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# SPECTROSCOPIC ANALYSIS OF DWARF AND SUBGIANT STARS IN 47 TUCANAE

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## ABSTRACT

Spectra at ~ 4 Å resolution have been obtained with the SIT vidicon detector on the CTIO 4 m telescope's Ritchey-Chrétien spectrograph for 11 dwarfs ($B \sim 18.2$ mag) and five brighter stars ($B \sim 16$ mag) in NGC 104 (47 Tuc, C0021−723). A range of CN strengths is observed among subgiant and dwarf stars of otherwise very similar spectra. The spectroscopic results are combined with photometric data to argue that some, if not all, of the dwarfs have the same temperature. Spectrum synthesis calculations are then used to infer that the observed range of CN strengths could be produced by a star-to-star range of nitrogen abundances of ~ 5. This result is in accord with a previous analysis based upon much lower resolution data. The range inferred is similar to that required to explain observations of highly evolved stars in 47 Tuc.

*Subject headings:* clusters: globular — spectrophotometry — stars: abundances — stars: Population II

## I. INTRODUCTION

It is now quite clear that the evolved stars in the metal-rich globular cluster 47 Tucanae ( = NGC 104 = C0021−723) exhibit a range of CN band strengths. This conclusion is based on low-dispersion spectroscopy and DDO photometry carried out by Hesser, Hartwick, and McClure (1976, 1977), Hesser (1978), Mallia (1978), Dickens, Bell, and Gustafsson (1979, hereafter DBG) and Norris and Cottrell (1979, hereafter NC). Norris and Freeman (1979) have suggested that the distribution of CN strengths is, in fact, bimodal. Analyses of these observational data, with the aim of obtaining carbon and nitrogen abundances, have been carried out by DBG and by NC.

The observational data available for the fainter cluster stars are, first, DDO photometry for stars with $M_v < 2.5$ mag, and, second, low-dispersion spectroscopy for stars down to $M_v \sim +4.3$ mag. These spectroscopic data do suggest that CN strength variations occur in the subgiants and in stars which are only slightly evolved (Hesser 1978; Hesser and Bell 1980, hereafter HB). The cluster 47 Tuc is, of course, ideal for such studies inasmuch as it is populous, relatively nearby, nearly unreddened, and located at high galactic latitude. Furthermore, its main-sequence turnoff region stars are cool enough that CN bands are visible in their spectra.

The problem of the overall metal abundance has been addressed by DBG using photometry, and by Pilachowski, Canterna, and Wallerstein (1980), using spectroscopy. This abundance is not yet as well known as might be hoped. Recent work has shown that the cluster is probably more metal-poor than [M/H] = −0.5, the value used for many years. DBG obtained [M/H] = −0.8 from synthetic color analysis of *uvby* colors of red horizontal branch stars observed by Gustafsson and Ardeberg (1978). Pilachowski, Canterna, and Wallerstein (1980) found [Fe/H] = −1.2 from analysis of echelle spectra of two of the brighter giant stars. In view of the assumptions made in the different analyses, the differences may not be too surprising, but their existence causes uncertainty in the analysis of a number of problems. A similar problem holds for other metal-rich clusters such as M71, but the discrepancy between photometric and spectroscopic abundances is even greater in that cluster (Bell and Gustafsson 1982).

The spectroscopic data available to DBG were not of sufficient caliber for them to draw firm conclusions on the carbon abundances, except for the AGB stars where they concluded that [C/*A*] = −0.5. DDO photometry is very valuable for studies of carbon and cyanogen abun-

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dances, and DBG showed that, if the carbon abundance in the cluster stars was "normal," the *N* abundance in some stars was considerably enhanced, by more than a factor of 3 in some cases. Any reduction in the carbon abundance found for a particular object does, of course, lead to a higher *N* abundance being deduced. Unfortunately, DBG were unable to deduce carbon abundances of high precision from the photometry. The carbon abundances found for the AGB stars were deduced under the assumption that the oxygen abundance was "normal" since no data were available for the [O I] lines or the CO bands. The DBG photometric interpretation was checked by comparison of the values found for Arcturus with those found from high-dispersion spectroscopy.

A different result on the CN abundances was obtained in the NC analysis of the spectra of two AGB stars. Assuming an overall metal abundance of [M/H] $= -0.5$, NC found one star to have slightly enhanced carbon and a very low nitrogen abundance. This latter overdeficiency would be reduced if lower overall metal abundance had been used, but it is unclear whether their results might still be systematically different from the DBG values.

Using $\sim 16$ Å resolution spectra of seven stars and spectrum synthesis techniques, HB showed that some slightly evolved stars ($M_v \sim 4.3$ mag) in 47 Tuc were overabundant in N (assuming that carbon and oxygen were normal) by a factor comparable to that found by DBG for the giants, i.e., nitrogen overabundances of about a factor of 5. This result is rather surprising. It had been widely assumed that the cyanogen variations in the giant stars were the result of mixing of material from the center of the star to the surface, but invocation of that mechanism on the upper main sequence represents a radical departure from long-held (but not necessarily correct) beliefs. Although a number of other mechanisms can be postulated to explain the CN enhancement in the dwarfs (cf. Bell *et al.* 1981 and § IV), none of them are completely satisfactory. The hypothesis that the enhanced nitrogen abundances are primordial in nature seems to be supported by stellar evolution calculations showing that mixing is unable to produce such large N overabundances (Da Costa and Demarque 1982) as well as by the observation that the CN-strong stars with $M_v < -0.6$ mag possess sodium abundances which are about twice those of the CN-weak stars (Cottrell and Da Costa 1981; Da Costa 1981; Lloyd Evans, Smith, and Menzies 1982). There appears to be no evidence for a range in the overall metal abundance, nor in the abundances of other light elements such as magnesium, although it is possible that enhancements of the abundances of $^{25}$Mg and $^{26}$Mg would be masked by a dominant abundance of $^{24}$Mg (the terrestrial/solar isotopic abundance ratio is $^{24}$Mg:$^{25}$Mg:$^{26}$Mg 8:1:1; White and Cameron 1948).

Since instrumental developments at Cerro Tololo Inter-American Observatory have made it possible to obtain spectra with much higher resolution than those available to HB, we undertook a further program of observations of faint 47 Tuc stars. The objectives of this work were to see if (*a*) the new data confirmed the results of HB; (*b*) more extreme examples of CN strengths could be found by an extension of the HB survey; and (*c*) it were possible to obtain information on the abundance of carbon, using the G band, and of calcium, using the H and K lines. We also obtained spectra of the star HH 1–9038, a subgiant suspected of having very strong CN as judged from DDO photometry, and four other faint subgiants.

## II. OBSERVATIONS

Spectra with $\sim 4$ Å resolution were obtained using the SIT vidicon camera on the spectrograph at the Ritchey-Chrétien focus of the CTIO 4 m telescope during the nights of 1980 September 8–11 (UT), in a manner identical to that described by Hesser and Harris (1981). The instrumental configuration consisted of 300 $\mu$m (2''0) slit; KPNO Grating Lab grating number 1 (632 lines mm$^{-1}$) in the first order blue (angle 59.°20); and an RCA 4804 UV transmitting SIT vidicon (Atwood *et al.* 1979) with a 250 mm focal length, f/1.4 camera. With the exception of the first night, when most of the observations of the five brighter subgiant stars were secured, the seeing was better than 2''5 and the skies were clear for most of the observing time.

We wished to reexamine, at higher resolution, several of HB's stars to see if the deduced range in CN strengths was in whole or part due to noise in their lower resolution data. On our first night of good seeing we consequently reobserved stars 1–9004, 3–2153, and 3–2195 by taking two 45 minute exposures of each. "Quick look" facilities at the telescope indicated that these spectra, particularly in the crucial CN (0,0) band region near 3883 Å, did appear to be similar to HB's. We also wished to search for stars exhibiting more extreme CN differences than those of 1–9004 and 3–2153. For this survey aspect, carried out on the final two nights of the run, only a single spectrum, sometimes at larger hour angles and/or briefer exposure times, was obtained per star.

The total sample of stars observed, selected from Hesser and Hartwick's (1977) study of the color-magnitude (*C-M*) diagram, is listed in Table 1, together with relevant photometric data, the journal of spectroscopic observations, and the radial velocities derived from them. The locations of the stars in the cluster *C-M* diagram are given in Figure 1. In this paper, we will concentrate our analysis on the turnoff region stars for which two spectra were obtained.

TABLE 1

SUMMARY OF OBSERVATIONAL DATA FOR 47 TUCANAE STARS[a]

| Star | $V_{pg}$ (mag) | $(B-V)_{pg}$ (mag) | U.T. (Start)[b] (1980 Sep) (dd/hh:mm) | Hour Angle (Start) (hh:mm) | Exp. (min.) | $v_{r,\odot}$ (km s$^{-1}$) | $n$ |
|---|---|---|---|---|---|---|---|
| 1–9038 ... | 14.58 | 0.88 | 08/01:59 | 03:52 E | 10 | +30 | 9 |
| | | | 08/03:06 | 02:45 E | 10 | +46 | 9 |
| | | | 09/03:35 | 02:13 E | 3 | 26 | 9 |
| | | | 09/03:41 | 02:07 E | 6 | −1 | 9 |
| | | | 09/09:54 | 04:07 W | 5 | −2 | 9 |
| | | | 10/03:08 | 02:36 E | 5 | −25 | 12 |
| | | | 11/02:37 | 03:03 E | 5 | −26 | 11 |
| 1–9403 ... | 15.11 | 0.84 | 08/02:28 | 03:30 E | 30 | 12 | 9 |
| 1–9015 ... | 15.47 | 0.85 | 08/04:16 | 01:36 E | 30 | 61 :: | |
| 1–9055 ... | 15.53 | 0.85 | 08/08:44 | 02:48 W | 30 | −13 | 9 |
| | | | 08/09:17 | 03:22 W | 20 | 15 | 7 |
| 1–9047 ... | 15.54 | 0.81 | 08/08:03 | 02:11 W | 30 | 14 | 10 |
| 3–2153 ... | 17.46 | 0.60 | 09/05:40 | 00:12 E | 45 | | |
| | | | | | | −1 | 8 |
| | | | 09/06:31 | 00:39 W | 45 | | |
| 3–2234 ... | 17.48 | 0.62 | 09/09:09 | 03:18 W | 37 | 7 | 11 |
| 3–2262 ... | 17.48 | 0.59 | 10/08:12 | 02:25 W | 45 | −35 | 8 |
| 3–2455 ... | 17.50 | 0.64 | 11/07:32 | 01:50 W | 45 | −90 | 7 |
| 1–9004 ... | 17.42 | 0.62 | 09/07:25 | 01:36 W | 45 | | |
| | | | | | | −36 | 8 |
| | | | 09/08:17 | 02:38 W | 45 | | |
| 3–2384 ... | 17.51 | 0.61 | 11/02:54 | 02:49 E | 45 | −30 | 7 |
| 3–2397 ... | 17.52 | 0.64 | 11/03:50 | 01:54 E | 45 | −22 | 7 |
| 3–2183 ... | 17.53 | 0.59 | 10/03:21 | 02:27 E | 45 | −43 | 6 |
| 3–2467 ... | 17.53 | 0.58 | 11/09:07 | 03:24 W | 35 | 42 | 9 |
| 3–2278 ... | 17.55 | 0.63 | 10/09:05 | 03:18 W | 40 | +6 | 8 |
| 3–2195 ... | 17.58 | 0.57 | 09/03:56 | 01:56 E | 45 | | |
| | | | | | | −37 | 6 |
| | | | 09/04:48 | 01:03 E | 45 | | |

[a] ID numbers (in the form "figure number–ID number"), $V_{pg}$, $(B-V)_{pg}$ from Hesser and Hartwick 1977. For stars from Fig. 1, photoelectric values are also available as follows (top of table to bottom) in the order star, $V$, $B-V$: 1–9038, 14.61, 0.95; 1–9403, 15.11, 0.87; 1–9015, 15.47, 0.85; 1–9055, 15.53, 0.85; 1–9047, 15.54, 0.81; 1–9004, 17.42, 0.62.

[b] Observations on 1980 Sep 8 were taken under conditions of poor seeing and high humidity. In addition, data for star 1–9015 were affected by a temperature control problem (cf. Hesser and Harris 1981), which undoubtedly accounts for the high velocity.

## III. SPECTROSCOPIC ANALYSIS

### *a*) *Radial Velocities*

Radial velocities were derived for our stars following the methods described earlier (Hesser and Harris 1981). During the run, data were also secured for stars in NGC 6752 (C1906−600; declination −60°) and NGC 288 (C0050−268; declination −27°). Comparison of the mean cluster radial velocity from our observations of NGC 104 and NGC 6752 with Webbink's (1981) weighted averages from earlier velocity studies revealed an average systematic difference, $v_{\rm CT} - v_{\rm Webbink} = -38$ km s$^{-1}$; no such difference was apparent for NGC 288.[2] The zero-point difference has been applied to the values given in Table 1, although it is largely irrelevant for our purposes, because the radial velocity of 47 Tuc is small, −14 km s$^{-1}$ (Webbink 1981), so that low-precision (~25 km s$^{-1}$) velocities such as ours may only be used to remove a chance high-velocity field star from the sample. Inspection of the velocities in Table 1 provides no convincing evidence for nonmembership of any of

[2] We note for completeness that a similar difference of opposite sign was found during the 1980 June run (Hesser and Harris 1981) and that a third run in 1981 April produced a null zero-point error. While the origins of these zero-point differences is not completely understood, conversations with the CTIO staff, particularly Dr. B. Atwood, suggest that they may more likely be associated with changes in orientation of the SIT tube (due to its having been removed from the cold box between runs), rather than to possible effective wavelength errors, as suggested by Hesser and Harris 1981. Finally, we note, from inspection of the velocities for star 1–9038, that a change in velocity scale zero-point *may* have occurred during the 1980 September run, particularly after the first night. Largely because our data are insufficient in number to map the suspected problem (which might have largely originated in a brief temperature controller failure that occurred on the first night), we have not attempted to correct for it.

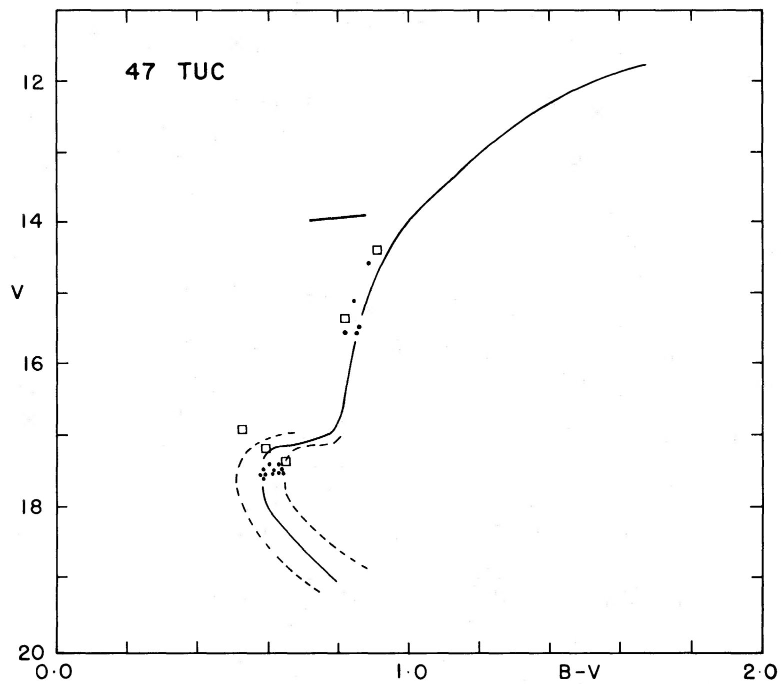


FIG. 1.—A schematic color-magnitude diagram for 47 Tuc. The total width of the main-sequence and turn-off region observed by Hesser and Hartwick 1977 is indicated by the dashed lines. The dots are the stars for which spectra were obtained (identifications are in Table 1) and the squares represent the colors and magnitudes of model atmospheres (given in Table 3).

the stars. Additional arguments for high membership probabilities come both from the general discussions of HB and the similarity of the spectra themselves.

### *b) The Observed Spectra*

An atlas of the spectra is given as Figure 2. The first four spectra are data obtained on each of the four nights of the observing run of star 1–9038, a strong CN star according to the DDO photometry of Hesser, Hartwick, and McClure (1977). Intercomparison of these spectra allows evaluation of the data quality. Spectra of other, somewhat fainter, subgiant stars (1–9403 through 1–9407) are followed in Figure 2 by the spectra of 11 upper–main-sequence stars ($M_v \sim 4.3$ mag) in order of decreasing $V$ magnitude.

Examination of the spectra of stars 3–2153 and 1–9004 shows a noticeable depression at $\lambda \sim 3883$ Å [the wavelength of the violet degraded CN (0,0) band head] in the former and not in the latter. (Other pairs demonstrating the same differences are seen in the sample; e.g., 3–2183 and 3–2234, 3–2195 and 3–2278.) This immediately confirms the lower resolution ($\sim 16$ Å) results of Hesser (1978) and HB that provided the first evidence for spectral (CN) differences among globular cluster dwarfs. The differences in the spectra of these two stars may be appreciated in Figure 3, which is a superposition of them. Another quite obvious difference in the spectra of Figure 2, namely the changes in average CH G band and CN band strengths between the dwarfs and faint giants, is due primarily to temperature and gravity differences.

### *c) The Temperature Spread on the Upper Main Sequence*

Before undertaking the comparison with the synthetic spectra (described in § III*e*), it is necessary to have an idea of the temperature to be used for each star. In the case of our data for 47 Tuc dwarfs, there are two aspects to this problem.

First, the available *C-M* diagram (Hartwick and Hesser 1974; Hesser and Hartwick 1977) shows the scatter in $B-V$ colors at the turnoff luminosity which is to be expected for the number of plates measured. For the brighter stars in the spectroscopically observed sample (cf. Table 1 and Figs. 1 and 2), one might argue that the individual photoelectric or photographic colors are sufficiently precise that they should be adopted for estimating the temperature when modeling the spectrum while, for the faint turnoff-region stars, an equally plausible argument might be advanced that the photometric errors are such that a mean color should be used to estimate the temperature. To initiate a study of the merits of these approaches, Hesser, Egles, and Liller (1982) have remeasured a sample of $\sim 100$ stars in

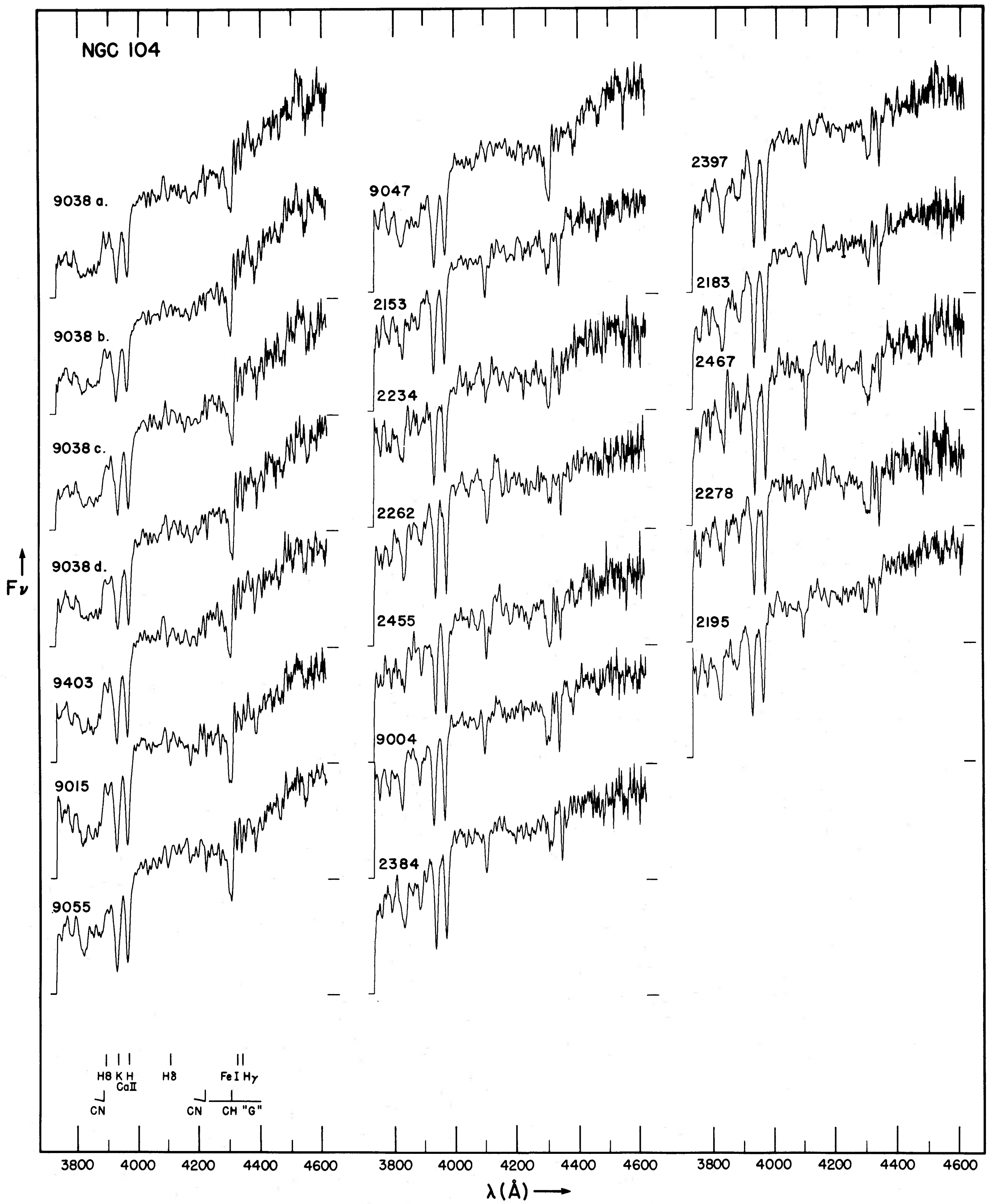


FIG. 2.—An atlas of the spectra obtained, arranged columnwise in order of increasing $V$ magnitude. The spectra for star 9038 were obtained on each of four nights. Further details of the stars are given in Table 1. Some spectral features are identified at the foot of the first column. The giants are in the first column and the top of the second.

1983ApJ...269..580B



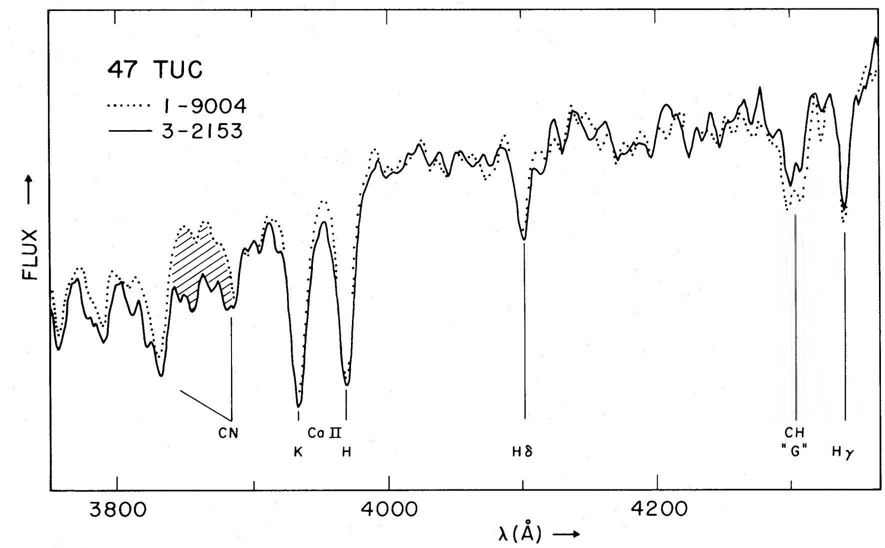


FIG. 3.—A comparison of the spectra of 1–9004 and 3–2153, showing their pronounced difference in the region of 3883 Å CN

Hesser and Hartwick's (1977) *C-M* diagram. These stars lie within 0.2 mag of the $V$ magnitude of the stars in Table 1. The three $V$ and two $B$ direct plates used in the Hesser and Hartwick *C-M* diagram, as well as two more $B$ direct plates taken as part of their original 1.5 m telescope observing program, were scanned with the DAO PDS microdensitometer and reduced with a slightly modified version of the Stetson (1979) program. The results are given for the turnoff-region stars of our spectroscopic sample in Table 2, where it can be seen that the dispersion in $B-V$ colors has been slightly reduced. In the larger sample of stars, though, the dispersion has been halved for stars with $0.40 \leq B-V \leq 0.70$ mag; however, the stars of Tables 1 and 2 were selected to have nearly the same colors and magnitudes and, therefore, do not represent some of the more extreme cases included in the larger sample. (It should also be noted that the small differences of $\langle B-V \rangle$ in the data of Table 2 probably represent minor differences in the handling of the color equations.) While these results do not eliminate the possibility of an intrinsic temperature spread among stars of our spectroscopic sample, they do suggest it is small ($0.56 \leqslant B-V \leq 0.62$ mag implies 5800 K $> T_{\mathrm{eff}} >$ 5500 K) and also suggest that much of the scatter in the original low mass sequence of the Hesser and Hartwick color-magnitude diagram is due to observational errors. (For instance, some stars have moved in the two sets of photographic photometry measurements by an amount equal to the total width of the sample.) To improve constraints on the existence of range of temperatures among the upper–main-sequence stars requires an extensive effort involving plate material which is more extensive and homogeneous than presently available. In a separate investigation, Harris, Hesser, and Atwood (1983) report a new determination of the 47 Tuc CMD to $M_v \sim +9$ with the same SIT vidicon used here operated in its direct imaging mode. They find (1) excellent agreement with the CMD turnoff determined by Cannon or Hesser and Hartwick; and (2) a more precisely defined main-sequence locus. The actual scatter in $B-V$ along the main sequence between $17 < V < 20$ is consistent with the observational errors. The rms dispersion in the observed CMD about a mean line drawn through the upper main sequence is $\sigma\ (B-V) = 0.042$ mag. They conclude that the *intrinsic* star-to-star differences are probably $\leq \pm 0.02$ mag.

A second aspect of the problem relies on the observed spectra: are temperature differences discernible from

TABLE 2

PHOTOGRAPHIC MAGNITUDES FOR THE TURNOFF REGION STARS

| | HH 77 | | HEL 82 | |
|---|---|---|---|---|
| STAR | $V_{\mathrm{pg}}$ | $(B-V)_{\mathrm{pg}}$ | $V_{\mathrm{pg}}$ | $(B-V)_{\mathrm{pg}}$ |
| 3–2153 .... | 17.46 | 0.60 | 17.46 | 0.58 |
| 3–2234 .... | 17.48 | 0.62 | 17.49 | 0.61 |
| 3–2262 .... | 17.48 | 0.59 | 17.47 | 0.59 |
| 3–2455 .... | 17.50 | 0.64 | 17.57 | 0.59 |
| 1–9004 .... | 17.42 | 0.62 | 17.43 | 0.56 |
| 3–2384 .... | 17.51 | 0.61 | 17.52 | 0.59 |
| 3–2397 .... | 17.52 | 0.64 | 17.55 | 0.62 |
| 3–2183 .... | 17.53 | 0.59 | 17.53 | 0.61 |
| 3–2467 .... | 17.53 | 0.58 | 17.59 | 0.59 |
| 3–2278 .... | 17.55 | 0.63 | 17.55 | 0.60 |
| 3–2195 .... | 17.58 | 0.57 | 17.60 | 0.58 |
| Std. dev. ... | ...... | $0.02_4$ ...... | ...... | $0.01_7$ |

line strengths in them? We independently classified the spectra, primarily on the basis of hydrogen line strengths, and found that a consistent ranking is possible. This ranking may be indicative of a finite temperature range on the upper main sequence. In the subsequent discussions we will comment on specific choices for the temperatures of individual stars as they arise from comparison with the synthetic spectra. We emphasize, however, that one of our principal conclusions, namely the existence of evidence for a range of CN strengths on the upper main sequence, is, in part, based upon such stars as 3–2153 and 1–9004 that we each ranked as having the strongest hydrogen lines of the stars in our sample (and for which the $B-V$ values of Table 2 differ by only 0.02 mag). The similarity of their hydrogen lines can be ascertained in Figure 3. The possible existence of a small temperature spread among the sample as a whole apparently does not solve the problems raised by the observation of a range of CN strengths (e.g., HB and below).

### *d*) *Synthetic Spectra Calculations*

The general methods used to analyze the spectra have been described elsewhere (Bell and Gustafsson 1978, hereafter BG; DBG; and HB). The procedure begins with the derivation of effective temperatures and gravities for the stars. We initially adopt a metal abundance of $[M/\mathrm{H}]=-0.8$ and assume, by default, that the abundances of all elements vary in unison.

We computed a series of flux constant model stellar atmospheres for ($T_{\mathrm{eff}}/\log g/[A/\mathrm{H}]$) 6000/4.0/−0.8, 5500/4.0/−0.8, 5500/3.0/−0.8, 5000/3.0/−0.8, and 4750/2.5/−0.8. Since no opacity distribution function (ODF) was available for $[A/\mathrm{H}]=-0.8$, we used the ODF for $[A/\mathrm{H}]=-0.5$ and used $[A/\mathrm{H}]=-0.8$ elsewhere in the model calculations. The model 5750/4.0/−0.8 was available from HB. Using masses of 0.8 $m_{\odot}$, the gravities of the models were converted to radii and the $M_{\mathrm{bol}}$ of the models were then calculated. The bolometric corrections of BG were then used to derive the $M_v$ of the models.

The $B-V$ color of the model 5750/4.0/−0.8 has been computed to be 0.58 mag, using the methods and programs of Gustafsson and Bell (1979). The $B-V$ colors of 6000/4.0/−0.8, 5500/4.0/−0.8, 5000/3.0/−0.8, and 4750/2.5/−0.8 are estimated in the same way and are given in Table 3. The resulting CM diagram of the models is also given in Figure 1.

Some caution must be used in applying these colors. The Bell and Gustafsson (1978) computations give a color of $B-V=0.62$ mag for the Sun. This value may well be too blue by 0.05 mag (cf. Tüg and Schmidt-Kaler 1982, for example). The Gustafsson and Bell solar model is too bright in the ultraviolet and too faint in the red, as compared to the Sun. The models of the 47 Tuc dwarfs may well be a better representation of these stars than the solar model is of the Sun, owing to the much lower metal abundance of 47 Tuc. For these reasons, as well as the problem of finding precise colors of 47 Tuc dwarfs, we have placed more emphasis on using the hydrogen lines as a temperature discriminant when analyzing the dwarf spectra than we have on using the photometry. We believe these profiles should be satisfactory for this purpose as solar model hydrogen line profiles give a good fit. In the giant models, however, the hydrogen lines are too weak when compared with the stars.

Synthetic spectra were then computed for the models. The wavelength interval covered depended on the chemical composition used: the "standard" models covered the wavelength interval 3750–4650 Å; models with depleted carbon ($[\mathrm{C}/A]=-0.3$) covered 3750–4400 Å. These spectra were computed using a wavelength resolution of 0.1 Å and a Doppler broadening velocity (DBV) of 2 km s$^{-1}$. Note that a higher DBV is allowed for the light molecule CH.

These synthetic spectra are plotted in Figure 4. The effect of carbon depletion and nitrogen enhancement are shown. The changes in the appearance of the $\log g=4.0$ spectra with changes in $T_{\mathrm{eff}}$ are as expected. The hydrogen lines, which are among the strongest features at 6000 K, weaken with decreasing $T_{\mathrm{eff}}$ and are less conspicuous at 5500 K. The CN features and the G band increase in strength with decreasing $T_{\mathrm{eff}}$. The CN is weak in the 6000 K models, even with enhanced nitrogen, while the G band is very inconspicuous at this $T_{\mathrm{eff}}$ when the carbon abundance is reduced. These temperature effects are even more enhanced in the cooler, lower gravity models.

### *e*) *Comments on the Comparison of Synthetic and Observed Spectra*

We have discussed the problems of ascertaining the correct temperatures for use in the model calculations in § III*c*, above. Consequently, in the following comments on the spectra, we first compare the observed spectra of the dwarfs with those from models calculated with $T_{\mathrm{eff}}=5750$ K. If the hydrogen lines then suggest that a different temperature might be more appropriate, we indicate that value and its effects on the comparison.

TABLE 3

Colors and Absolute Magnitudes of Selected Models

| Model $T_{\mathrm{eff}}/\log g/[A/\mathrm{H}]$ | $(B-V)$ | $M_v$ |
|---|---|---|
| 6000/4.0/−0.8 | 0.49 | 3.7 |
| 5750/4.0/−0.8 | 0.55 | 4.0 |
| 5500/4.0/−0.8 | 0.62 | 4.3 |
| 5000/3.0/−0.8 | 0.78 | 2.2 |
| 4750/2.5/−0.8 | 0.87 | 1.3 |

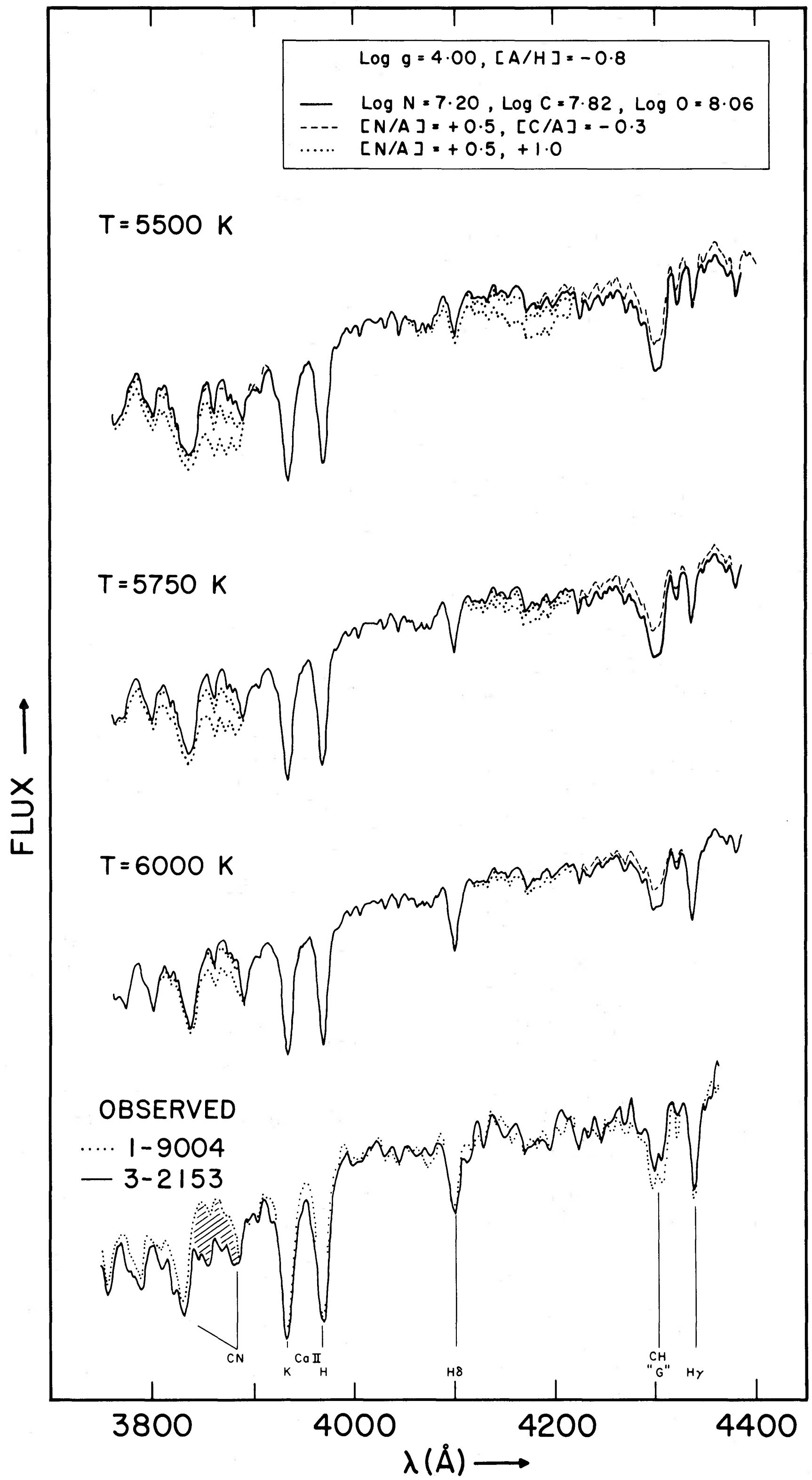


FIG. 4.—The spectra of the models 5500/4.0/−0.8, 5750/4.0/−0.8, and 6000/4.0/−0.8 are shown. The calculations have been carried out for a number of carbon and nitrogen abundances. Spectra of 1–9004 and 3–2153 are also shown. The spectroscopic differences at 3883 Å resulting from enhancing the nitrogen abundance to [N/A] = +1.0 in the model 5750/4.0/−0.8 closely resemble the differences between the two stars.

Comments on the strengths of the G band and CN bands are also given. The models 6000/4.0/−0.8 and 5750/4.0/−0.8 are subsequently referred to as the 6000 K model and the 5750 K model, respectively, and the same nomenclature holds for the 5000/3.0/−0.8 model and the 4750/2.5/−0.8 model.

We begin with the three stars for which exposures totaling 90 minutes apiece were obtained, and then comment succinctly upon the survey spectra of the other eight stars. We proceed in order of increasing luminosity.

*Star 3−2195.*—The spectrum of the 5750 K model is fairly similar to the observed one except that the calculated G band is stronger than the observed one. If carbon depletion is ruled out, the stellar spectrum would be better matched by the 6000 K model. In that case the observed CN 3883 Å strength is then greater in the star than in the model; if $T_{\mathrm{eff}} = 5750$ K the CN strength is probably not unusual.

*Star 1−9004.*—The 5750 K model has a stronger G band and weaker hydrogen lines than the observed spectrum, so that the 6000 K model is a better match. In particular, the comparison of observed and synthetic spectra in the 3800–3900 Å region is very good and there is no evidence for enhanced nitrogen. The G band in the 6000 K model may be slightly weaker than the observed one. The spectra of this star and 3-2153 are compared with the models in Figure 4.

*Star 3−2153.*—As for star 1−9004 (cf. Fig. 3), the observed hydrogen lines are stronger and the G band weaker than those of the 5750 K model. The observed CN 3883 Å strength is, however, already stronger in this star than in the 5750 K model. Thus adoption of the same 6000 K model that best fits the spectrum of the similar star 1−9004 implies that an even greater nitrogen abundance (possibly greater than a factor of 10) is necessary to reproduce the CN enhancement observed in 3−2153.

Among the remaining dwarfs, for which only the shorter exposure survey spectra exist, we find that stars 3−2278, 3−2467, 3−2455, 3−2262, and 3−2234 appear, in general, to be fitted better by the 5750 K model, while stars 3−2183, 3−2397, and 3−2384 are fitted better by the 6000 K model. However, as noted in the previous discussion of photometric errors (cf. § III*c*), the errors in $B - V$ correspond to this temperature range, and we believe that the observational uncertainties are such that these survey spectra of rather faint stars are probably consistent with the assumption of a single temperature. (Indeed, there is no correlation between the temperatures assigned above on spectroscopic criteria and either set of $B - V$ colors in Table 2. If a true temperature spread of ~250 K did exist, a $B - V$ color spread of 0.06 mag would be expected.)

As noted previously (cf. Fig. 3), the spectra of 3−2153 and 1−9004 differ significantly in the region of the 3883 (0,0) band of CN. The colors and apparent magnitudes of these stars are nearly identical, with Hesser, Egles, and Liller (1982) finding $V_0 = 17.34$, $(B - V)_0 = 0.54$ for 3−2153 and $V_0 = 17.31$, $(B - V)_0 = 0.52$ for 1−9004 (adopting $A_V = 0.12$ and $E(B - V) = 0.04$ mag.). Spectra of the model 5750/4.0/−0.8, which has $B - V = 0.58$ mag., are shown in Figure 4. The spectra have been computed with two different carbon abundances and three different nitrogen abundances. It is apparent that the differences between 3−2153 and 1−9004 shortward of 3883 Å are just those arising from differences in CN strength. The nitrogen enhancement required to produce the CN strength observed in 3−2153 in this cooler model is about a factor of 5; and, were the better matching 6000 K model used, an enhancement of over a factor of 10 would be required. The small difference which would be expected shortward of 4215 Å is presumably hidden by noise in the spectra. The G band in 3−2153 appears to be weaker than in 1−9004. This may be indicative of a carbon abundance difference of about a factor of 2. If the carbon is depleted by this amount, then a nitrogen enhancement of well over a factor of 5 is required to fit the CN. As noted earlier, the present evidence on stellar colors does not support the hypothesis of a temperature range. However, it is noticeable from Figure 4 that the predicted strength of the G band is very temperature sensitive in such stars, so that the observed spectra might be interpreted as implying that 3−2153 is hotter than 1−9004. If, contrary to the color and spectral evidence cited, 3−2153 is hotter than 1−9004, then the difference in CN abundance is even greater, which, in view of the problems already raised by these observations (cf. HB; Da Costa and Demarque 1982), seems unlikely.

We note (from Fig. 2) that several stars other than 3−2153 and 3−2195 appear to show the 3883 Å CN band (e.g., 3−2183, 3−2397, and 3−2384). The combination of these results with the spectra of three additional upper−main-sequence stars observed by HB at low resolution with the SIT vidicon and with the spectra of three stars observed earlier (J.E. Hesser 1976, unpublished) with the photographic image tube[3] leads us to believe that the existence of a range of CN strengths among the seventeen 47 Tuc dwarfs observed spectroscopically is well established.

One of our aims in this investigation was to see whether our 4 Å resolution spectra could give any information on the calcium abundance in the 47 Tuc stars. In order to do this, we studied the profiles of Ca II

[3]Stars 3−2019, 3−2026, and 3−2065 were observed on 1976 October 27 with the CTIO 4 m telescope and Ritchey-Chrétien spectrograph configured with a 120 μm slit, a sky suppressor, grating 250 (158 l mm$^{-1}$ yielding 188 Å mm$^{-1}$ in the first order blue), the Singer camera, and an RCA 33033 image tube. According to these spectra, the stars are listed in order of increasing CN (0,0) band strength.

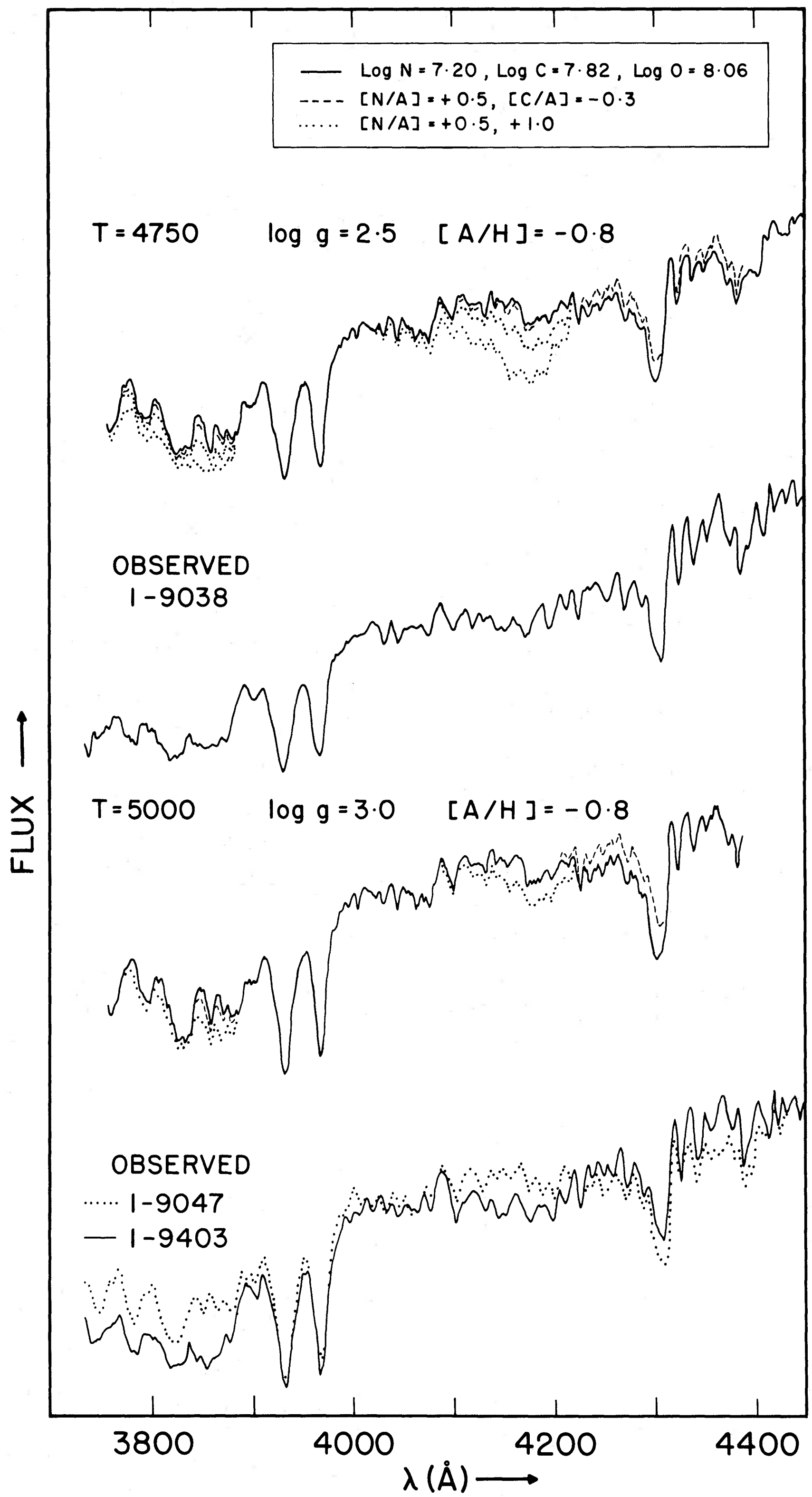


FIG. 5.—The spectra of the models 4750/2.5/−0.8 and 5000/3.0/−0.8 are shown. The calculations have been carried out for a number of carbon and nitrogen abundances. Spectra of 1–9038, 1–9047, and 1–9403 are also shown. The difference in CN strength in the latter two objects is apparent.

H and K—λ4226 of Ca I is visible in the observed spectra but seemed less suitable for abundance work. The spectra of 1–9004, 3–2153, and 3–2195 were compared with synthetic spectra computed using the model 5750/4.0/−0.8 and [Ca/H] = −0.3, −0.8, and −1.3. There is no evidence that [Ca/H] departs from −0.8 in the stars. The H and K lines in the synthetic spectra with [Ca/H] = −1.3 are markedly weaker than the observed ones. We estimate that the accuracy of this comparison is about a factor of 2; i.e., [Ca/H] = −0.8 ± 0.3 for these stars.

The remaining stars are two magnitudes or more brighter. Four of them, 1–9047, 1–9055, 1–9015, and 1–9403, have nearly the same $B-V$ color and 1–9403 is 0.3 mag more luminous than the other three. The model 5000/3.0/−0.8 is used as the comparison and is illustrated in Figure 5.

Both 1–9055 and 1–9047 have spectra which are very similar to that of the model 5000/3.0/−0.8, there being no strong evidence for either a weak G band or strong CN. The G band of 1–9015 is a good fit to the model, whereas the 3883 Å CN appears to be much stronger in the star, and there is certainly an impression that the 4215 Å CN is enhanced. The G band of 1–9403 is weaker than that of the 5000 K model, while the 3883 Å CN is strong and the 4215 Å CN may also be enhanced. We estimate that the nitrogen overabundance of the latter two stars is about a factor of three. These stars are about two magnitudes fainter than the giants analyzed by DBG and Da Costa (1981).

The case of star 1–9038 is puzzling. This object was observed mainly because the DDO photometry of Hesser, Hartwick, and McClure (1977) implied it had very strong CN. DBG concluded, from their synthetic color analysis, that the nitrogen abundance in this object must be enhanced by a factor of 3 or more. Comparison of the model 4750/2.5/−0.8 with the observed spectrum (cf. Fig. 5) shows a reasonable fit with a slight N (~0.5) enhancement. The photometry may be misleading, as it is based on only one observation.

A summary of the results obtained for all the stars is given in Table 4. On the basis of the above discussion of the photometry and of the appearance of the hydrogen lines in the spectra, we have adopted a temperature of 5875 K for all the faint stars in the sample. The temperatures of the more luminous stars are derived from the photometry alone. The values given in Table 4 are generally those found by comparison of observed and computed spectra. However, we have also made some use of indices derived from the spectra in a manner similar to, for example, the work of Canterna, Harris, and Ferrall (1981). The abundances of all metals other than C and N are taken to have the value of [M/H] = −0.8, this value being based on comparison of observed and computed H and K line profiles discussed above and on the results of other papers discussed earlier.

TABLE 4

TEMPERATURES AND ABUNDANCES OF CLUSTER STARS

| Star | $T_{\mathrm{eff}}$ | [C/H] | [N/H] |
|---|---|---|---|
| 1–9038 .... | 4750 | 0.0 | +0.5 |
| 1–9403 .... | 4800 | 0.0 | +0.5 |
| 1–9015 .... | 4800 | 0.0 | +0.5 |
| 1–9055 .... | 4800 | 0.0 | 0.0 |
| 1–9047 .... | 4900 | 0.0 | 0.0 |
| 3–2153 .... | 5875 | 0.0 | > 0.5 |
| 3–2234 .... | 5875 | 0.0 | 0.0 |
| 3–2262 .... | 5875 | −0.2 | 0.0 |
| 3–2455 .... | 5875 | 0.0 | 0.0 |
| 1–9004 .... | 5875 | 0.0 | 0.0 |
| 3–2384 .... | 5875 | 0.0 | 0.0 |
| 3–2397 .... | 5875 | 0.0 | +0.5 |
| 3–2183 .... | 5875 | −0.2 | +0.5 |
| 3–2467 .... | 5875 | 0.0 | 0.0 |
| 3–2278 .... | 5875 | −0.2 | 0.0 |
| 3–2195 .... | 5875 | 0.0 | +0.5 |

## IV. CONCLUSIONS

SIT vidicon spectra at ~4 Å resolution have been obtained for 11 dwarf stars in 47 Tuc, as well as for five brighter subgiants, in a continuing survey of the behavior of CN (and other strong) features among turnoff region stars. Spectra for the three dwarfs with the most observational data show a range of CN strengths similar to that observed earlier by HB using lower resolution data. All told, seventeen 47 Tuc dwarfs have now been observed spectroscopically in our programs. While many of the data for these faint stars are noisy, the existence of a range of CN strengths seems to be established. At the same time, there seems to be no compelling observational evidence for a range of temperature among these stars, thereby suggesting that these CN differences arise from abundance differences star to star. However, and entirely independent of arguments for or against a range of temperature throughout the sample, our best signal-to-noise-ratio, higher resolution data include a pair of stars for which the spectra are very similar except for differences in CN and, possibly, CH. Analysis of these spectra by synthetic spectrum techniques is consistent with HB's earlier conclusion, namely that nitrogen abundances appear to differ by factors of ~5 among the dwarfs in this cluster. The calcium abundances of these stars are equal within the errors; i.e., [Ca/H] = −0.8 ± 0.3. The subgiant stars also show a range in CN band strength, corresponding to nitrogen abundance variations of about a factor of three. The nitrogen differences in the dwarfs are comparable to those required to explain observations of highly evolved stars in the same cluster. It would be advantageous to repeat this experiment with stars around $V \sim 18.5$–19.0 mag in order to sample stars even nearer to the unevolved main sequence. One compensating advantage of studying such faint stars ($B \sim 19.5$ mag) would be that CN would be somewhat stronger and changes in CN strength might be easier to detect in these cooler stars. Precise independent determinations of the temperature spread among upper–main-sequence stars in 47 Tuc would also clarify further the interpretation of the available spectra.

Some consequences of the nitrogen abundance result in dwarf stars have been discussed by HB, Bell *et al.* (1981), Da Costa and Demarque (1982), Hesser (1982), and Smith and Norris (1982). Four possible ways in which a high nitrogen abundance can arise in stars are differences in abundance at the time of star formation (the primordial hypothesis), mixing of stars during their evolution, accretion of material lost by other cluster stars, and accretion of material lost by a binary companion. Recent observations (Cottrell and Da Costa 1981; Da Costa 1981) of 47 Tuc giants show correlations between CN and sodium strengths and lend credence to the probable occurrence of the first mechanism in globular clusters (but not necessarily to the exclusion of other mechanisms). A more detailed discussion of all of these mechanisms is given in Bell *et al.* (1981). None is entirely satisfactory in explaining nitrogen overabundances in dwarfs.

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REFERENCES

Atwood, B., Ingerson, T., Lasker, B. M., and Osmer, P. S. 1979, *Pub. A.S.P.*, **91**, 120.
Bell, R. A., and Gustafsson, B. 1978, *Astr. Ap. Suppl.*, **34**, 229 (BG).
______. 1982, *Ap. J.*, **255**, 122.
Bell, R. A., Harris, G. L. H., Hesser, J. E., and Cannon, R. D. 1981, *Ap. J.*, **249**, 637.
Canterna, R., Harris, W. E., and Ferrall, T. 1982, *Ap. J.*, **258**, 612.
Cottrell, P. L., and Da Costa, G. S. 1981, *Ap. J. (Letters)*, **245**, L79.
Da Costa, G. S. 1981, in *IAU Colloquium 68, Astrophysical Parameters for Globular Clusters*, ed. A. G. Davis Philip and D. S. Hayes (Schenectady: Davis Press), p. 75.
Da Costa, G. S., and Demarque, P. 1982, *Ap. J.*, **259**, 193.
Dickens, R. J., Bell, R. A. and Gustafsson, B. 1979, *Ap. J.*, **232**, 428 (DBG).
Gustafsson, B., and Ardeberg, A. 1978, in *Astronomical Papers Dedicated to Bengt Strömgren*, ed. A. Reiz and T. Andersen (Copenhagen: Copenhagen University Observatory), p. 145.
Gustafsson, B., and Bell, R. A. 1979, *Astr. Ap.*, **74**, 313.
Harris, W. E., Hesser, J. E., and Atwood, B. 1983, *Ap. J. Letters*, submitted.
Hartwick, F. D. A., and Hesser, J. E. 1974, *Ap. J. (Letters)*, **194**, L129.
Hesser, J. E. 1978, *Ap. J. (Letters)*, **223**, L117.
______. 1982, *J.R.A.S. Canada*, **76**, 69.
Hesser, J. E., and Bell, R. A. 1980, *Ap. J. (Letters)*, **238**, L149 (HB).
Hesser, J. E., Egles, D., and Liller, M. F. 1982, in preparation.
Hesser, J. E., and Harris, G. L. H. 1981, *Pub. A.S.P.*, **93**, 139.
Hesser, J. E., and Hartwick, F. D. A. 1977, *Ap. J. Suppl.*, **33**, 361.
Hesser, J. E., Hartwick, F. D. A. and McClure, R. D. 1976, *Ap. J. (Letters)*, **207**, L113.
______. 1977, *Ap. J. Suppl.*, **33**, 471.
Lloyd Evans, T., Smith, G. H., and Menzies, J. W. 1982, preprint.
Mallia, E. A. 1978, *Astr. Ap.*, **70**, 115.
Norris, J. E., and Cottrell, P. L. 1979, *Ap. J. (Letters)*, **229**, L69 (NC).
Norris, J. E., and Freeman, K. C. 1979, *Ap. J. (Letters)*, **230**, L179.
Pilachowski, C. A., Canterna, R., and Wallerstein, G. 1980, *Ap. J. (Letters)*, **235**, L21.
Smith, G. H., and Norris, J. 1982, *Ap. J.*, **254**, 549.
Stetson, P. B. 1979, *A.J.*, **84**, 1056.
Tüg, H., and Schmidt-Kaler, T. 1982, *Astr. Ap.*, **105**, 400.
Webbink, R. 1981, *Ap. J. Suppl.*, **45**, 259.
White, F. A., and Cameron, A. E. 1948, *Phys. Rev.*, **74**, 991.

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