

CCD PHOTOMETRY OF GLOBULAR CLUSTERS IN THE FOUR-COLOR SYSTEM

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Abstract. A program of four-color photometry of BHB stars in globular clusters has been underway, using the 0.9 m telescopes at Cerro Tololo and Kitt Peak National Observatories. With 2048×2048 pixel chips an entire globular cluster can be measured on one frame. The earlier chips allowed only a small section of a cluster to be measured. In M 92, for example, 184 blue stars have been found in comparison to the 32 found in earlier single-channel photometric studies. Two features of CCD photometry contribute to the finding of a greater number of blue stars. One is that the CCD frame, as reduced by the ALLSTAR reduction program, allows one to measure stars in very crowded regions. Another feature is that fainter stars can be measured with the CCD technique. Some problems with CCD photometry are the lack of faint standards and the creation of flatfield frames. The blue stars in a globular cluster CM-diagram have been classified into several different groups (classical BHB stars, stars above the BHB and an interesting group found well below the horizontal branch).

Key words: methods: observational – techniques: photometric – instrumentation: CCD detectors – stars: HR diagram – stars: horizontal-branch – globular clusters

1. INTRODUCTION

The advent of CCD astronomy has revolutionized all areas of optical observations, allowing astronomers to complete projects that were unimaginable pre-1980. This is especially true in the case of

astronomical photometry. An early CCD paper dealing with the photometry of globular cluster stars was the paper by Hesser et al. (1987) who discussed measures of 8800 stars in the globular cluster 47 Tuc. Their Fig. 9 (shown here as Fig. 1) compares observations made of 47 Tuc by means of photoelectric and photographic photometry, SIT vidicon + RICHFIELD and finally with a CCD + DAOPHOT. The color-magnitude diagram becomes much more tightly confined and reaches much fainter magnitudes as one goes from the left to the right panel. The tighter CMD allows a good fit to be made to isochrones. Fig. 2 shows Fig. 18 of the Hesser et al. (1987) article on which isochrones for 10, 12, 14 and 16×10^9 years are drawn. An age of 13 – 14 Gyr was inferred from the diagram.

Care has to be taken with CCD photometry. Many astronomers have pointed out some of the problems associated with obtaining and reducing CCD data. At IAU Symposium No.167, in The Hague last August, there were several papers which dealt with the advantages and disadvantages of using CCDs in astronomical observations.

Young (1995) pointed out the difficulty of matching filters to CCDs to obtain the correct colors in a photometric system. Individual CCDs vary in their spectral response and these differences should be taken into account when one is designing a set of filters to reproduce a given photometric system. There are variations, even in a single CCD, from pixel to pixel, which introduce errors in the derivation of photometric colors. Young recommends that each observatory should design a specific filter set for each CCD instrument being used for photometric measures. These filters should not be transferred from CCD to CCD but stay with the CCD for which they were designed.

Sterken (1995) reviewed the good and bad features of CCDs. In the section on disadvantages of CCDs he noted that all the objects on a single CCD frame are taken with the same exposure which means that the S/N ratio for each image measured varies as a function of the brightness of the object. Another disadvantage is the large amount of time needed to reduce CCD raw instrumental magnitudes to magnitudes and colors in a given photometric system. At DAO, Stetson (1990, 1993) has written a series of programs (DAOPHOT, ALLSTAR, DAOMASTER) which make the reduction of CCD data a much faster process than was available a few years ago. I have been reducing my CCD data at DAO using Stetson's programs and almost every time that I arrive for the next data reduction run there is a new program or an improvement in one of the programs already

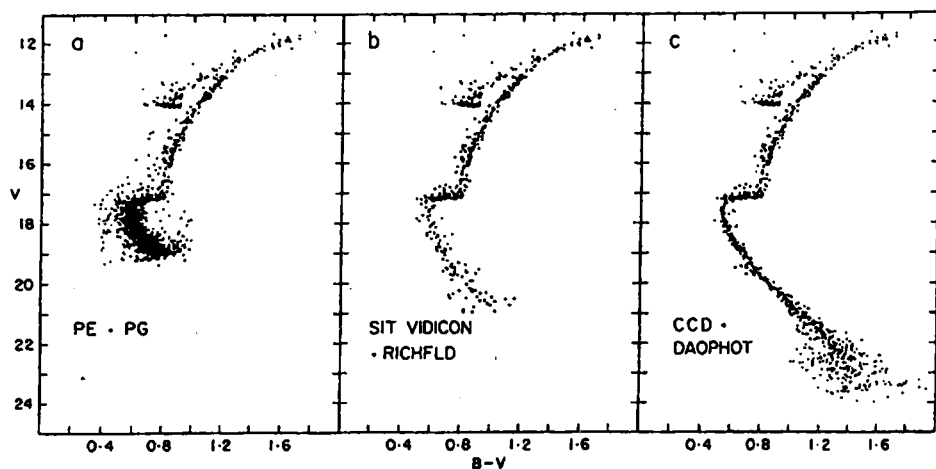


Fig. 1. CMDs for 47 Tuc derived from three independent studies (photoelectric, SIT Vidicon and CCD + DAOPHOT). The giant and horizontal branches are the same but the main sequence in each case reaches fainter magnitudes from (a) to (c), illustrating the progression in depth and internal precision that has been achieved. (Hesser et al. 1987)

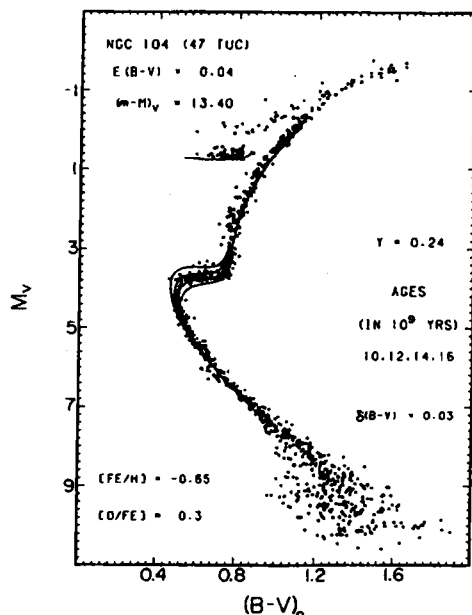


Fig. 2. Fit of theoretical models (solid curves) to the composite CMD of 47 Tuc. An age of 13 – 14 Gyr was inferred from this diagram. (Hesser et al. 1987)

written that make the job faster, more accurate or a combination of both.

Other problems noted by Sterken include the lack of standard stars for CCD photometry, the problem of a varying PSF in large CCD frames, the nonuniformity of the response within a pixel, the nonuniformity of the response from pixel to pixel, shutter timing and flatfielding. In the four-color system there is no faint standard star set over the sky to be used as standards. In my M 92 work it turned out that years ago I had observed BHB stars in M 92 with the Steward Observatory 2.3 m telescope using a single-channel photometer. I used these stars as standards to match the instrumental colors to the four-color system. As CCD frames get larger it is no longer safe to assume that the PSF is constant over the frame. In Stetson's ALLSTAR and DAOPHOT routines there is the possibility of solving for a variable PSF and then applying this solution to the measure of the unknown stars in the frame.

Nonuniformity within a pixel can reach 10 % and Sterken says that it is not uncommon to find that 1 % of the pixels in a chip can be of low sensitivity, noisy, dead or have high dark current. Flatfielding is a major problem. If one uses the white spot on the dome, one has to be sure that beams from the lamps should resemble beams received by the telescope from stars; the white spot has to be evenly illuminated and the color of the beam should be controlled by filters to match the energy distribution of stars being measured. Flatfields obtained from twilight exposures have their problems also. The sky is changing in brightness and it is more difficult to obtain a series of flats with identical exposures. The exposures tend to be short and shutter timing problems can then affect the exposure of the flats. It is a difficult task to obtain a sufficient number of flats in four different filters during the short twilight periods. Another potential problem concerns temperatures. If the detector temperature or the temperature of the filters change during the night, changes can occur in the reduced photometry.

Bessell (1995) is concerned with high precision stellar photometry with CCDs. It is necessary that the CCD passbands match the standard passbands as closely as possible. He recommends that CCD standards be set up in several declination zones, with stars having a good range in color on each frame. To compute a good CCD passband one must convolve the transmission of the filter with the sensitivity response of the CCD to obtain a net passband matching that of the standard system one is trying to match. Bessell notes

that there is great diversity in the wavelength response of CCDs, and all CCDs have a response that is different from that of a GaAs photocathode with which many of the standard photoelectric observations were made. In his paper he makes specific recommendations for filters to be used in some photometric systems.

Roberts et al. (1995) have been interested in the transformability of broadband photometry, especially for CCD photometry. They have taken the filter transmission curves for a number of common photometric systems at four major observatories and constructed instrumental passbands. From those they use Kurucz models to derive synthetic instrumental colors. They find that transformations from the instrumental CCD passbands to the standard systems are nonlinear. They recommend more reliable results are obtained by restricting one's standards, as much as possible, to stars similar in temperature, surface gravity, and metallicity to the program stars. Fig. 3 shows a copy of a plot for Strömgren four-color photometry (Roberts 1995). The differences (instrumental - fit) color indices are plotted versus color index for five of the four-color indices. What is interesting for those who work on horizontal-branch stars is that most of the large deviations occur for the redder, cooler stars. For stars in the color range $0 < (b - y) < 0.2$ (valid for HB stars), the relationships in each of the graphs are tightly defined and thus a good relationship exists between the instrumental and the system colors. For those who are investigating stars of widely different parameters, temperatures, gravities and metallicities, the problems presented by Roberts et al. (1995) must be taken into consideration.

2. THE TWAROG'S WORK ON GLOBULAR CLUSTERS

In Anthony-Twarog & Twarog (1991) the authors state, "the Strömgren *uvby* photometric system has become the dominant photometric tool for studying stellar populations and galactic structure". From a study of the color indices, and in combination with $H\beta$ indices, one can determine luminosity, temperature and metal abundance for stars of spectral type B through early G. The system has been extended to the study of giants and cool dwarfs by Ardeberg & Lindgren (1985). The Twarogs were among the first to use CCDs with the four-color system. Their first observations were taken of the open clusters M 67 (Anthony-Twarog 1987), IC 4651 (Anthony-Twarog & Twarog 1987) and NGC 3680 (Anthony-Twarog et al. 1989) and they found that their CCD observations reached two mag-

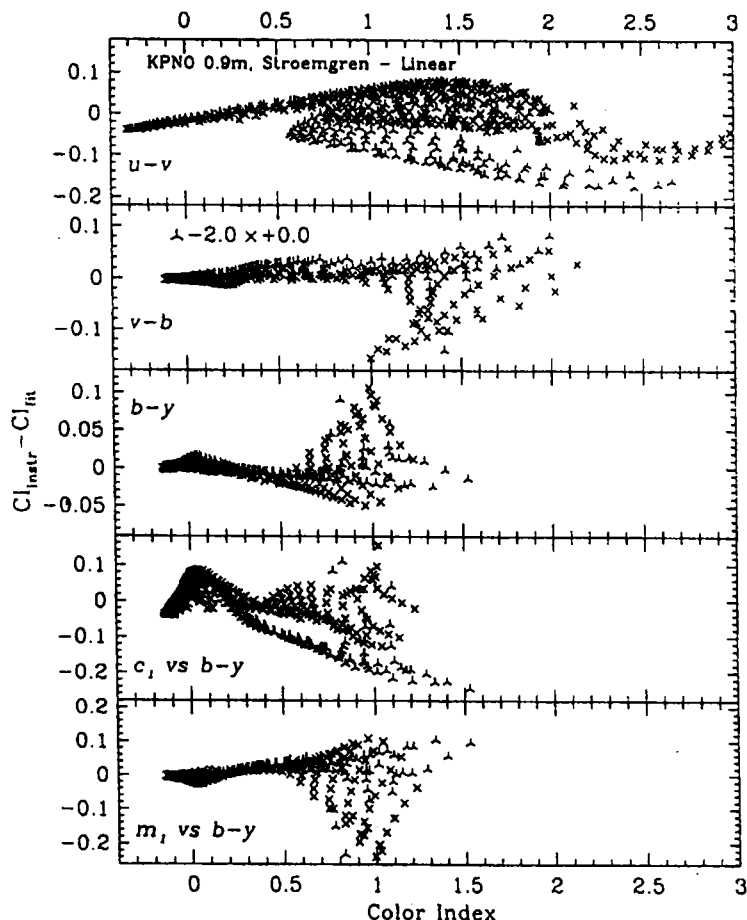


Fig. 3. Four-color residuals of the instrumental colors after subtraction of the line fit for the KPNO 0.9 m telescope CCD camera.

nitudes fainter than the published photoelectric photometry studies with photometric accuracies as good as the photoelectric results.

They have also applied CCD four-color photometry to globular clusters. The first cluster studied in this program was NGC 6397 (Anthony-Twarog 1987, Anthony-Twarog & Twarog 1992) and Fig. 4, from that paper, illustrates the use of the m_1 index to separate contaminating field stars from the cluster stars. In Fig. 4a the CM diagram for all the stars measured is shown. In Fig. 4b the stars with high m_1 indices have been removed leaving a much tighter CM diagram for the cluster. In Fig. 5, also from the same paper, plots are shown of a CM-diagram and $m_1, (b-y)$ diagram for candidate

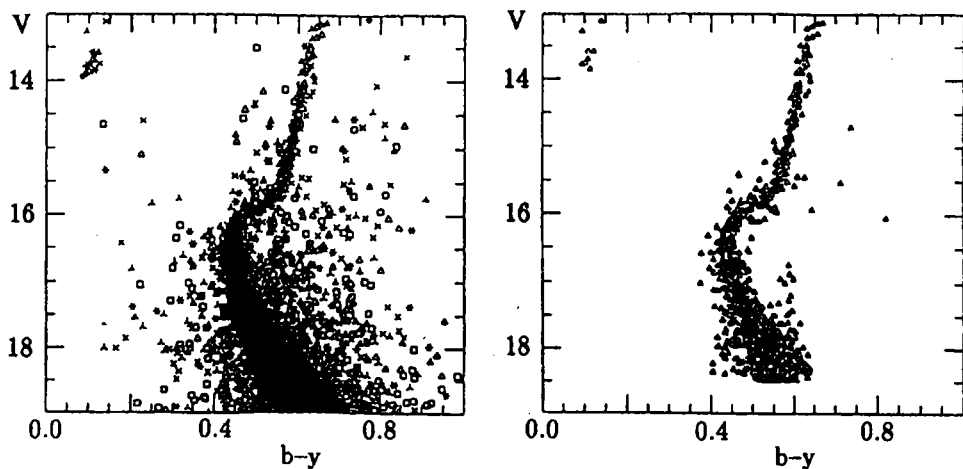


Fig. 4 a, b. The CM diagram for all stars measured in NGC 6397 is shown on the left. Stars with high m_1 indices have been removed in Fig. 4 b, on the right.

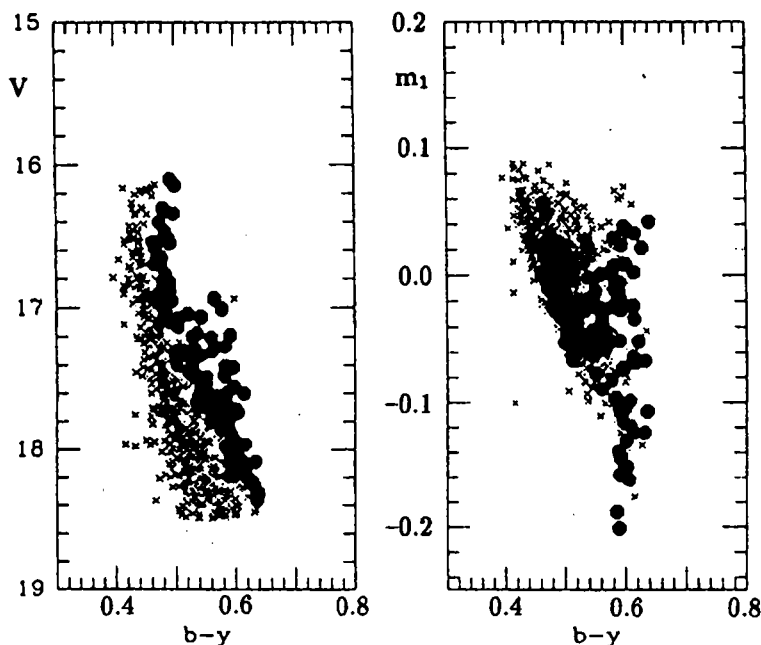


Fig. 5. CM-diagram and $m_1(b-y)$ diagram for probable main-sequence stars from the SO and EA fields (crosses) together with all binary candidates from the six fields (filled circles). [Fig. 7 from Anthony-Twarog & Twarog 1992].

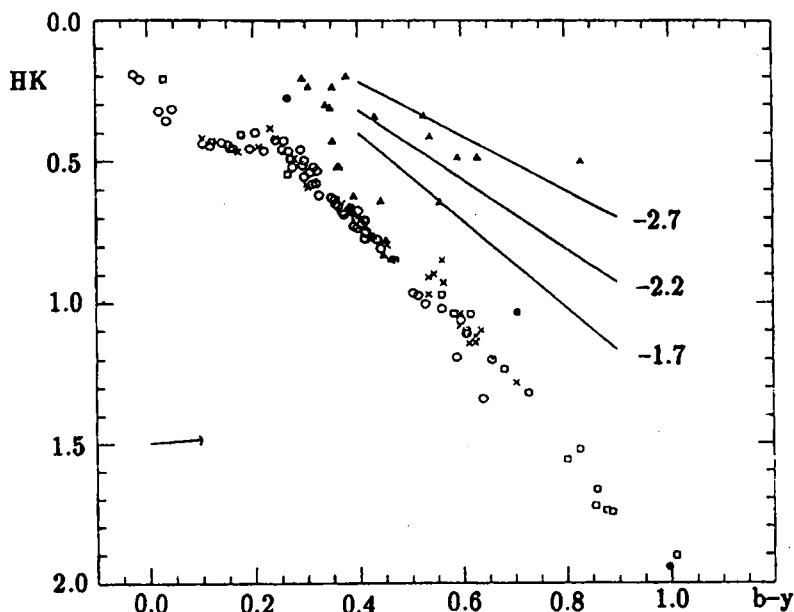


Fig. 6. The new index, HK plotted vs $(b-y)$, showing the separation of stars by metallicity. Stars of different luminosities fall fairly closely together.

binaries in NGC 6397 (filled circles). The filled circles fall off the fiducial main sequence in the diagram on the left but fall among the other points in the $m_1, (b-y)$ diagram. The four-color observations allow one to separate out binary candidates near the main sequence in globular clusters.

Mukherjee (1989) has reported on four-color observations made in the globular cluster, ω Cen, which showed a greater scatter near the turnoff and a greater scatter in m_1 than in NGC 6397. This scatter is greater than that predicted from the photometric errors and thus is assumed to be intrinsic to the cluster.

Anthony-Twarog et al. (1991) report on the use of a fifth filter, centered on Ca II H and K which is designed for application with metal-poor dwarf and red giant stars. For cool stars the m_1 index loses some of its sensitivity but the new filter (when substituted for v) makes the m_1 index more sensitive by a factor of about three. In their later papers they have used this new filter, the $uvby$ filters and IUE spectra to study metal-deficient giants and their reddening (Twarog & Anthony-Twarog 1991, Anthony-Twarog et al. 1992,

Anthony-Twarog & Twarog 1994). Fig. 6 reproduces their Fig. 5 (Anthony-Twarog et al. 1991) which plots HK vs $(b - y)$. Open circles, crosses, squares and filled circles represent luminosity classes V, IV, III and I-II, respectively. Mean isometallicity relations are shown as solid lines for red giants. The solid triangles represent metal-poor, high-velocity stars from Schuster & Nissen (1988).

3. THE RCA CCD

My CCD four-color observations started in 1985 with test CCD exposures taken of the globular cluster M 13 (a project done in co-operation with Don Hayes, then at Kitt Peak) with the No.2 90 cm telescope at Kitt Peak National Observatory. The tests showed that four-color photometry could be done with accuracies of ± 0.01 mag and so proposals were written to KPNO and CTIO to do four-color CCD photometry in a few globular clusters, using the RCA CCD chip. On the No.2 90 cm telescope the RCA chip saw an area of only 2 by 3.5 arcmin which meant that only a small portion of a globular cluster could be measured in one frame. Fig. 7 shows a chart of the globular cluster M 22 (NGC 6656) with the location of the CCD frame marked. In Fig. 8 a CM-diagram of the BHB stars measured in that frame is shown. A tight, curved line could be drawn through a lower envelope of points. There were four stars that were approximately 0.2 mag above the lower curve (Philip 1990).

These first CCD observations had two major problems. One was that the field of view was small and this meant that the number of BHB stars that would fall on any one frame was small. When the BHB stars were broken up into groups, the number of stars in each group was so small that the information presented was of low statistical significance. Another problem was that the ultraviolet sensitivity of the RCA chip was low and when that was combined with the low intensity of a BHB star in the ultraviolet, the u magnitudes that resulted had very high rms errors. The c_1 index could not be determined; only the y mag, $(b - y)$ and m_1 indices could be calculated with sufficient accuracy.

A way around the problem of the small number of BHB stars on a given frame was to make observations in several globular clusters and then combine the observations in a single CM-diagram. At CTIO and KPNO observations were made of areas in the globular clusters M 4 (NGC 6121), M 5 (NGC 5904), M 55 (NGC 6809) and M 92 (NGC 6341). The y magnitudes were fit to observed V magnitudes

from the literature, $(b - y)$ was fit to $0.7(B - V)$. The CM diagrams for each cluster were corrected to the unreddened $(b - y)$ colors and y magnitudes were corrected to the distance modulus of M 22 by sliding the respective diagrams up and down so that the lower envelopes fell in the same positions. The resulting CM-diagram is shown in Fig. 9. A dashed line has been drawn through the lower envelope of points. Above this line are many points, 0.2 magnitudes brighter, or more than the stars on the lower track.

Swiebart (1987) has published evolutionary horizontal-branch tracks for models with a helium abundance of 0.3 and a Z of 0.01 (shown in Fig. 10). These tracks can offer an explanation of the distribution of the points in Fig. 9. The tracks show that for stars, arriving on the horizontal branch, whatever their mass, they arrive on the Zero-Age Horizontal Branch and start evolving to the blue along the ZAHB. Then they turn off the ZAHB and start evolving towards the red asymptotic giant branch. It is assumed that the stars on the lower envelope are those stars which are evolving to the blue and the stars which fall 0.2 mags or greater above the envelope represent the stars which are further along their evolutionary track and are on their way to the red asymptotic giant branch. What was needed now was a set of observations in one cluster that would significantly raise the number of BHB stars in the frame. This became possible with the arrival, at major observatories, of larger CCD chips. This is discussed in Section 4.

4. THE TK2A CCD

The Tektronics TK2a chip has 2048×2048 pixels and on a 0.9 m telescope it is able to see over 20 arcminutes of sky. The filters at KPNO were 2 inches square but the telescope did not image the entire field of view. The chip was prepared so it saw 17 arcminutes, the area of the chip that was not vignetted by the edge of the filters. The new chip had a good ultraviolet response and this time c_1 indices could be calculated, with rms errors of approximately ± 0.01 mag.

4.1. M 92

The first cluster to be investigated with the new chip was M 92 (NGC 6341). The area of sky being exposed during the exposures covered the entire cluster. In the classic paper on M 92 by Sandage (1969), 32 blue horizontal-branch stars were identified in his Table 6.

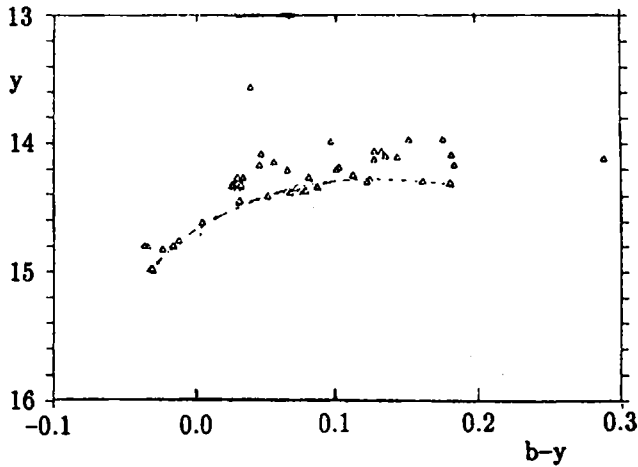


Fig. 9. Combined CM-diagram for BHB stars in the globular clusters M 4, M 5, M 22, M 55 and M 92.

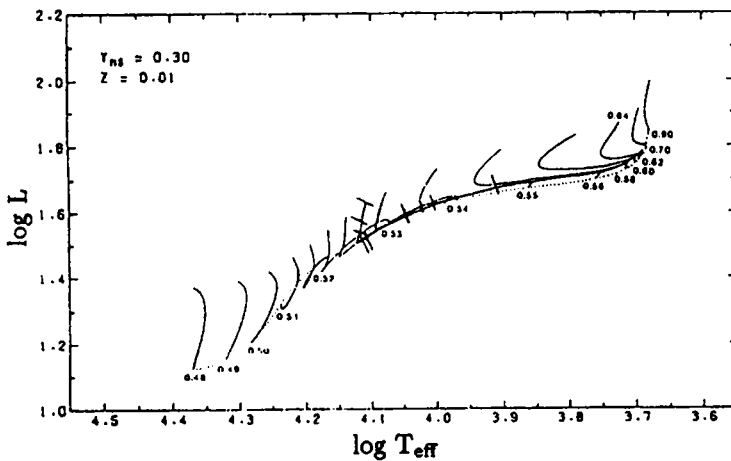


Fig. 10. Sweigart (1987) evolutionary horizontal-branch tracks for models with a helium abundance of 0.3 and a Z of 0.01.

All of these stars were recovered in the CCD photometry except for one star that lay just outside the area covered by the frames. Nine of the Sandage BHB stars had been observed with a single channel photometer on the University of Arizona's 2.3 m telescope and these stars were used as standards to calibrate the four-color CCD photometry. The stars and their four-color values are listed

in Table 1. The equations used to transform the CCD instrumental magnitudes and colors to the *uvby* system are listed below the table.

The data were reduced using Stetson's programs at DAO. First, DAOPHOT was used to derive stellar magnitudes but then a new program, ALLSTAR, was ready and so I used it to calculate the final magnitudes.

I tested reducing the data with a single PSF and then with a variable PSF and found a difference of $+0.01$ to -0.01 mag in the magnitudes of stars at the top and the bottom of the frame between the NSTAR and ALLSTAR reductions. The variable PSF routines were taking care of small variations in magnitude across the CCD frame. As a check on the reliability of the magnitudes calculated for stars near the central regions, plots were made of stars in the center (solid symbols) and stars away from the center (hollow symbols). Fig. 11 shows the CM-diagram for 800 stars measured on the CCD frame. It can be seen that the ridge line for the solid and hollow symbols on the tip of the red giant branch and on the red horizontal branch coincide. From this distribution I conclude that there are no serious photometric differences between the magnitudes calculated for the stars in the central regions as compared to the outer regions.

4.2. The blue horizontal branch of M 92

In the interval $-0.07 < (b - y) < 0.18$, 184 blue stars were identified on the cluster frames. Many of these stars were located in the central regions of M 92. Tests were done to check on the reliability of the photometry from these regions. The area surrounding each central star was investigated on the monitor and printed out. The stars were divided into two groups. One group had no star of comparable brightness nearby, the second group contained stars that had a star of comparable magnitude within one image radius. The two groups plotted in the same areas of the CM-diagram; there were no systematic shifts in color or magnitude.

In Fig. 11 one can see the distribution of the blue stars in the CM-diagram of M 92. Extending from $y = 15$, $(b - y) = 0.16$ to $y = 16$, $(b - y) = 0.0$ one can see a group of stars that fall on the ZAHB. Above this relation are a number of stars with y magnitudes that are ≥ 0.2 mag brighter. Below the ZAHB one finds a scattering of stars, about half a magnitude fainter. I was interested in finding out if these groups persisted in the other four-color diagrams. Figs. 12 and 13 show these same stars in c_1 vs $(b - y)$ and m_1 vs $(b - y)$

Table 1. Standard stars set up in M 92.

Name	<i>V</i>	<i>B-V</i>	<i>U-B</i>	<i>X</i>	<i>Y</i>	<i>y</i>	<i>b-y</i>	<i>c</i> ₁	<i>m</i> ₁
VI 3	15.32	0.08	0.08	522	1355	15.393	0.044	1.343	0.154
VI 55	15.18	-0.02	-0.04	651	1186	15.080	0.047	1.102	0.069
VII 18	16.19	-0.08	-0.38	1111	1207	16.098	-0.027	0.810	0.060
X 5	15.48	0.01	0.00	1253	708	15.393	0.017	1.193	0.157
X 22	15.16	0.17	0.08	1098	880	15.056	0.108	1.176	0.144
X 23	15.38	0.06	0.07	1084	885	15.293	0.055	1.266	0.130
XII 9	15.09	0.15	0.09	953	528	14.982	0.149	1.141	0.099
XII 10	15.27	0.07	0.05	936	534	15.152	0.072	1.132	0.141
XII 26	15.25	0.15	0.12	791	545	15.180	0.054	1.342	0.159

$$y = y' + 0.0851, \quad (b - y) = (b - y)' - 0.3113, \quad c_1 = c'_1 - 0.2877, \\ m_1 = m'_1 + 0.5520.$$

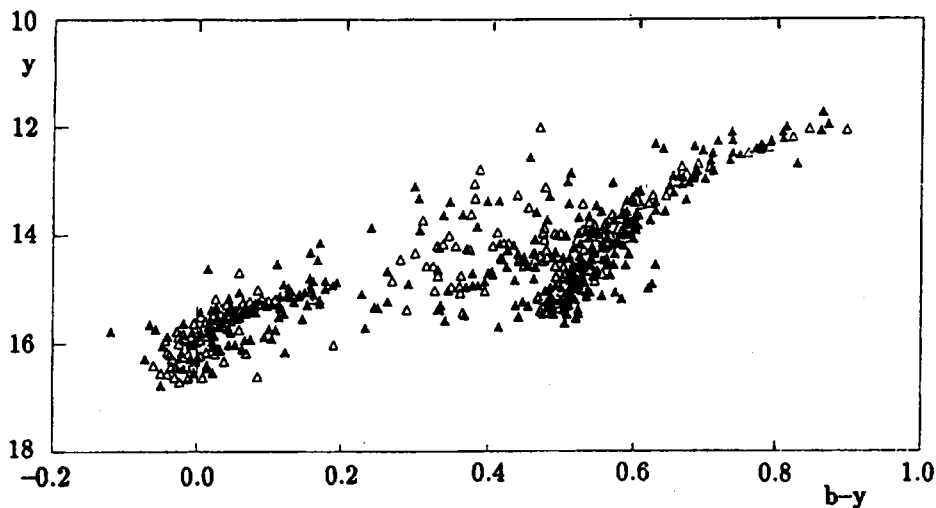


Fig. 11. The four-color CM-diagram for M 92. Solid symbols represent stars in the central part of the cluster, hollow symbols represent stars not in the central regions.

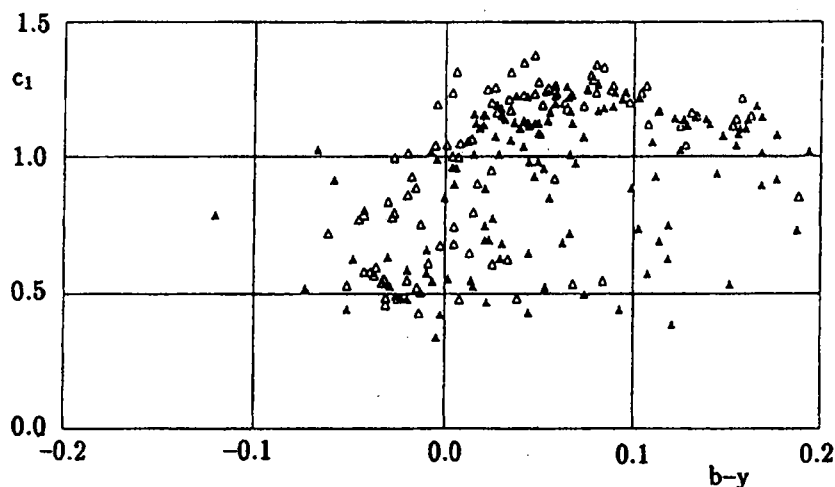


Fig. 12. c_1 vs $(b-y)$ diagram for the blue stars in M 92. The symbols are the same as in Fig. 11.

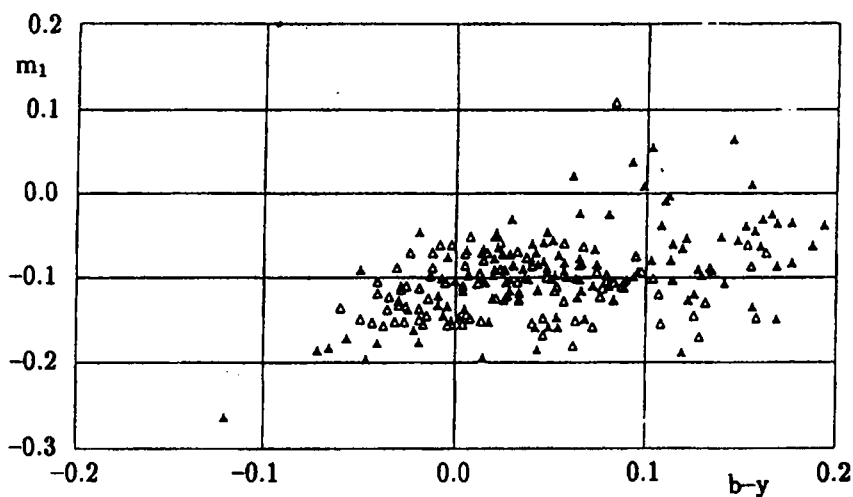


Fig. 13. m_1 vs $(b-y)$ diagram for the blue stars in M 92. The symbols are the same as in Fig. 11.

diagrams. In each of these diagrams the hollow symbols represent stars found in the outer regions of the cluster and solid symbols represent stars in the central regions.

Tundra Vole Software wrote a TrueBasic program which allows one to plot a set of data points, mark a selected set with the cursor

and then save the new group as a separate file. This new file can then be plotted in other, related diagrams. This program was used to select groups of stars from the CM-diagram and then plot each group in the c_1 vs $(b - y)$ and m_1 vs $(b - y)$ diagrams. The groups that were selected in the CM-diagram were: the ZAHB stars, stars ~ 0.2 mag above the ZAHB, stars ~ 1 mag above the ZAHB, stars ~ 0.5 mag below the ZAHB and stars ~ 1 mag below the ZAHB. In Fig. 14 the CM-diagram for the blue stars in M 92 are replotted, grouped by symbols into these groups. Figs. 15 and 16 present the new c_1 vs $(b - y)$ and m_1 vs $(b - y)$ diagrams using the same symbols shown in Fig. 14. It can be seen that the groups detected in Fig. 14 persist in the other two figures. These natural groups thus are saying something about the nature of the stars in the cluster and are not the result of random errors in the photometry.

As has been noted in Section 3, it has been assumed that the stars falling on the lower envelope of the main distribution of stars in Fig. 11 are stars on the ZAHB, evolving bluewards before they turn up and head to the right in their evolutionary tracks (See Fig. 10). The stars which fall approximately 0.2 mag above the ZAHB are assumed to be stars that are on a redward track towards the asymptotic giant branch. The stars that fall approximately 1 mag above the ZAHB are almost all from central regions of the cluster. Their higher luminosities could be explained if they are binaries.

4.3. *The BHB of M 15*

A set of four-color frames has been taken of the globular cluster M 15. The data are in the process of reduction. At the present time, instrumental colors have been calculated and some of the same features noticed in M 92 can be seen. Fig. 17 shows the CM-diagram for M 15 and one can see the same tightly defined red giant branch, the blue horizontal branch and the group of stars ~ 1 mag fainter, below. M 15 is a much more difficult cluster in which to work since the field is very crowded. Stars well isolated from their neighbors are rare, unlike the case for M 92.

5. CCD PHOTOMETRY

One should be aware of all the problems listed in Section 2. But with care, accurate CCD photometry can be performed. Frequent tests of the data should be made (including checking the bias and

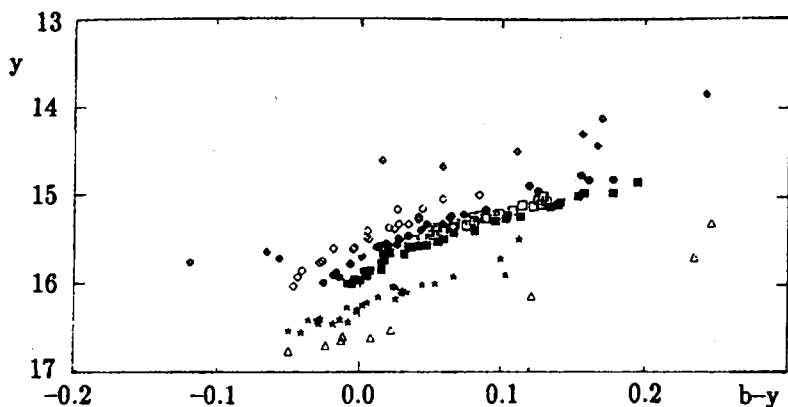


Fig. 14. CM-diagram for the blue stars in M 92. The stars on the ZAHB are indicated by solid squares. More luminous stars are represented by solid circles, hollow circles and diamonds. Two groups of stars less luminous than the ZAHB are represented by star symbols and hollow triangles.

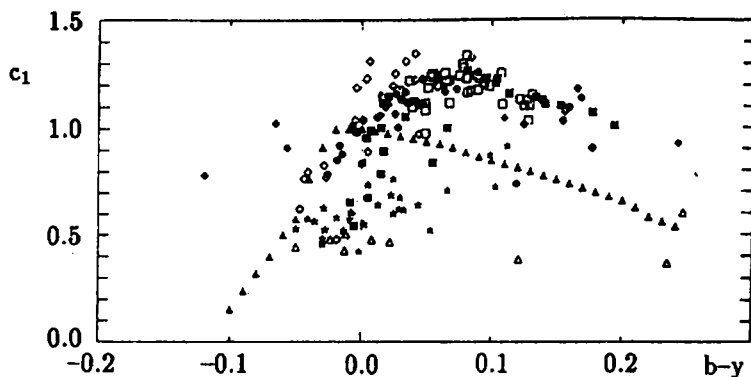


Fig. 15. c_1 vs $(b-y)$ diagram for the blue stars in M 92. The symbols are the same as in Fig. 14.

flatfield frames). It helps to measure stars in a narrow spectral range, as is the case in the present investigations of horizontal branches. All the precepts of photoelectric photometry should be obeyed. Standards, which cover the range of temperature and luminosity of the stars being investigated, should be observed. For CCD photometry this means that astronomers will have to create sets of new, fainter standards. Fields containing early- and late- type stars should be set up in regions of intermediate declination, spaced in right ascension so

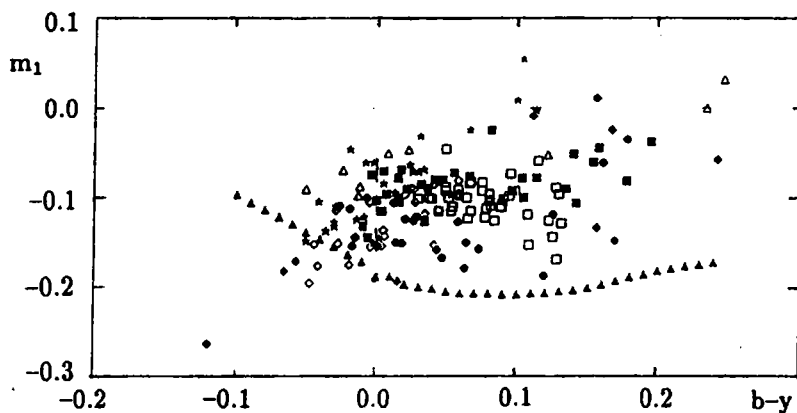


Fig. 16. m_1 vs $(b-y)$ diagram for the blue stars in M 92. The symbols are the same as in Fig. 14.

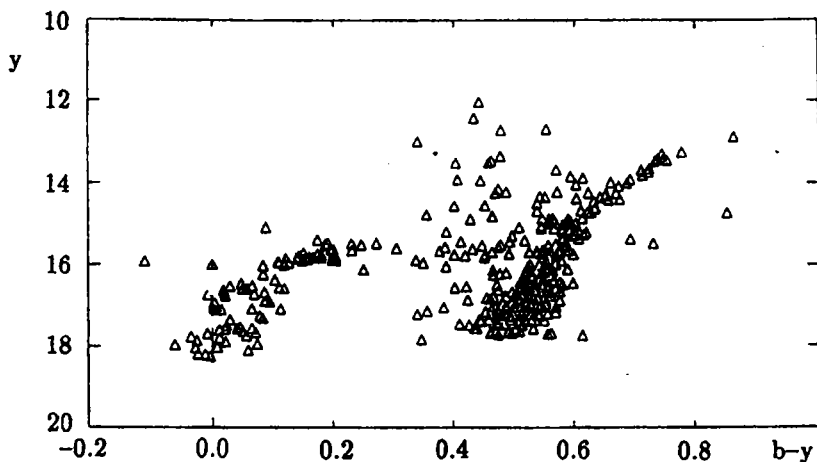


Fig. 17. Four-color CM-diagram for the globular cluster M 15. Instrumental magnitudes and colors are plotted.

they can serve as standards for southern and northern observations at any time of the year.

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