) show that they can be identified with field subdwarf B stars. Mallia (1977, 1978), Bell and Dickens (1980), DaCosta and Cottrell (1980), Cottrell and DaCosta (1981), Norris *et al.* (1981), and Pilachowski, Sneden, and Wallerstein (1983) have analyzed spectroscopic and/or narrow-band photometric observations. Both the overall metal abundance and the properties of the CH and CN bands have been discussed. Unfortunately, high-dispersion spectroscopic data on O I lines have been obtained only for one very luminous giant star, and photometric observations of CO bands became available only recently (Frogel, Persson, and Cohen 1983). This has meant that C and N abundances have previously been deduced under the assumption that the oxygen abundance is normal; i.e., [O/A] = 0.0.[2]

The general consensus, based on low-dispersion spectra of individual stars, is that the overall metal abundance of NGC 6752 is about [M/H] ≈ −1.5. Mallia's value of −1.8 seems relatively low. Bell and Dickens found that −1.5 gave synthetic spectra which agreed with their low-dispersion spectra. DaCosta and Cottrell (1980) used −1.5, whereas Norris *et al.* (1981) used −1.4. Photometric abundance indicators give slightly higher results. Cannon (1974) gives $(B-V)_{0,g} = 0.81$ and $\Delta V = 2.5$, and his photometric data give $S = 5.0$. The definition of these quantities can be found in Bell and Gustafsson (1983), whose calibration gives abundances of −1.1, −1.0, and −1.3, respectively. Carney (1979) interpreted his $\delta(U-B)_{0.6}$ for dwarf stars as implying [Fe/H] = −1.5. Pilachowski, Sneden, and Wallerstein (1983) have used high-dispersion spectra to analyze three very luminous ("tip") giants. They report [Fe/H] = −1.32, and an abundance for the α process elements of [α/H] = −0.99.

Similar conclusions on the cluster abundance are reached from studies of integrated light. However, some care must be taken in interpreting these measurements in view of the number of extremely hot BHB stars. For example, Kinman (1959) and Hesser and Shawl (1984) assigned spectral types of F6 and F4, respectively, indicative of low abundance. Harris

[1] Visiting Astronomer, Cerro Tololo Inter-American Observatory, which is supported by the National Science Foundation under contract AST 78-27879.

[2] [X] = log X − log $X_\odot$. [A/H] is used to refer to abundances employed in calculations, A being an element other than H and He. Abundances deduced from photometric observations are denoted by [M/H].

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1984ApJ...283..615B

and Canterna (1977) inferred $[Fe/H]_K = -1.5$ from Q_{CMT} while Zinn (1980) gave $[Fe/H] = -1.54$ from Q_{39} measurements. Frogel, Cohen, and Persson (1983) estimated $[Fe/H] = -1.35$ from infrared photometry of cluster giants.

Bell and Dickens (1980) used their spectra and DDO photometry to find that $[C/A] = -0.5$ for a sample of stars $-2.0 < M_V < +1.0$, while the N abundances were found to be enhanced by about $[N/A] = +0.5$. The photometry suggests the possibility of a change in this abundance pattern at $M_V \sim -1.0$.

Norris *et al.* (1981) give a number of observational results for NGC 6752. Among these are: (1) a large range in CN strength on the giant branch, with the likelihood of a bimodal distribution; (2) small G-band variations in the giant branch stars, anticorrelating with the CN variations; (3) a small range in absorptions in the Ca II H and K region, correlating with the CN variations; and (4) weak CH and CN in the AGB stars, the CH being weaker than in giant branch stars of the same color.

The second point was examined in detail by DaCosta and Cottrell (1980), who studied two giant branch stars of similar V, $B-V$ but different CH and CN band strengths. They found that the "CN-strong" star had a slightly depleted carbon abundance and a much higher nitrogen abundance than the "CN-weak" star. Cottrell and DaCosta (1981) extended the analysis to three pairs of NGC 6752 giant stars having weak and strong CN and found that both Na and Al are enhanced in its strong CN stars.

As part of a general project of studying the spectra of near-main-sequence stars in globular clusters, we obtained low-dispersion ($\sim$3–4 Å resolution) spectra of a number of such stars in NGC 6752, using the SIT vidicon spectrograph (Atwood *et al.* 1979) on the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope. In order to obtain overlap with the earlier work reviewed above, we also observed some bright stars. A total of 26 stars were observed, the overall sample lying in the approximate range[3] $-1.5 < M_V < +3.8$. These data, together with UBV photometry of fainter stars (Carney 1979; Cannon and Lee, unpublished) lends itself to a study of the following questions:

First, can stars be excluded from cluster membership, either on the basis of their radial velocities or on the basis of their spectra?

Second, what information can be obtained about the overall cluster abundance as well as the abundance variations of individual elements? Is there any suggestion of star-to-star variations in this quantity?

Third, is there any evidence for unusual CH or CN band strengths in the spectra of the fainter stars? Any such unusual strengths might help to distinguish between primordial or mixing hypotheses for the abundance variations in the brighter stars.

Fourth, do abundances inferred from comparison of theoretical and observed spectra of luminous and faint cluster stars agree?

Finally, do the spectra of the fainter, near-main-sequence stars give any indication of a spread of temperature among stars at a given luminosity? Or is the observed scatter in the C-M diagram due mainly to measuring errors which would mask any intrinsic color spread?

[3] As Cannon and Stobie (1973) emphasize, the lack of horizontal-branch stars near the RR Lyrae gap makes it difficult to ascertain the distance modulus for NGC 6752. They suggest $V_0 - M_v \sim 13.5$, while Newell and Sadler (1978) use $V_0 - M_v \sim 13.2$ and Sandage (1982) chooses $V_0 - M_v = 12.98$. In this paper we adopt 13.5. The reddening used is the $E(B-V) = 0.05$ value of Cannon and Stobie.

II. OBSERVATIONS

Stars were selected for observation from the C-M diagram study of Cannon and Stobie (1973) and the faint photoelectric sequence of Cannon (1981*b*). The numbering systems of these authors are used subsequently, with prefixes CS and C, respectively. The C-M diagram of the stars we observed is plotted as Figure 1. The approximate width of various cluster branches is also sketched in this diagram on the basis of the Cannon and Lee C-M diagram, which agrees well with that of Carney (1979). We have also indicated $(B-V)_0$ and M_V scales in Figure 1 adopting $E(B-V) = 0.05$ mag and $V_0 - M_V = 13.5$ (see n. 3).

Spectra of the NGC 6752 stars were obtained during observing runs in 1980 September and 1981 April with the CTIO 4 m telescope equipped with its R-C focus spectrograph and the 16 mm, UV-transmitting SIT detector. The properties of the equipment, as well as the conditions during these runs, have been thoroughly described elsewhere (Hesser and Harris 1981); Bell, Hesser, and Cannon 1983; Hesser *et al.* 1984) and need not be repeated here. The spectra were reduced to approximate flux values and wavelengths using the software then available at the La Serena computer system (now referred to as the "old" SIT reduction package and described by Schaller *et al.* 1978).

For each observed star Table 1 contains the V and $B-V$ values from CS (photoelectric) or C (smoothed photographic), some parameters of the observations, the derived heliocentric radial velocities, v_r (of estimated 25–30 km s^{-1} precision and rounded to the nearest 10 km s^{-1}), and the number of lines used in the velocity determination. As described by Bell, Hesser, and Cannon (1983), the 1980 data appear to require an additive correction of approximately 38 km s^{-1} to bring them onto the radial velocity system defined by the globular clusters

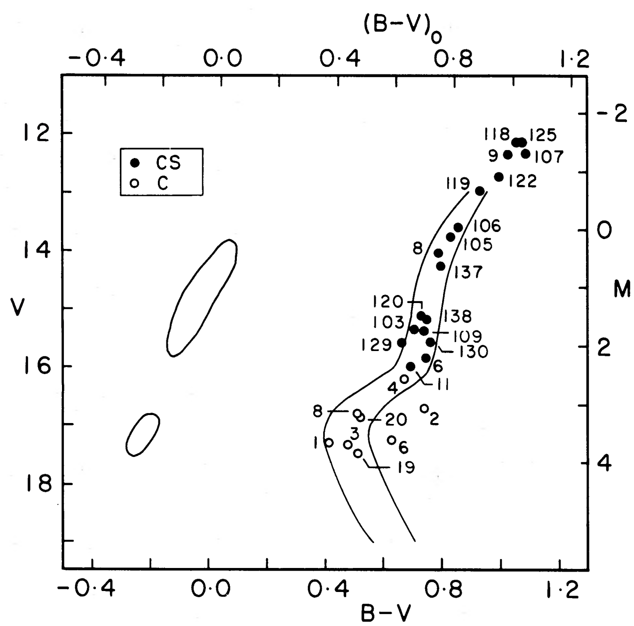

FIG. 1.—The color-magnitude diagram of NGC 6752. The widths of various cluster branches are sketched using data from Cannon and Stobie (1973) and Cannon and Lee (unpublished). The arrow indicates the faint limit of the Norris *et al.* (1981) survey.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1984ApJ...283..615B

TABLE 1

NGC 6752 Observational Results

Star	V (mag)	$B-V$ (mag)	UT. Start (yr:mo:day:hr:min)	HA Start (hr:min)	Expo (min:sec)	v_r (km s^{-1})	No. of Lines Used	Remarks
CS 125	12.16	1.08	80:09:07:23:44	0:59E	2:00	[a]		
			07:23:50	0:53E	3:00			
			81:04:06:09:44	1:10E	0:45	−30	12	
			06:09:46	1:08E	0:45			
			08:10:06	0:40E	0:40	−50	11	
CS 118	12.18	1.07	81:04:08:09:32	1:13E	0:30	−60	12	
			08:09:35	1:11E	0:35			
CS 107	12.34	1.09	81:04:08:10:02	0:43E	0:35	−60	10	
			08:10:03	0:41E	0:45			
CS 9	12.37	1.03	81:04:08:09:45	1:01E	0:30	−60	10	
			08:09:47	0:59E	0:30			
CS 122	12.73	1.00	81:04:08:09:20	1:27E	0:50	−80	12	
CS 119	13.00	0.93	81:04:08:09:23	1:23E	0:50	−80	10	
			09:26	1:20E	0:70			
CS 106	13.60	0.86	81:04:08:09:57	0:47E	2:30	−50	9	
CS 105	13.76	0.83	81:04:08:09:52	0:53E	2:40	−80	10	
CS 8	14.06	0.79	81:04:08:09:38	1:07E	4:00	−90	10	
CS 137	14.26	0.80	81:04:08:09:10	1:36E	5:00	−50	11	
CS 120	15.15	0.73	80:09:11:01:04	0:31W	8:00	−30	7	
CS 138	15.21	0.75	80:09:11:01:54	1:21W	8:00	−10	6	
CS 103	15.40	0.74	80:09:11:01:37	1:06W	10:00	−30	10	
CS 109	15.44	0.75	80:09:11:01:18	0:40W	10:00	−40	9	
CS 129	15.59	0.66	80:09:11:00:48	0:15W	10:00	+10	8	
CS 130	15.59	0.76	80:09:11:00:27	0:06E	15:00	−60	8	Overexposed
CS 6	15.84	0.74	80:09:10:01:30	0:56W	20:00	−30	11	
CS 11	16.02	0.69	80:09:10:02:21	1:46W	20:00	−60	8	
C4	16.23	0.67	80:09:09:23:48	0:50E	20:00	−60	8	
C2	16.72	0.74	80:09:08:00:09	0:35E	30:00	[a]		
			81:04:06:08:34	2:19E	30:00	−20	9	Field star
C20	16.83	0.51	80:09:09:00:41	0:01W	30:00	−80	5	
C8	16.85	0.52	80:09:08:00:49	0:06W	30:00	[a]		
			81:04:06:09:08	1:45E	30:00	−10	7	
C6	17.24	0.63	80:09:10:00:54	0:19W	30:00	−60	6	Field star
C1	17.27	0.41	80:09:09:01:18	0:40W	30:00	−30	6	
C3	17.32	0.48	80:09:10:00:16	0:20E	30:00	−10	6	
C19	17.47	0.51	80:09:09:02:38	1:58W	30:00	−60	6	

Note.—All velocities rounded to nearest 10 km s^{-1}.

[a] No comparison spectrum available.

observed during the run; no such corrections appear necessary for the 1981 data. After applying the zero-point correction found by Bell, Hesser, and Cannon (1983) for the 1980 data, the average velocity found from all 27 observations is -45 ± 5 (s.d.m.) km s^{-1}, which compares favorably with the value compiled by Webbink (1981), $v_r = -32.2$ km s^{-1}. Given both the low cluster radial velocity and the low precision of our velocities, no stars are clearly eliminated as members on the basis of velocity data alone.

Several of the stars in our sample have been observed by others; e.g., CS 125 was observed by Bell and Dickens (1980), while all 10 stars in our sample which are brighter than $V = 14.5$ were observed by Norris *et al.* (1981), who also give DDO photometry for five of the brighter stars (CS 9, 118, 119, 122, and 125). On the basis of radial velocity data, Norris *et al.* (1981) concluded that CS 9, 105, 107, 118, 122, and 125 are members; on the basis of photometric properties they also consider the remaining stars in common with ours to be members.

III. SPECTRAL CHARACTERISTICS

Our spectra, presented in Figure 2 as a function of decreasing visual magnitude, allow us to note the following characteristics:

In the most luminous subsample of stars (CS 125, 118, 107, and 9), CS 107 has a much weaker CN band and a marginally stronger G band than the other three.[4] CS 122 has weaker CN than CS 119, which is of nearly comparable luminosity, but is hotter. Among the next luminosity group, CS 8 has much weaker CN and a somewhat stronger G band than do CS 106, 105, and 137. Thus, among the 10 luminous NGC 6752 giant stars in common with Norris *et al.* (1981), we are in excellent agreement that CS 8, 107, and 122 possess weaker CN than the other comparison stars at comparable luminosities.[5]

Turning to the groups of stars lying at luminosities fainter than those studied spectroscopically in previous investigations, we find that, among stars CS 120, 138, 103, 109, 129, and 130, only CS 129 and 130 have spectra which suggest the strength-

[4] Carney (1979) called attention to the peculiar nature of CS 118 in his DDO photometry and low-dispersion spectra of CS 6, 118, 122, and 126. In our spectra, CS 118 is distinguished only by virtue of its stronger CN bands. Since the general dichotomy of CN strengths among NGC 6752 giants was not recognized until after Carney's work (see Norris *et al.* 1981) and since Carney's small sample otherwise consisted of CN-weak stars, the CS 118 "anomaly" receives a natural explanation in the recognition of a class of CN-strong stars in the cluster.

[5] The footnote with the double dagger (‡) in Norris *et al.*'s Table 1 states that "open and closed symbols indicate CN strong and weak objects," whereas the reverse is the case.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1984ApJ...283..615B

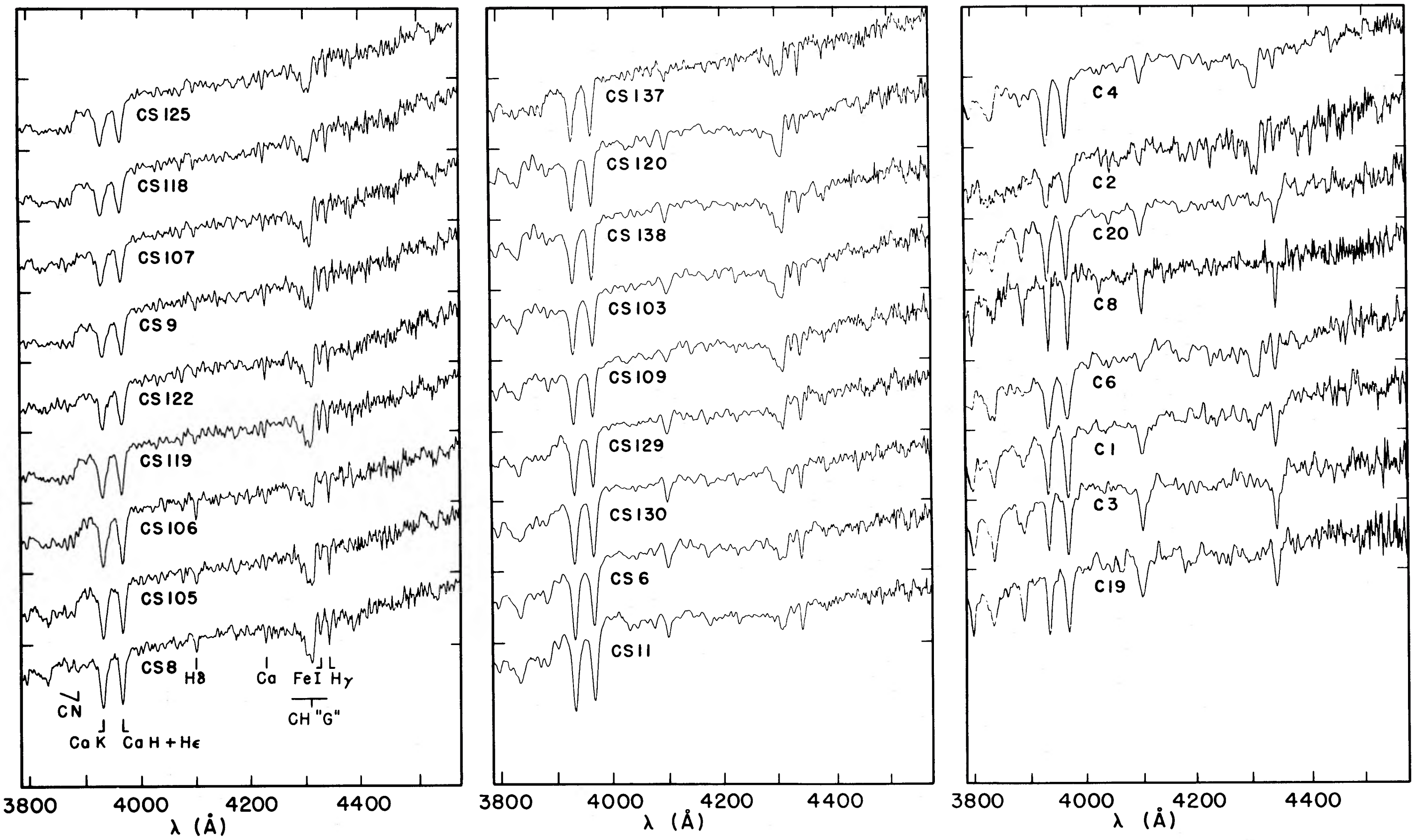

FIG. 2.—The observed spectra are plotted as a function of absolute magnitude

ening of the CN bands at $\lambda \sim 3880$ Å. It is our impression, from our limited sample, that the average CN strength is higher in the more luminous stars considered earlier, which may be contrasted to the situation occurring among faint giants in 47 Tuc, where the CN strengths seem quite comparable throughout the CMD (Hesser 1978; Hesser and Bell 1980). In the next group (CS 6 and 11, C4 and 2) the dramatically increased line blanketing of C2 runs counter to the homogeneity seen in other NGC 6752 stars and argues against its membership in the cluster, as does its location some 0.15 mag to the red of the subgiant branch (cf. Fig. 1). CS 6 and 11 seem to have some 3883 Å CN, and C4 may have a somewhat enhanced G band. Finally, the faintest group of stars presents (to the best of our knowledge) the first spectra of turnoff region stars in a metal-poor globular cluster. Not surprisingly, they look like mid-F type stars, in agreement with the integrated spectral type. The reader may compare these spectra to the somewhat larger sample of more metal-rich stars observed in 47 Tuc during the same 1980 observing run (Bell, Hesser, and Cannon 1983). Star C6 shows a G band and other features appropriate to a Population I field star of its color, which is $\sim$0.1 mag redder than the remainder of the presumed main-sequence stars, and it seems likely that this star is not a member of NGC 6752. The spectra of the remaining turnoff region stars appear to be quite similar, taking into consideration the constraints imposed by signal-to-noise ratio considerations for these short-exposure, survey data of very faint stars. Their hotter temperatures preclude, of course, comparing G-band and CN-band strengths. The spectra of C1 and C19 are very similar and suggest that the observed $B-V$ difference of 0.1 mag probably arises from observational scatter in the faint photometry, rather than from an intrinsic temperature spread on the main sequence. The same is true of the brighter stars CS 129 and CS 130. In other words, with the possible exception of C8 (§ IV*b*), there is no evidence from our small sample for any real spread in temperatures among the fainter NGC 6752 stars. A similar result was found from a spectroscopic study of 47 Tuc (Bell, Hesser, and Cannon 1983) while improved photometric data have reduced the observed sequence widths both in that cluster (Harris, Hesser, and Atwood 1983) and in M4 (Richer and Fahlman 1984).

In the following section we compare the observed spectra with ones calculated from model atmospheres.

IV. COMPARISON OF SYNTHETIC AND OBSERVED SPECTRA

A number of synthetic spectra have been computed and are compared with the spectra of the 26 stars. This comparison is carried out in both an analog and a digital mode; i.e., using spectral tracings as well as spectral indices. Some observed CO band strengths are also discussed. The discussion necessarily becomes quite complicated. For this reason the reader may prefer to read the summary of the results, contained in § V, prior to reading the detailed comments which follow.

a) *Methodology*

The general methods used to analyze the spectra follow those employed in earlier work (e.g., Bell and Dickens 1980). The analysis is based on the use of spectrum synthesis, the spectra being computed using flux-constant, line-blanketed model stellar atmospheres. These models have been computed

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1984ApJ...283..615B

using the program MARCS described by Gustafsson *et al.* (1975). The analysis begins with the derivation of effective temperatures and surface gravities for the stars. These are obtained from $B-V$ colors and absolute magnitudes. The $B-V$ colors used were found either directly or by interpolation in the color tables of Bell and Gustafsson (1978). The absolute bolometric magnitudes of the models are obtained from the model gravities and the solar $M_{\rm bol}$ and gravity using the equation $M_{\rm bol} = 4.72 + 2.5[g] - 10[T_{\rm eff}] - 2.5[m]$ with g, $T_{\rm eff}$, and m being surface gravity, effective temperature, and mass, respectively. The stars are assumed to have a mass of 0.8 $m_{\odot}$. The bolometric corrections were found from the values given by Bell and Gustafsson (1978) and M_v values were then obtained. The oxygen abundance is initially assumed to be [O/A] = 0.0. The question of variations in this abundance is discussed in § IV.d.

The (M_v, $B-V$)-values of various models with metal abundance [A/H] = −1.5 are given in Figure 3, together with the stellar values. A distance modulus of $V_0 - M_v = 13.5$ and a reddening of $E(B-V) = 0.05$ were used to obtain the stellar values. The uncertainty of about 0.5 in distance modulus causes an uncertainty of about 0.2 in the log g values derived from M_v. This is relatively unimportant in the derivation of metal abundances, corresponding to an uncertainty of about 0.15 in [M/H], as judged by work on Arcturus by Bell, Edvardsson, and Gustafsson (unpublished).

In principle, the analysis of the data can follow either of two paths. There is the direct approach in which the observed spectra are compared with theoretical spectra. Since the 2″ width of the spectrograph entrance slit was generally not sufficient to have encompassed all of the starlight, the observed spectra are unlikely to have an accurate relative flux scale. For this reason the flux scales of the theoretical spectra are varied arbitrarily to obtain a reasonable fit of theory and observation for the continuum (background) spectrum, after which the strengths of stronger spectral features are compared. Other authors, such as Canterna, Harris, and Ferrall (1982), have obtained SIT spectra using a wider spectrograph slit and then measured spectral indices by comparing the flux in a region containing a spectral feature with that in a nearby comparison region. This approach can be readily calibrated using synthetic spectra, although there are again some possible uncertainties in the relative zero points—at least for some indices. One uncertainty arises from the need to interpolate the absolute calibration between the 3704 and 4032 Å passbands of the standard absolute calibration (Hayes and Latham 1975). In the following section we present the results of both these approaches.

b) Direct Comparison between Observed and Synthetic Spectra

Comparisons of the (M_v, $B-V$) of the models 4500/2.25/−1.5 and 4500/1.5/−1.5 show that the four stars CS 9, 107, 118, and 125 all must have $T_{\rm eff}$ close to 4500 K and log $g \sim 1.5$. From Bell and Gustafsson (1978), it appears that a change of [A/H] from −1.0 to −2.0 at this $T_{\rm eff}$ and log g alters $B-V$ by only 0.02. It is difficult to assesss the Ca abundance from the H and K lines of these four stars. The G band is markedly weaker in the stars, implying [C/A] ~ −0.5 for CS 125 and [C/A] ~ −0.3 for CS 9 and CS 107, although CS 107 has strong G band. The 3883 CN bands are stronger in the former two stars. If [C/A] is −0.5 for these objects, then nitrogen is enhanced, since the 3883 band does not show the structure expected for [N/A] = 0.0. A value of [N/A] ~ 0.5 is possible. The spectra do not show the strengthening of the λ4215 CN which should be observable for [N/A] = +1.0. If [C/A] is −0.3 for CS 9 and CS 107, then CS 9 has enhanced N, i.e., [N/A] ~ +0.5, whereas the 3883 band is inconspicuous in CS 107 where [N/A] must be ~0.0. CS 122 is a bluer and fainter star, probably having $T_{\rm eff} \sim 4600$ K. Comparison of the models 4500/1.5/−1.5 and 4750/1.75/−1.5 suggests that [C/A] − 0.3

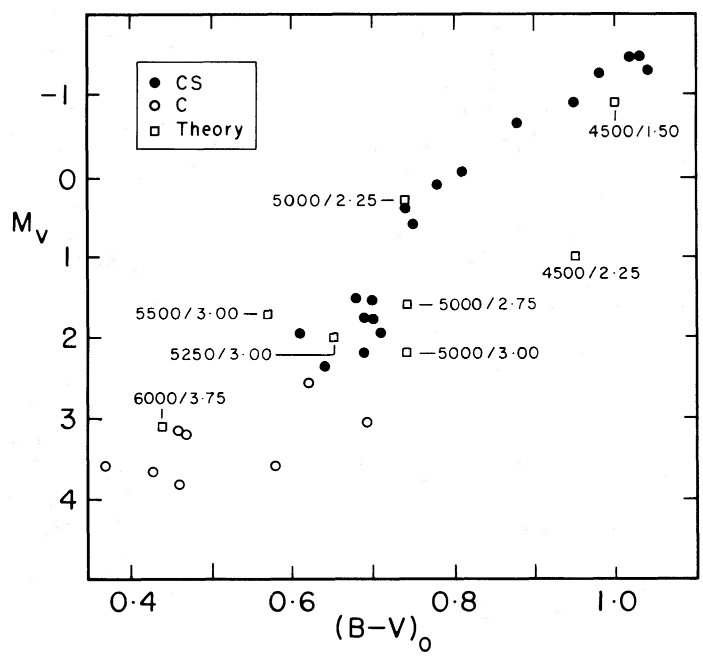

FIG. 3.—The (M_v, $B-V$)-values of various models, computed using the methods described in the text, are compared with values found for the stars. Stars observed spectroscopically are identified individually. The observed values have been corrected for a reddening of $E(B-V) = 0.05$ and a distance modulus of $V_0 - M_v = 13.5$.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1984ApJ...283..615B

while the 3883 Å CN does not appear strengthened. CS 119 has been compared with 4750/1.75/−1.5. The strengths of the 3883 CN, H and K, and the G band seem comparable in the star and the model. The 4325 feature, which is due to CH and Fe, is stronger in the star—a fact which we attribute to noise.

The four stars CS 8, 105, 106, and 137 have all been compared with the 5000/2.25/−1.5 model. The G bands in CS 8 and 105 do not suggest carbon depletion, while the G bands in CS 106 and 137 are weaker in the star than in the model, corresponding to an abundance of [C/A] ≈ −0.3 in both cases. The 3883 Å CN is stronger in both CS 106 and 137 than in 105, and CS 8 has the strongest CN.

The group of nine stars with $1.5 \le M_v \le 2.6$ have been compared with the models 5500/3.0/−1.5, 5250/3.0/−1.0, 5250/3.0/−1.5, 5250/3.0/−2.0, and 5000/3.0/−1.5. The comparison of stars and models in this region is clouded by uncertainty regarding the hydrogen line calculations. The computed lines are certainly weaker than the observed ones for giants with $T_{eff} \le 5000$ K, while the agreement for the Sun is satisfactory. Comparison of the star CS 6 with the models shows that the hydrogen lines are consistent with $T_{eff} \approx 5500$ K. The G band is quite weak even for this temperature, which is about 400 K hotter than that implied by the model colors. If we ignore the evidence of the hydrogen lines and adopt $T_{eff} = 5125$ K (consistent with $B-V$), then the G band implies [C/A] ≤ −0.3. The same comments can be made about CS 130, 11, and C4, although this latter object does have a G band which is similar to that of 5500/3.0/−1.5. The spectrum of CS 129 is very similar to that of CS 130, for example, but the $B-V$ color of CS 129 is only 0.04 mag redder than that of 5500/3.0/−1.5, and so the temperature inconsistency is much less severe. As expected from visual inspection, the m_{CN} indices are somewhat larger than for comparable stars. The remaining stars in the group, viz., CS 109, 138, 103, and 120, have hydrogen line profiles which are more consistent with the cooler 5250/3.0/−1.5 model. In CS 109, the G band is weaker in the star than in the model. CS 138 is similar but has a G band which is similar to CS 109, while CS 120 is consistent with CS 138.

As noted previously the spectra of C6 and C2 indicate that they are not cluster members.

The remaining stars, with $3.0 < M_v < 4.0$, have been compared with the models 6000/3.75/−1.5 and 6250/4.0/−1.5. The computed hydrogen line profiles should be reliable at this T_{eff}. Stars C1, 3, 19, and 20 have hydrogen lines consistent with the model 6000/3.75/−1.5, while H and K seem stronger. The spectrum of C8 is very noisy but appears to have hydrogen lines which are stronger than those in 6250/4.0/−1.5. If these observations are trustworthy, this object may have a temperature of 6500 K. This result deserves observational verification since C8 is the only faint star with a different temperature in the group of upper-main-sequence stars.

These temperatures are generally consistent with the temperatures deduced from $B-V$ colors, although the $B-V$ color of star C1 implies it is hotter than its spectrum indicates while C8 is cooler.

The estimates of stellar abundances for the brighter, cooler stars (deduced from both spectra and spectral indices) are collected in Table 2 as are the temperature estimates of the fainter, hotter stars (deduced from $B-V$ and the spectroscopic hydrogen line profiles).

c) *Spectral Indices*

We now turn to the question of interpretation of spectral indices. The indices are defined in Table 3 and are those used by Canterna, Harris, and Ferrall (1982). The measured values of the indices are given in Table 4. These values were obtained using the program RETICENT (Pritchet, Mochnacki, and Yang 1982), which was also used for plotting the spectra. The indices are discussed in order m_{HK}, m_{Ca}, m_{Fe}, m_G, and m_{CN}. We regard the first three indices as providing data on the overall metal abundance, although obviously the first two will be affected by any change of Ca abundance relative to other metals. The m_G index depends substantially on the carbon abundance and the m_{CN} index depends on both C and N. Following Searle and Zinn (1978), we have analyzed the stars using (M_v, index)-diagrams. The indices computed for various models are given in Table 5. The standard deviations are

TABLE 2

A. Carbon and Nitrogen Abundances of Brighter Stars

Star	[C/A]	[N/A]
CS 125	−0.5	+0.5
CS 118	−0.5	+0.5
CS 107	−0.3	0.0
CS 9	−0.3	+0.5
CS 122	−0.3	...
CS 119	...	+0.5
CS 106	−0.3	+0.5
CS 105	...	+0.5
CS 8	...	...
CS 137	−0.3:	+0.5
CS 120	...	...
CS 109	...	...
CS 129	...	...
CS 130	< −0.3:	...
CS 6	< −0.3:	...
CS 11	< −0.3:	...
C4	< −0.3:	...

B. Temperatures of Fainter Stars

Star	T_{eff} ($B-V$)	T_{eff} (H Lines)
C2	Nonmember	Nonmember
C20	6000	6000
C8	6000	6500
C6	Nonmember	Nonmember
C1	6500	6000
C3	6250	6000
C19	6000	6000

TABLE 3

A. Bandpass Definitions

Bandpass	λ_c(Å)	$\Delta\lambda$(Å)
CN 39	3840	140
HK	3964	110
HK continuum	4075	110
Ca I	4226	30
CH	4276	80
CH continuum	4335	40
Fe	4397	85
Fe continuum	4530	60

B. Index Definitions[a]

m_{CN} = CN 38 − HK continuum
m_{HK} = HK − HK continuum
m_{Ca} = Ca I − CH continuum
m_G = CH − CH continuum
m_{Fe} = Fe − (Fe continuum + CH continuum)/2

[a] Where CN 38 = $-2.5 \log \int_{3770}^{3910} F(\lambda)d\lambda$, etc.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1984ApJ...283..615B

TABLE 4

OBSERVED SPECTROSCOPIC INDICES

Star	m_{CN}	m_{HK}	m_{Ca}	m_G	m_{Fe}	$(B-V)_0$	M_v	No. of Observations
CS 125	0.97	0.52	0.21	0.22	0.09	1.03	−1.49	4
CS 118	0.97	0.52	0.22	0.21	0.09	1.02	−1.47	2
CS 107	0.80	0.51	0.18	0.26	0.10	1.04	−1.31	2
CS 9	1.00	0.51	0.20	0.22	0.09	0.98	−1.28	2
CS 122	0.74	0.49	0.16	0.22	0.11	0.95	−0.92	1
CS 119	0.81	0.43	0.18	0.21	0.08	0.88	−0.65	2
CS 106	0.68	0.39	0.15	0.16	0.06	0.81	−0.05	1
CS 105	0.70	0.38	0.13	0.17	0.08	0.78	0.11	1
CS 8	0.49	0.36	0.09	0.19	0.07	0.74	0.41	1
CS 137	0.60	0.35	0.11	0.13	0.05	0.75	0.61	1
CS 120	0.47	0.34	0.11	0.18	0.03	0.68	1.50	1
CS 103	0.49	0.35	0.04	0.13	0.03	0.69	1.75	1
CS 138	0.43	0.34	0.07	0.15	0.02	0.70	1.56	1
CS 109	0.47	0.34	0.06	0.14	0.01	0.70	1.79	1
CS 129	0.53	0.31	0.13	0.14	0.02	0.61	1.94	1
CS 130	0.51	0.30	0.07	0.08	0.02	0.71	1.94	1
CS 6	0.53	0.29	0.08	0.09	0.01	0.69	2.19	1
CS 11	0.43	0.23	0.04	0.07	0.01	0.64	2.37	1
C4	0.43	0.30	0.08	0.13	0.03	0.62	2.58	1
C2	0.84	0.39	0.22	0.25	0.12	0.69	3.07	1
C20	0.37	0.17	0.01	0.00	−0.02	0.46	3.18	1
C8	0.25	0.09	−0.01	−0.02	0.00	0.47	3.20	1
C6	0.56	0.35	0.06	0.13	0.03	0.58	3.59	1
C1	0.36	0.16	0.01	0.02	−0.05	0.36	3.62	1
C3	0.35	0.11	−0.06	−0.10	−0.08	0.43	3.67	1
C19	0.36	0.15	−0.01	0.01	−0.03	0.46	3.82	1
σ	0.025	0.011	0.010	0.013	0.010			

TABLE 5

COMPUTED SPECTRAL INDICES AND ABSOLUTE MAGNITUDES

Model	M_v	[C/A]	[N/A]	m_{CN}	m_{HK}	m_{Ca}	m_G	m_{Fe}
4500/1.5/−1.5	−1.4			0.734	0.480	0.124	0.292	0.108
		−0.3		0.676	0.489	0.130	0.242	0.115
		−0.3	+0.5	0.769	0.483	0.142		
			+0.5	0.845	0.467	0.144		
5000/2.25/−1.5	+0.3			0.370	0.263	0.033	0.212	0.065
		−0.3		0.342	0.268	0.039	0.175	0.068
		−0.3	+0.5	0.396	0.266	0.042		
			+0.5	0.446	0.260	0.039		
5250/3.0/−1.5	+2.0			0.261	0.210	0.005	0.153	0.034
		−0.3		0.246	0.210	0.007	0.113	0.035
		−0.3	+0.5	0.274	0.209	0.008		
			+0.5	0.306	0.208	0.008		
6000/3.75/−1.5	+3.6			0.125	0.081	−0.089	−0.043	−0.039
		−0.3		0.123	0.078	−0.090	−0.058	−0.039
		−0.3	+0.5	0.124	0.078	−0.090		
			+0.5	0.128	0.081	−0.089		
3750/0.75/−0.5	−0.8			1.702	1.198	0.945	0.483	0.253
4000/1.25/−0.5	−0.4			1.411	0.910	0.518	0.395	0.206
4500/2.25/−0.5	+0.6			0.942	0.552	0.252	0.325	0.143
5000/3.00/−0.5	+2.5			0.612	0.398	0.125	0.247	0.088
4000/0.90/−1.0	−1.9			1.250	0.820	0.371	0.367	0.184
4500/1.80/−1.0	−0.4			0.773	0.523	0.168	0.292	0.120
5000/3.00/−1.0	+1.5			0.431	0.327	0.069	0.219	0.070
4000/0.50/−2.0	−2.4			0.837	0.566	0.208	0.270	0.118
4500/1.50/−2.0	−1.4			0.435	0.362	0.084	0.238	0.074
5000/2.50/−2.0	+0.6			0.198	0.191	0.014	0.122	0.021
4250/0.75/−3.0	−2.6			0.440	0.288	0.121	0.144	0.042
4500/1.50/−3.0	−1.8			0.297	0.179	0.061	0.139	0.031
5000/2.25/−3.0	+0.2			0.143	0.076	−0.002	0.013	−0.007

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1984ApJ...283..615B

deduced from 19 observations of the star ROA 65 in ω Cen made in the same run. This value should be appropriate for the NGC 6752 stars, the exposure times being increased with increasing apparent magnitude. In fact, comparisons of repeat observations of faint stars are consistent with this, apart from an occasional errant value.

It is apparent that the models plotted in Fig. 3 do not have identical (M_v, $B-V$) to the stars. For example, 4500/1.5/$-$1.5 is about 0.5 mag fainter in M_v than the corresponding stars. Consequently, we interpolate or extrapolate indices from the set of computed models to obtain indices for models which will lie on the (M_v, $B-V$)-diagram defined by the stars. For example, we use an interpolated 4500 K model with log $g \sim 1.3$ and $M_v = -1.5$ to analyze the stars CS 107, 125, 118, and 9. Theoretical giant branch lines for [A/H] $= -1.0$ and -2.0 are also displayed in the (M_v, index)-diagrams. The indices for these lines have been computed from the synthetic spectra of Bell and Gustafsson (1983) and their estimates of the variation of log g and $T_{\rm eff}$ along the giant branches of clusters of these abundances.

In Figure 4 we have plotted the (M_v, $m_{\rm HK}$)-diagram (again using $V_0 - M_v = 13.5$ mag). The observed indices of the stars have all been reduced by 0.07 mag to obtain the best fit between observation and theory. We believe it to be plausible that such a shift exists since our spectra were obtained with a narrow slit, and the relative absolute stellar fluxes are affected by refraction losses. We also believe that a shift which is constant from star to star is not unreasonable since it could arise from problems of converting the spectra to an absolute flux scale. The accuracy demanded for this conversion is quite high. We note that the stars were observed at similar low air masses. It is also possible that systematic errors exist in the synthetic spectra. In this latter case, we might expect the errors to depend on $B-V$ and M_v. At present, we have no way of distinguishing between these two possibilities but regard the former as probably the most likely. However, the arbitrary nature of the shift means that Figure 4 does not give definite information on the absolute abundances of the cluster stars. We note that the mean theoretical cluster line does fit the observed colors fairly well at all M_v. This is interpreted as evidence that the cluster stars all have the same calcium abundance. The nonmember stars C2 and C6 lie well off the cluster line. (The strength of the H and K lines depends on more than the Ca abundance since other elements contribute lines to the smoother "background" spectrum; but, since we have no data on abundances of these other species, we refer to the abundance derived from H and K as the calcium abundance. Similar comments hold for other indices.) We also note that the cluster giant branch for [A/H] $= -1.0$ has a very different slope from that observed, arguing for an abundance of < -1.0.

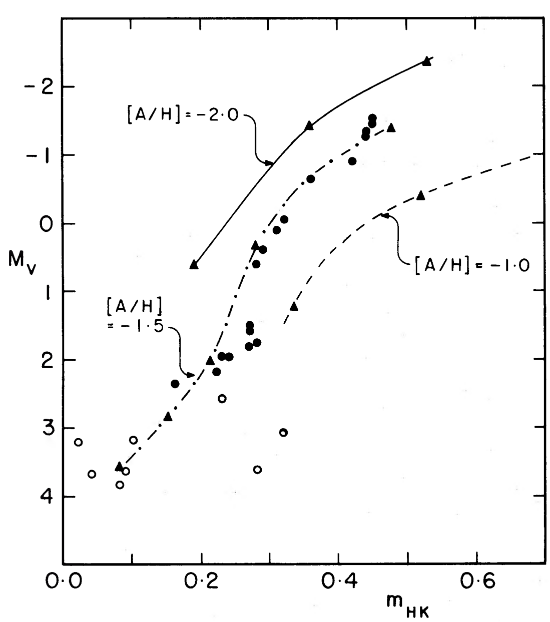

FIG. 4.—The M_v, $m_{\rm HK}$ of NGC 6752 stars (*dots*) are compared with the corresponding model values (*triangles*) for the subgiant and/or giant branches of clusters of metal abundance [A/H] $= -1.0$, -1.5, and -2.0. Following the discussion in the text, the observed $m_{\rm HK}$ values have all been reduced by 0.07 mag before plotting.

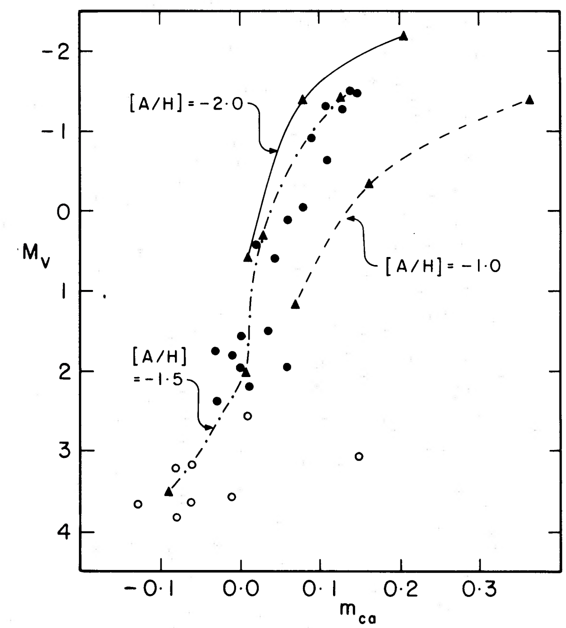

FIG. 5.—The (M_v, $m_{\rm Ca}$)-diagram for NGC 6752 stars and model subgiant and/or giant branches. Following the discussion in the text, the observed $m_{\rm Ca}$ values have been reduced by 0.07 mag before plotting.

The (M_v, $m_{\rm Ca}$)-diagram is given as Figure 5. A zero point shift of 0.07 mag again brings the observed indices onto the theoretical cluster line for [A/H] $= -1.5$. We believe it is coincidental that this shift is the same as for M_v, $m_{\rm HK}$. When this shift is applied, the theoretical cluster line fits the observations quite nicely at all M_v. While the necessity of applying the shift makes it impossible to obtain the cluster metal abundance directly, it is possible to obtain a weak estimate since the cluster line for [A/H] $= -1.0$ has a quite different slope to the lines for [A/H] $= -1.5$ and -2.0, and the latter two are in better accord with observation.

The (M_v, $m_{\rm Fe}$)-diagram is given as Figure 6. The index changes by only 0.1 mag for $2.0 > M_v > -1.5$, and the difference in $m_{\rm Fe}$ for $-1.0 \geq$ [A/H] ≥ -2.0 is typically less than 0.1 mag. This places a premium on accurate measurement. The observations fit the theoretical line for [A/H] $= -1.5$ quite well with no need for a zero point shift. The observed points at $M_v \sim 2.0$ are $\sim$0.015 mag bluer than theory, whereas they are about 0.015 mag redder at $M_v \sim 0.0$. Owing to the small size of these deviations, we do not regard them as significant.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1984ApJ...283..615B

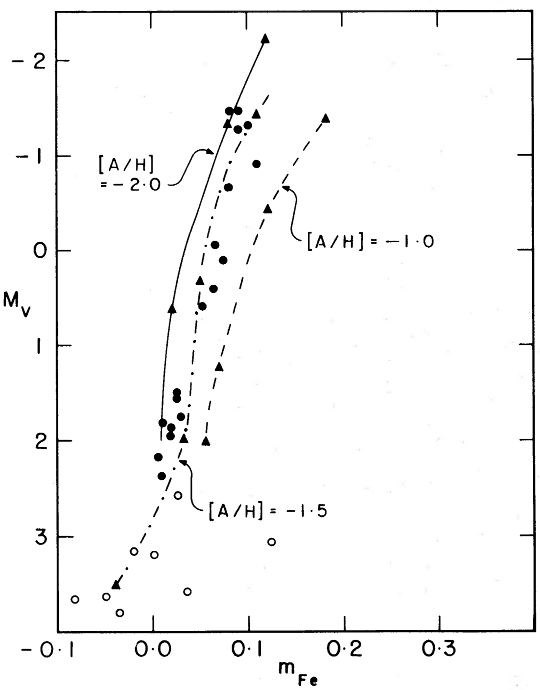

FIG. 6.—The (M_v, m_{Fe})-diagram for NGC 6752 stars and for model subgiant and/or giant branches.

The (M_v, m_G)-diagram is given as Figure 7. The mean theoretical cluster line is sketched in, as is the mean theoretical line for [C/A] = −0.3. In general, this diagram bears out the previous comments which were made concerning the appearance of the G band in the spectra. The star CS 107 has a larger m_G index than stars 118, 125, and 9. When the observed values of m_G are used without any zero point shift being applied, the stars, in general, lie between the cluster lines computed for [A/H] = −1.5 and [C/A] = 0.0 and [C/A] = −0.3. Some stars appear to have normal carbon (viz., CS 8 and CS 120), whereas others (e.g., CS 118, CS 125, CS 9, CS 137, and CS 130) have [C/A] ~ −0.5. There is a suggestion that the majority of the stars at $M_v \sim 2.0$ are carbon depleted, but we do not regard this as a firmly established result. There is considerable scatter in m_G for $M_v > 3.0$—we do not regard this as being caused by carbon abundance changes. In these objects, the Hγ line occurring in the comparison band pass is strong, and the index is sensitive to temperature changes.

The (M_v, m_{CN})-diagram is given as Figure 8. In view of the refraction explanation which is given to explain the shift in the (M_v, m_{HK})-diagram, it is not surprising that a similar, larger shift is necessary if the m_{CN} indices are to fit the theory. Accordingly, the observed m_{CN} indices in Table 4 have been reduced by 0.2 mag prior to plotting in Figure 8. A number of objects have measured indices placing them to the right of the cluster line for [A/H] = −1.5 (e.g., CS 119, CS 106, CS 105, and CS 137). If these objects have normal carbon, the observed displacements correspond to nitrogen abundance enhancements of a factor of about 3. If the carbon depletions implied for CS 137 by the (M_v, m_G)-diagram and by comparison of observed and synthetic spectra are real, even greater nitrogen enhancements are required.

We note, for completeness, that a comparison of observed and computed M_v index diagrams has also been made using the data of Canterna, Harris, and Ferrall (1982). Their data were obtained with a much wider slit than ours and, with the probable exception of m_G, which is being studied further, there appear to be no zero point shifts between theory and observation.

d) *The Oxygen Abundance*

It is well known that the formation of CO must be taken into account before carbon abundances can be deduced from the strength of CH lines in the spectra of cool stars. The discussion in the present paper has hitherto assumed that [O/A] = 0.0, an assumption which is now examined.

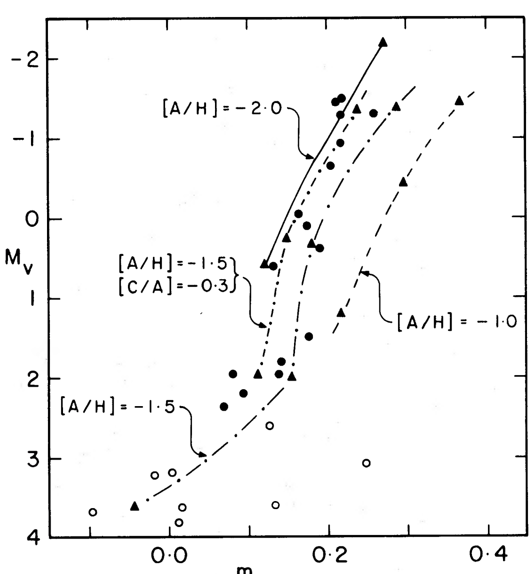

FIG. 7.—The (M_v, m_G)-diagram for NGC 6752 stars and for model subgiant and/or giant branches. The model line for a cluster with [A/H] = −1.5 and [C/A] = −0.3 is also shown.

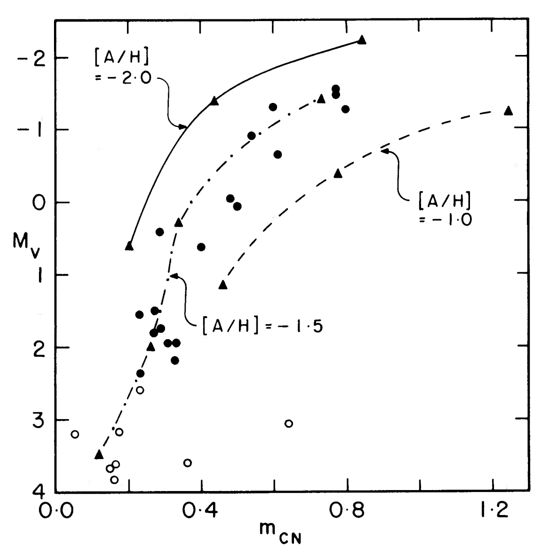

FIG. 8.—The (M_v, m_{CN})-diagram for NGC 6752 stars and for model subgiant and/or giant branches. The observed m_{CN} values have been reduced by 0.20 mag before plotting.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1984ApJ...283..615B

Estimates of oxygen abundances can be made from studies of [O I] lines, but the only datum available for NGC 6752 is a measurement for the λ6300 line in the star A31 (Pilachowski, Wallerstein, and Sneden 1983), and this star is much cooler than those considered here. Frogel, Persson, and Cohen (1983, hereafter FPC) have presented photometric observations of the 2 μm CO bands. An analysis of similar data for M3 and M13 has been given by Bell and Dickens (1980, hereafter BD). These earlier results can be used to examine the FPC data. While there are no stars in common between FPC and the present paper, there is an overlap in temperature as judged from $V-K$ color since Bell and Gustafsson (unpublished) find $V-K = 2.68$ for both 4500/1.5/−1 and 4500/1.8/−2.

The CO observations and calculations, from FPC and BD respectively, are presented in Figure 9. It is clear that, if the calculations are correct, both the oxygen and the carbon in the evolved NGC 6752 stars must be depleted. While it is difficult to assess errors in the calculations, BD found a difference of only 0.02 mag between observation and calculation for the field weak G-band star HD 165634. If we use this result as a guide to the precision that can be obtained, it appears that [O/A] = [C/A] = −0.5 gives a reasonable fit to the CO band strength while [O/A] = 0.0, [C/A] = −0.5 can probably be excluded. The former abundance pair gives an m_G index which is a little larger than that for the latter pair, and it is possible that [O/A] = −0.5, [C/A] = −0.7 is better. This latter change is quite tentative since the corresponding spectroscopic change is hard to detect from our data. It appears to be quite certain, however, that the CO data preclude any pronounced overabundance of oxygen in the evolved NGC 6752 stars, even though it is seen in field subdwarfs (Sneden, Lambert, and Whitaker 1979). We have no way of detecting such an overabundance in the fainter NGC 6752 stars. The CN fits use the C abundance obtained from the CH feature and not the actual C and O abundances; consequently, the N abundance derived from CN is not critically dependent on the C and O values used in the calculations.

V. SUMMARY

A number of points have emerged from our spectroscopic survey of NGC 6752 stars which has included the first spectra of main-sequence stars in a metal-poor globular cluster and the calculation of several new model spectra. In turn, these allow us to address the questions raised in the Introduction, and we have determined the following:

1. On the basis of the strengths of their spectral features, the relatively red stars C2 and C6 are probably field stars.
2. Comparison of a number of spectral features with the corresponding features calculated using synthetic spectrum techniques give an overall metal abundance which is consistent with the value of [M/H] ≈ −1.5 inferred from the earlier studies noted previously. With the exception of CN and CH band strengths, no evidence has emerged for intracluster metal abundance differences.
3. Throughout the entire giant branch of NGC 6752 we see a range in CN band strengths at any given magnitude. For the bright giants in common with Norris *et al.* (1981), our assessment of CN band strengths in the brighter giants is in excellent agreement. Several of the brighter giants may have nitrogen abundances enhanced by factors $\gtrsim 3$ depending on the exact amount of carbon depletion. Stars fainter than $M_v \sim 0.8$ had not been studied spectroscopically prior to this investigation. It is our impresssion that the average CN strength is higher in the more luminous stars than in the less luminous ones—in agreement with trends predicted by the model calculations for constant composition. If our inference from the small sample is correct, the behavior of CN as a function of M_v for NGC 6752 stars would seem to differ from that seen in the more metal-rich cluster 47 Tucanae. Our small sample size precludes commenting on the modality of the CN strength distribution among the fainter NGC 6752 stars. Among brighter giants, some stars seem to suffer carbon depletion ([C/A] ~ −1.5). Among fainter giants, near $M_v \sim 2.0$, there is a suggestion (requiring better S/N ratio spectra for confirmation) that the majority of our sample also suffers carbon depletion. The CO band observations preclude an overabundance of oxygen in the evolved stars. The depletion of carbon relative to other metals is not an artifact caused by a very high oxygen abundance.
4. The mean abundances of the cluster stars are independent of M_v within the uncertainties of both the observations and the models. This conclusion is based on comparison of our spectra with model calculations extending from the main sequence to the giant branch tip. This is the first time that model calculations of dwarf and giant stars observed in an identical manner in the same globular cluster have been compared. It would be interesting to repeat this experiment with higher signal-to-noise ratio (and well fluxed) data for enlarged samples of stars in several clusters of differing metal abundances (and CN strength distribution characteristics).
5. Temperatures inferred from colors and our spectra of the main-sequence turnoff stars suggest that most, if not all, of the spread in observed $B-V$ colors in the C-M diagram at that M_v is due to normal observational scatter and not to differences in metal abundances.

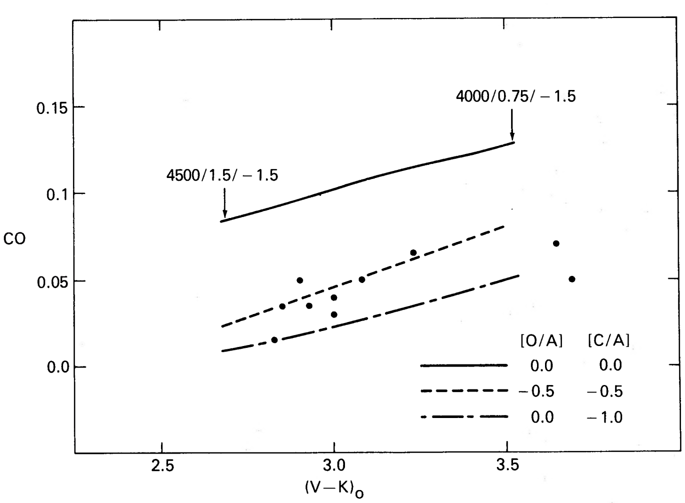

FIG. 9.—The CO indices of NGC 6752 stars are plotted versus $V-K$. They are compared with computed indices. The observations are from Frogel, Persson, and Cohen (1983), and the calculations are from Bell and Dickens (1980) and Bell and Gustafsson (unpublished).

We are grateful to the CTIO Director and Telescope Allocation Committee for the strong support of our work. B. Atwood, J. Baldwin, A. Gomez, G. Martin, M. Navarette, C. Poblete, O. Saá, S. Schaller, and R. Venegas all provided excellent support with the observations and reductions thereof in Chile. B. and R. Aguirre and B. and R. Gayoso extended warm hospitality

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1984ApJ...283..615B

during the reductions. The help of C. Pritchet, R. McClure, and S. Mochnacki with RETICENT was extremely important to our study. J. Ohlmacher helped us with the calculations, which were carried out using the facilities of the University of Maryland Computer Science Center. We are grateful to Drs. Cohen, Frogel, and Persson for sending us preprints.

REFERENCES

Alcaino, G., and Liller, W. 1980, *A.J.*, **85**, 680.
Atwood, B., Ingerson, T., Lasker, B. M., and Osmer, P. S. 1979, *Pub. A.S.P.*, **91**, 120.
Bell, R. A., and Dickens, R. J. 1980, *Ap. J.*, **242**, 657 (BD).
Bell, R. A., and Gustafsson, B. 1983, *M.N.R.A.S.*, **204**, 249.
Bell, R. A., Hesser, J. E., and Cannon, R. D. 1983, *Ap. J.*, **269**, 580.
Caloi, V., Castellani, V., Cannon, R. D., Danziger, I. J., and Hill, P. W. 1984, in preparation.
Cannon, R. D. 1974, *M.N.R.A.S.*, **167**, 551.
———. 1981*a*, in *IAU Colloquium 68, Astrophysical Parameters for Globular Clusters*, ed. A. G. D. Philip and D. S. Hayes (Schenectady: L. Davis Press), p. 501.
———. 1981*b*, *M.N.R.A.S.*, **195**, 1.
Cannon, R. D., and Stobie, R. S. 1973, *M.N.R.A.S.*, **162**, 227.
Canterna, R., Harris, W. E., and Ferrall, T. 1982, *Ap. J.*, **258**, 612.
Carney, B. W. 1979, *A.J.*, **84**, 515.
Cottrell, P. L., and DaCosta, G. S. 1981, *Ap. J. (Letters)*, **245**, L79.
DaCosta, G. S., and Cottrell, P. L. 1980, *Ap. J. (Letters)*, **236**, L83.
Frogel, J. A., Cohen, J. G., and Persson, S. E. 1983, *Ap. J.*, **275**, 773.
Frogel, J. A., Persson, S. E., and Cohen, J. G. 1983, *Ap. J. Suppl.*, **53**, 713 (FPC).
Gustafsson, B., Bell, R. A., Eriksson, K., and Nordlund, Å. 1975, *Astr. Ap.*, **42**, 407.
Harris, H. C., and Canterna, R. 1977, *A.J.*, **82**, 798.
Harris, W. E., Hesser, J. E., and Atwood, B. 1983, *Ap. J. (Letters)*, **268**, L111.
Hayes, D. S., and Latham, D. W. 1975, *Ap. J.*, **197**, 593.
Hesser, J. E. 1978, *Ap. J. (Letters)*, **223**, L117.
Hesser, J. E., and Bell, R. A. 1980, *Ap. J. (Letters)*, **238**, L149.
Hesser, J. E., and Harris, G. L. H. 1981, *Pub. A.S.P.*, **93**, 139.
Hesser, J. E., Harris, H. C., van den Bergh, S., and Harris, G. L. H. 1984, *Ap. J.*, **276**, 491.
Hesser, J. E., and Shawl, S. J. 1984, in preparation.
Kinman, T. D. 1959, *M.N.R.A.S.*, **119**, 538.
Mallia, E. A. 1977, *Astr. Ap.*, **60**, 195.
———. 1978, *Astr. Ap.*, **70**, 115.
Newell, E. B., and Sadler, E. 1978, *Ap. J.*, **221**, 825.
Norris, J., Cottrell, P. L., Freeman, K. C., and DaCosta, G. S. 1981, *Ap. J.*, **244**, 205.
Pilachowski, C. A., Sneden, C., and Wallerstein, G. 1983, *Ap. J. Suppl.*, **52**, 241.
Pritchet, C., Mochnacki, S., and Yang, S. 1981, *Pub. A.S.P.*, **94**, 733.
Richer, H., and Fahlman, G. 1984, *Ap. J.*, **277**, 227.
Sandage, A. 1982, *Ap. J.*, **252**, 553.
Schaller, S., Osmer, P. S., Albrecht, R., and Lasker, B. M. 1978, in *CTIO Facilities Manual* (2nd ed.), ed. J. E. Hesser (Tucson: AURA, Inc.), p. [9]. 2.205.
Searle, L., and Zinn, R. 1978, *Ap. J.*, **225**, 357.
Sneden, C., Lambert, D. L., and Whitaker, R. W. 1979, *Ap. J.*, **234**, 964.
Webbink, R. 1981, *Ap. J. Suppl.*, **45**, 259.
Zinn, R. J. 1980, *Ap. J.*, **241**, 602.

R. A. BELL: Division of Astronomical Sciences, National Science Foundation, Washington, D.C. 20550

R. D. CANNON: Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, U.K.

J. E. HESSER: Dominion Astrophysical Observatory, 5071 W. Saanich Road, Victoria, B.C. V8X 4M6, Canada

© American Astronomical Society • Provided by the NASA Astrophysics Data System