PART V

HR DIAGRAMS, HORIZONTAL BRANCH

https://doi.org/10.1017/S0074180900145541 Published online by Cambridge University Press

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https://doi.org/10.1017/S0074180900145541 Published online by Cambridge University Press

HORIZONTAL-BRANCH STARS IN THE LOG T_{eff}, LOG G DIAGRAM

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ABSTRACT

A review of the available Strömgren four-color data concerning horizontal-branch (HB) stars is presented. Several observers have studied seven globular clusters (with [Fe/H] values from -2.2 to -1.3) and more than 100 HB stars in fields at high galactic latitudes over the last ten years at Kitt Peak, Cerro Tololo, Mt. Wilson and Steward Observatories. The predictions of model atmospheres (Kurucz, 1976) allow one to calculate atmospheric parameters such as θ_{eff}, log g, and M_V (Philip, Miller and Relyea, 1976). These parameters then can be compared with the predictions of evolutionary models (Sweigart and Gross, 1976).

A comparison of the observed data with evolutionary tracks indicates that within the rms error of observation and the computational error of the models the data and the tracks agree quite well. This matches the case for Population I stars, where a similar analysis shows a good match between observational data and evolutionary tracks (Philip, et al. 1977).

1. INTRODUCTION

Humason and Zwicky (1947) were pioneers in the study of faint blue stars at high galactic latitudes. In the years since many additional surveys have been made, some of them colorimetric,

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A. G. Davis Philip and D. S. Hayes (eds.), The HR Diagram, 209-220 and 406.

https://doi.org/10.1017/S0074180900145541 Published online by Cambridge University Press

others spectroscopic. Some of the colorimetric surveys are those made by Luyten (A Search for Faint Blue Stars) in a long series of papers, Iriarte and Chavira (1957), Chavira (1958), Iriarte (1959) (The last three papers define the Tonantzintla stars.), Feige (1959), and Haro and Luyten (1962) (The PHL Stars.). Some of the spectroscopic surveys of early-type stars are those made by Slettebak, Bahner and Stock (1961) at the North Galactic Pole; Philip and Sanduleak (1968), Sanduleak and Philip (1968), and Slettebak and Brundage (1971) at the South Galactic Pole. Some spectrographic surveys of stars of all spectral types in various regions have been made by Upgren (1962) at the NGP and Philip (1966, 1968), Philip and Drilling (1970), Drilling and Philip (1970), and Philip and Relyea (1971) in various areas at high galactic latitudes.

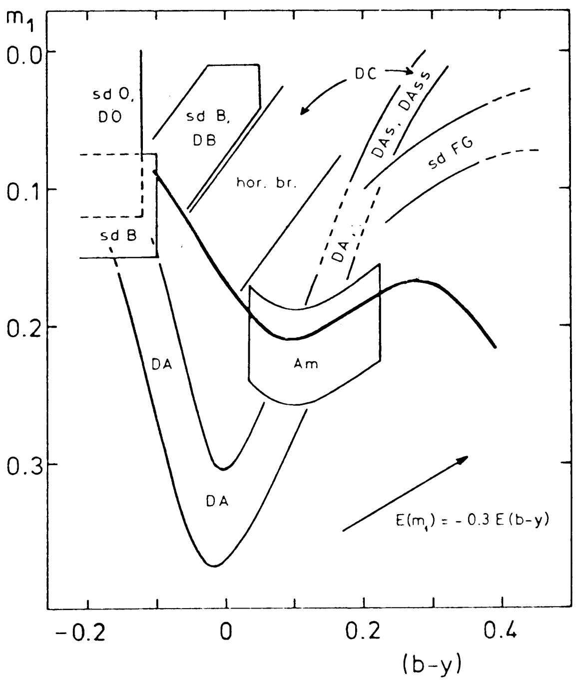
As a result of all these surveys and other surveys a large number of faint blue stars have been identified. Four-color measures of such stars in the magnitude range $10<V<14^m$ have indicated that they are about equally divided between Pop I and Pop II (see Philip and Tifft (1971), Philip (1974), and Rodgers (1971)). Two important studies of blue halo stars have been made in recent years. Greenstein and Sargent (1974) made a spectroscopic study and Newell (1973) made a photometric study in another photometric system. In each paper log T_{eff}, log g diagrams are plotted showing the distribution of various types of halo stars. This paper will be concerned only with horizontal-branch stars.

The method of identifying early-type Pop II stars will be described, then four-color and Hβ measures of field and globular cluster horizontal-branch stars will be discussed. The method by which four-color measures are transformed to the astrophysical parameters log T_{eff} and log g is described in a paper in the poster session, Relyea and Philip (1978). These parameters are then compared with the predictions of evolutionary theories in Section 4.

2. FOUR-COLOR MEASURES OF HORIZONTAL-BRANCH STARS

A number of papers have been written concerning photometric classification in the Strömgren four-color system. Among these are papers by Graham (1970), Philip (1973), and Kilkenny and Hill (1975). A figure taken from the last mentioned paper and reproduced here as Fig. 1 illustrates the method. In the spectral range A0-F8 horizontal-branch stars can be recognized by their high c_1 indices and low m_1 indices. Philip (1972) has shown that the Hβ index of A-type HB stars is smaller than that for main sequence stars of Pop I of similar spectral type.

To identify Pop II A-type stars one first obtains four-color and Hβ measures of the candidate star. The candidate stars are selected from Schmidt spectral plates taken with a 4 degree or thin prism (dispersion 280 or 1360 Å/mm at Hγ). Since the four-color



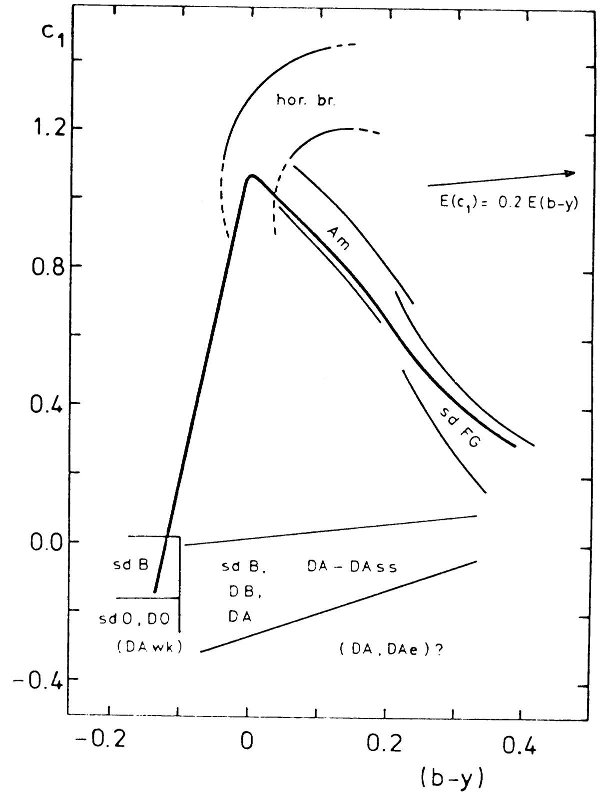


Fig. 1. m_1 <u>versus</u> (b-y) and c_1 <u>versus</u> (b-y). The location of various types of stars are indicated in the diagram as well as the ZAMS (heavy line). From <u>Mon. Not. R. Astron. Soc.</u> <u>173</u>, 625.

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indices are affected by interstellar reddening, the indices must be corrected. At the present time there is no formula by which one can deredden Pop II early-type stars so the reddening must be determined in other ways. A common method is to measure faint Pop I stars in the general field and then use the formulae derived by Crawford (1975) to derive the color excess in the region. The instrinsic four-color indices can be plotted in diagrams such as Fig. 1 and the photometric classification made. If Hβ measures are available this index can be used to confirm the classification.

On the next page a list of papers concerning the identification and measurement of HB stars is presented in Table I. In the first part of the table those FHB stars identified in part by means of four-color photometry are listed. Papers concerning the measurement of BHB stars in globular clusters and FHB stars are listed in parts two and three.

All the four-color measures of the HB stars in these papers plus unpublished data (Philip and Philip, 1978) are plotted in the following figures. The intrinsic $(c_1)_o$ color index is plotted against the intrinsic $(b-y)_o$ color index in Fig. 2, for field stars in the upper part of the figure and for globular cluster stars in the lower part. The interstellar reddening was calculated from tables in Philip (1973) and Philip, Miller and Relyea (1976) in which the values of E_{b-y} for many special areas are listed. For areas in which no measures have been made, a value of E_{b-y} was estimated by interpolation from nearby areas. In regions of high galactic latitude (where almost all these stars are located) this procedure works well and leads to errors of only a few hundredths of a magnitude in E_{b-y} and still smaller errors in the dereddened color indices $(c_1)_o$ and $(b-y)_o$.

The intrinsic color index $(m_1)_o$ is plotted against the $(b-y)_o$ index in Fig. 3; field stars are shown on the left side and cluster stars on the right. In each of these two sets of diagrams the ZAMS is indicated by the heavy line and the indices of the HB stars by points. Note that in each case the distribution of points in the diagram pairs is similar, in agreement with the hypothesis that the FHB stars are correctly classified as Pop II stars. Other evidence confirming this hypothesis has been noted in Philip (1973). This distribution of the indices of the four proto-type FHB stars (HD 2857, 86986, 109995 and 161817) is the same as that for the group of FHB stars. The velocity dispersion of 33 FHB stars is $\pm$ 113 km/sec (Philip 1969, 1970 and Rodgers 1971) matching the velocity dispersion of the globular clusters. The equivalent widths of the calcium K lines for 15 FHB stars measured by Rodgers (1971) fall below the relation between W(K) and $(B-V)_o$ for normal main sequence stars. More recently Danford (1976) has made a spectroscopic study of many FHB stars from the lists in Table I, Part 1 and he concludes that these stars are correctly classified as Pop II stars.

TABLE I

PAPERS CONCERNING DISCOVERY AND MEASUREMENT OF FIELD HB STARS AND MEASURES OF GLOBULAR CLUSTER BHB STARS

Part 1

Field Horizontal-Branch Stars

Identified by a combination of Schmidt Spectra and/or 4-Color Photometry

MacConnell, D.J., Frye, R.L., Bidelman, W.P. and Bond, H.E. (1971). Publ. Astron. Soc. Pacific 83, 98.

Philip, A.G.D. (1967). Astrophys. J. 148, L143.	(List I)
______ (1968). Astrophys. J. 152, 1107.	(List II)
______ (1969). Astron. J. 74, 209.	(List III)
______ (1969). Astron. J. 74, 812.	(List IV)
______ (1970). Astron. J. 75, 957.	(List V)
______ (1973). Publ. Astron. Soc. Pacific 85, 68.	(List VI)

Part 2

Globular Cluster Blue Horizontal-Branch Stars

Measured in the 4-Color Photometric System

Graham, J.A. and Doremus, C. (1968). Astron. J. 73, 226. (NGC 6397).

Philip, A.G.D. (1972). In The Evolution of Population II Stars, A.G.D. Philip, ed., Dudley Obs. Rept. No. 4, 35.

______ (1973). Astrophys. J. 182, 517. (M4).

______ (1978). in preparation.

Part 3

Field Horizontal-Branch Stars

Measured in the 4-Color Photometric System

Bond, H.E. and Philip, A.G.D. (1973). Publ. Astron. Soc. Pacific 85, 332.

Drilling, J.S. and Pesch, P. (1973). Astron. J. 78, 47.

Graham, J.A. (1966). Publ. Astron. Soc. Pacific 78, 433.

______ (1970). Publ. Astron. Soc. Pacific 82, 1305.

Hilditch, R.W., Hill, G. and Barnes, J.V. (1976). Memoirs Roy. Astron. Soc. 82, 95.

Kilkenny, D., Hill, P.W. and Brown, A. (1977). Mon. Not. R. Astron. Soc. 178, 123.

Kilkenny, D. and Hill, P.W. (1975). Mon. Not. R. Astron. Soc. 173, 625.

Newell, B. and Graham, J.A. (1976). Astrophys. J. 104, 804.

Philip, A.G.D. (1973). Dudley Obs. Rept. No. 8.

______ (1973). IAU Symposium No. 50, Spectral Classification and Multicolor Photometry, Ch. Fehrenbach and B. Westerlund, eds. D. Reidel, Dordrecht, p. 230.

Philip, A.G.D. and Tifft, L.E. (1971). Astron. J. 76, 567.

Philip, A.G.D. and Philip, K.D. (1973). Astrophys. J. 179, 855.

Slettebak, G., Wright, R.R. and Graham, J.A. (1968). Astron. J. 73, 152.

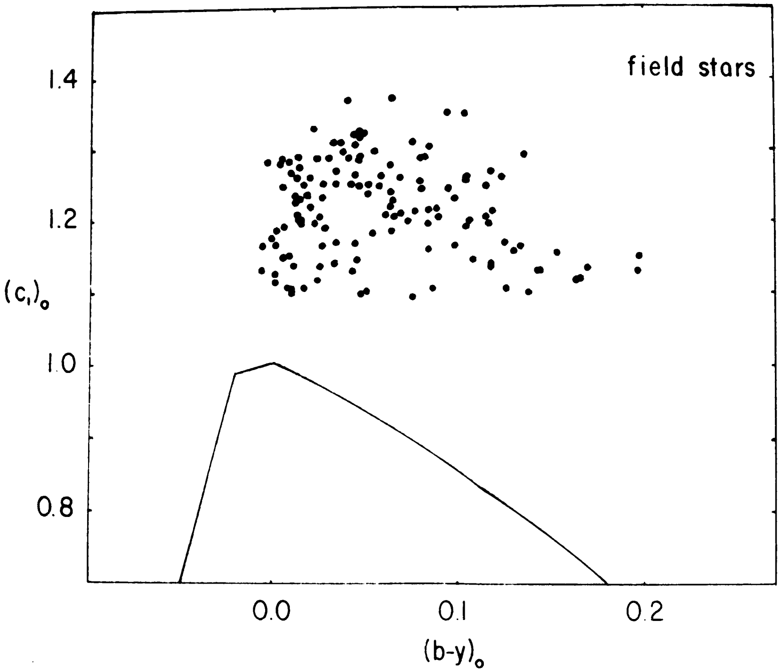
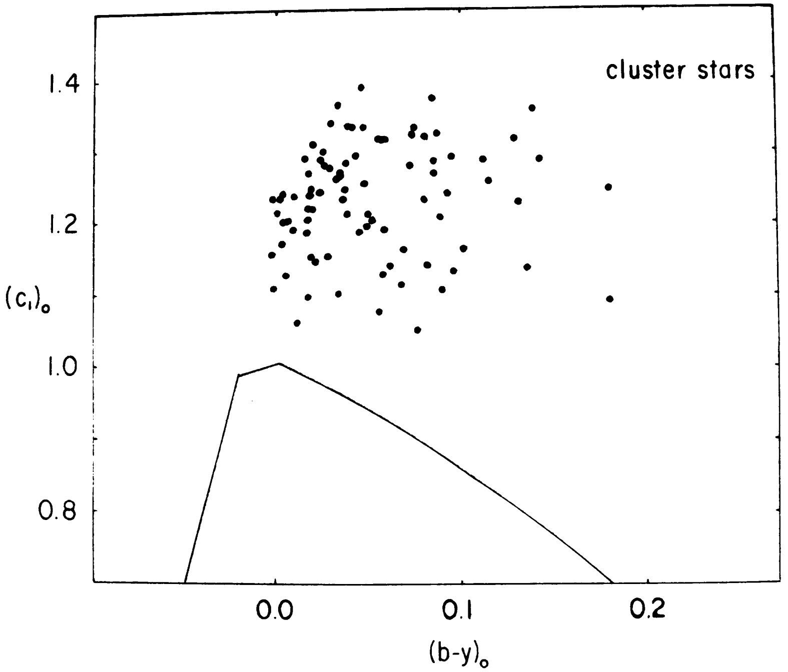


Fig. 2. $(c_1)_o$ <u>versus</u> $(b-y)_o$ for field (above) and cluster stars (below).



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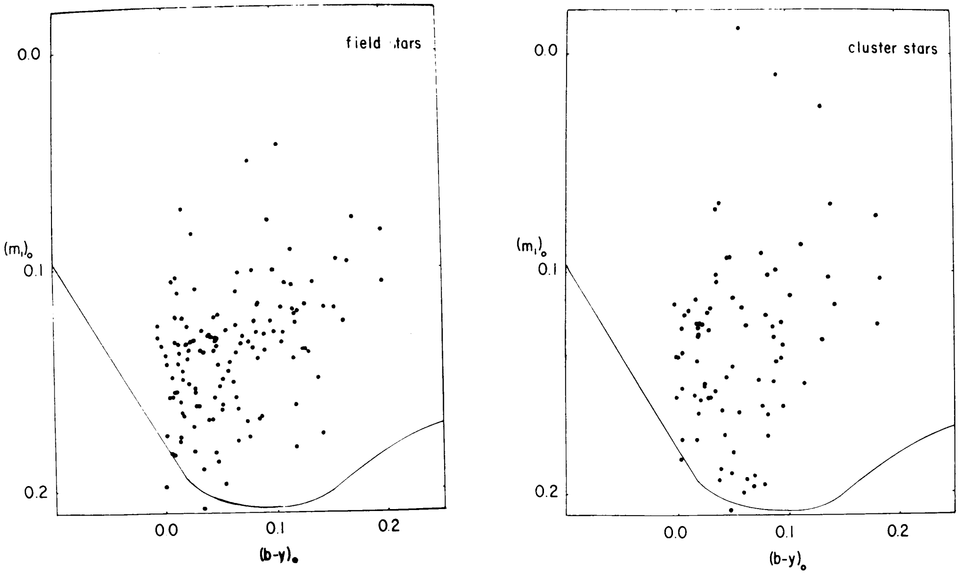


Fig. 3. $(m_1)_o$ versus $(b-y)_o$ for field (left) and cluster stars (right).

3. THE TRANSFORMATION OF PHOTOMETRIC INDICES TO LOG T_{eff} AND LOG G

The method of transforming the $(c_1)_o$, $(b-y)_o$ indices to log T_{eff} and log g is described fully in a paper by Philip and Relyea (1978) and outlined in a paper in the poster session, Relyea and Philip (1978). There are three grids which relate the color indices $(c_1)_o$, $(b-y)_o$ to log T_{eff}, log g for metal abundances equal to the solar metal abundance, 1/10 and 1/100 solar abundance. One plots the indices in the appropriate grid and then reads off log T_{eff} and log g. As a check that the method works it has been shown by Philip, et al. (1977) that the transformed indices of early-type stars in seven open clusters fall along isochrones calculated by Ciardullo and Demarque (1977). As an example of the fit the distribution of points in the log T_{eff}, log g diagram for the Hyades is reproduced from Philip et al. (1977) in Fig. 4. The isochrone lines represent ages of 0.5, 1.0, and 25 x 10^9 years. This agreement gives one confidence that the transformation is valid for early-type Pop I stars.

To check the transformation for Pop II stars the four-color indices of the four proto-type FHB stars were transformed to log T_{eff} and log g and the resulting values compared with those predicted by Kodaira (1975) and Oke et al. (1966). The log g values agreed well; no systematic trend was found. In Θ_{eff} however, a correction formula was derived to correct the temperatures calculated from the grid. The equation used is:

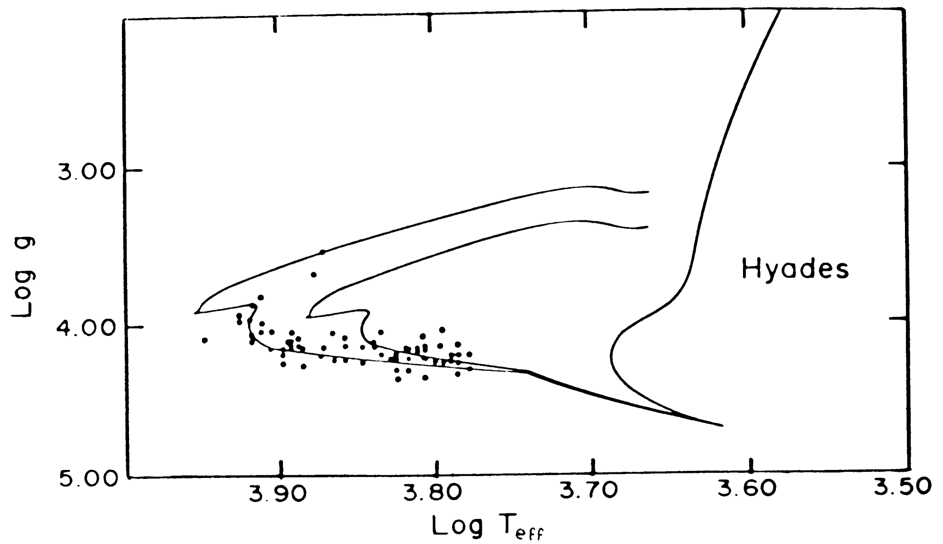


Fig. 4. Observations and theory compared for Pop I stars (From Publ. Astron. Soc. Pacific **89**, 534).

$$\Theta_{eff} = 1.713\ \Theta_{grid} - 0.457. \quad (0.57 < \Theta_{eff} < 0.68)$$

4. COMPARISON WITH EVOLUTIONARY MODELS

The log T_{eff}, log g values are plotted in Fig. 5, field stars on the upper left and cluster stars on the upper right. Some of the theoretical horizontal-branch evolutionary tracks (Sweigart and Gross, 1976) are shown in the bottom part of Fig. 5. All the models shown are for core masses of 0.475 $M_{\odot}$ but the total mass, helium and metal abundances vary as shown in the diagram.

Because there are so many parameters that can vary one can not pick a unique set and determine masses and abundances for HB stars from these diagrams. Additional information will be needed to do this. But it is interesting that the models all have a similar slope in the log T_{eff}, log g diagram and that this slope is matched by the distribution of the transformed observational points in the diagrams for field and cluster stars. Extreme values of the physical parameters can be ruled out.

As in the case for Pop I stars, theory and observation seem to be agreeing within the rms errors determined from the theoretical and observational side.

5. CONCLUSIONS

Photometric indices of Pop I and Pop II stars of spectral

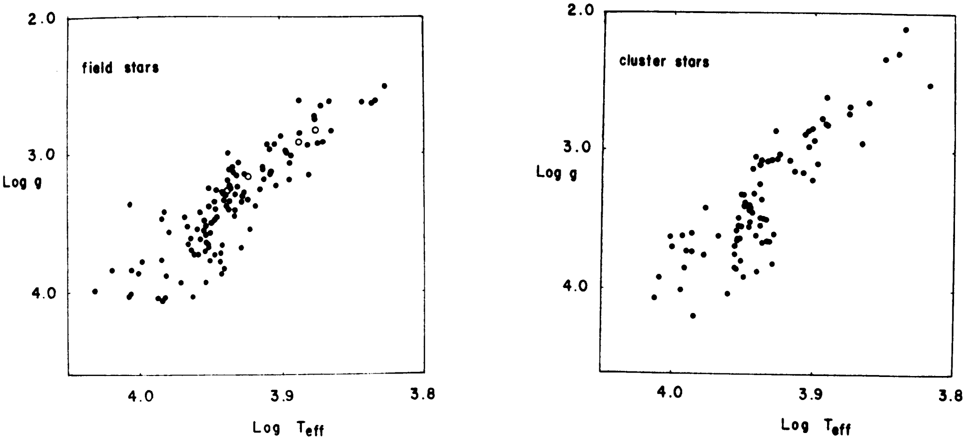
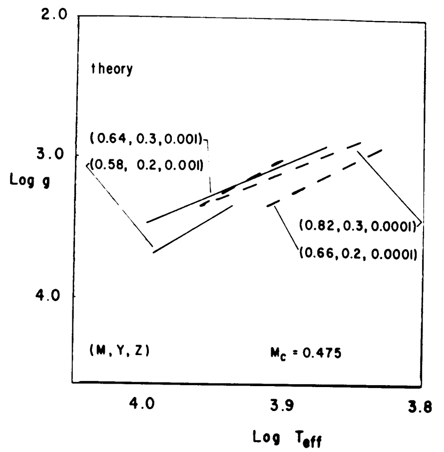


Fig. 5. Log g versus log T_{eff} for field stars and cluster stars. Evolutionary models are shown to the right.



types A - F, luminosity classes V - III can be transformed successfully into a form of the theoretical HR diagram, the log g, log T_{eff}, diagram. For both Pop I and Pop II stars the distributions in such diagrams agree with the distributions predicted by current theory. The distributions also agree, in the spectral range A - F, with distributions determined by Greenstein (1974) and Newell (1973).

A temperature correction was needed for Pop II A - F stars. Since there were only four Pop II early-type stars for which log T_{eff} and log g are known the temperature correction used is not well determined. Additional bright FHB stars should be measured by a photoelectric scanning technique and fundamental values of log T_{eff} and log g derived. A correction formula to the $(c_1)_o$, $(b-y)_o$ grid derived from 20 such sets of observations would be a great improvement over the present situation.

BHB stars in many globular clusters of varying [Fe/H] values can be measured and transformed to the log T_{eff}, log g diagram. Since these stars are faint many measures will be needed with telescopes of aperture 2.5m or greater. If accurate data for many stars in different globular clusters could be obtained one could investigate to see if the scatter found in the giant branches of some globular clusters is also found in the horizontal branch. Such data would help to determine if the scatter is caused by inhomogeneity in the proto-cluster or if the scatter is caused by mixing in some later evolutionary stage.

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Relyea, L.J. and Philip, A.G.D. (1978). In IAU Symp. 80, The HR Diagram, A.G.D. Philip and D.S. Hayes, eds., Reidel, Dordrecht, p. 443.
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DISCUSSION

BUTLER: Suppose there is a population of metal-rich ([Fe/H]∿0) blue horizontal-branch stars in the solar neighborhood. Is it possible to use your techniques in discovering any of these (as yet hypothetical) stars?

PHILIP: It would depend on the spectral type of the star being investigated. If the star is of spectral type B or A0 it is very difficult, but as the spectral type becomes later, A3, A5 to A7 a high metal abundance would show up in the metal index (the metal index, m_1, would become larger than that for a metal poor star of the same color).

McNAMARA: How does your $(c_1)_o$ versus $(b-y)_o$ diagram compare with Breger's and could you comment on the so called c_1 anomaly in the Hyades?

PHILIP: Dave Crawford, who is in the audience, would be the best person to comment on the c_1 anomaly in the Hyades. As for the comparison of our $(c_1)_o$ $(b-y)_o$ diagram with that of Breger's, Breger used the atmospheric models of Osmer and Peterson; Philip and Matlock used the 1966 atmospheric models of Mihalas. The various $(c_1)_o$, $(b-y)_o$ diagrams were compared in the paper in Multicolor Photometry and the Theoretical HR Diagram, Dudley Observatory Report No. 9 and all were found to agree within the rms errors.

CRAWFORD: Being naturally conservative, I have no suggestion about the Hyades solution. It could be due to blanketing or structure differences, due to metal abundance, or it could be helium differences, which haven't been talked about much here yet, or to other things. It is certainly there (the δc_1 anomaly for F-type stars), and I'd be glad to hear people's idea about the causes.

McNAMARA: I just worry about using the Hyades as a calibration for the diagram.

PHILIP: I am not using the Hyades as a calibration. It was just one cluster out of seven which were plotted to check out the systems as applied to Pop I stars. Kurucz's atmospheric models were used and Vega was used to make the zero point corrections. Since I don't like calibrations based on only one star I went through the literature and found 28 A-F type stars for which spectroscopic determinations of log T_{eff} and log g had been made. We then calculated the residuals (published - observed) and found that the rms errors were ± 0.015 in θ_{eff} and ± 0.2 in log g. These values are about the same as obtained from spectroscopic determinations.

LUB: Considering your plot of log T_{eff}, log g it seems to me that you have in there several stars which appear to be in the RR Lyrae instability strip; have you checked any of these stars for variability?

PHILIP: No, I have not made a systematic check for variability. On low dispersion spectral plates the differences would be hard to detect and in most cases I have only a few plates for each region. The four proto-type stars have been measured about 100 times each and I detect no signs of variability. The other program stars have been measured from 2 to 20 times each, and while I have no firm indications of variations, these data are not sufficient to decide on variability.

LUB: HD161817 is just 100 K beyond the blue edge of the RR Lyrae instability strip and you have some stars that would be in the instability strip.

PHILIP: That could be. It just means that someone has to obtain additional observations of those stars.

COX: Can I ask you a technical question about the calibration of your c_1 and m_1 indices? This morning we heard that Y can vary from less than 0.2 to over 0.35. What is the difference in your calibrations for these varying Y's?

PHILIP: The calculations are based on the Kurucz models which used a conventional Pop I helium abundance (0.9 hydrogen and 0.1 helium by number).

GREENSTEIN: Much theoretical attention has been devoted to horizontal-branch stars and it seems to me Dr. Philip's work provides an extension to what I and others have done. We worked on the hotter, you have worked on the cooler group. The plot of g and θ is almost certainly an extension of plots valid for the field horizontal-branch hot stars, with a

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