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PHOTOMETRIC CLASSIFICATION OF STARS ON THE BLUE HORIZONTAL BRANCH

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RESUMEN

Se realizó fotometría Strömgren *uvby* con un CCD para algunos cúmulos globulares, en los observatorios KPNO y CTIO. Las primeras observaciones se hicieron con un CCD RCA de dimensiones efectivas de 322 × 511 pixeles, equivalente a un campo de 2.8 × 4.0 minarc^2 para un telescopio de 0.9-m. En M22 se encontraron en un sólo campo 12 estrellas de la rama horizontal azul (BHB), pero en algunos de los otros cúmulos se encontraron sólo 6 estrellas BHB y cuando estas estrellas se separan en dos grupos, las estadísticas son poco significativas. Los detectores CCD RCA son poco sensibles en el ultravioleta y no se pudieron obtener magnitudes u confiables; el índice c_1 no fue calculado. En los diagramas $(b-y), m_1$ la distribución de estrellas BHB en distintos cúmulos muestra rasgos comunes. Se observa una distribución estrecha de puntos sobre una envolvente inferior y arriba de ella hay otros puntos más brillantes al menos 0.2 mag. La interpretación de esta distribución es que los puntos en la envolvente inferior representan estrellas de la rama horizontal de edad cero, evolucionando hacia el azul. Los puntos dispersos arriba representan estrellas más viejas que evolucionan hacia la rama asintótica roja. Por lo tanto, por medio de la fotometría *uvby* se pueden distinguir estrellas en la rama horizontal en distintos estados evolutivos.

ABSTRACT

CCD Strömgren *uvby* photometry has been done on a number of globular clusters at KPNO and CTIO. The first CCD observations were made with an RCA chip with effective dimensions of 322 × 511 pixels, giving a viewing area of 2.8 × 4 arcmin^2 with a 0.9-m telescope. In M22, 12 blue horizontal-branch (BHB) stars were found in one field, but in some of the other clusters only 6 BHB stars were found and when these stars are broken into two different groups the statistics become very poor. The RCA chips were insensitive in the uv and no reliable u magnitudes could be obtained; thus no c_1 index could be calculated. In $(b-y), m_1$ diagrams the distribution of points representing BHB stars in different clusters showed common features. There was a tight distribution of points on a lower envelope and above this relation there were other points, 0.2 mag or brighter. The interpretation of this distribution is that the points falling on the lower relation represent stars that are on the zero-age horizontal branch, evolving to the blue. The points scattered above represent more evolved stars that are evolving back up towards the red asymptotic branch. Thus, *uvby* photometry can distinguish stars of different evolutionary stages on the horizontal branch.

Key words: **STARS: HORIZONTAL BRANCH — TECHNIQUES: PHOTOMETRIC — GLOBULAR CLUSTERS: INDIVIDUAL (NGC 1904, M92)**

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[1]The facilities of the National Optical Astronomical Observatories (KPNO and CTIO) were used for the observations and the facilities of the Dominion Astrophysical Observatory for the data reductions.

1. SINGLE CHANNEL PHOTOMETRY

Strömgren *uvby* observations have been made with single-channel photometers on the 90-in Steward Observatory and the CTIO 60-in telescopes. The clusters investigated were M4, M13, M55 and M92 (Philip 1987). The probable errors of a single measure were about +0.04 mag and the probable error of the mean of six observations was +0.014. Stars with only two measures each were not plotted because their mean errors were too high. Accurate astrophysical parameters could not be calculated for the blue horizontal branch (BHB) stars because the range of possible $T_{\rm eff}$ and log g values was too large. The number of stars investigated was small.

The *uvby* photometry did indicate that the distribution of field horizontal-branch (FHB) stars and that of BHB stars in globular clusters was the same in the *uvby* diagrams. The main difference was a somewhat higher scatter in the BHB star diagrams, due to the fainter magnitudes of these stars relative to the FHB star group. Other indications of the similarity of FHB stars to BHB stars were: 1. The high z velocity dispersion of FHB stars at the galactic poles, matching the velocity dispersion of Pop II stars, 2. The low calcium abundance of FHB stars as determined from low-dispersion dispersion spectra, 3. Photoelectric scans of FHB and BHB stars made at Palomar show sets of FHB stars that have identical relative intensities, within +0.02 mag, with regard to BHB stars in globular clusters (Philip & Hayes 1984; Hayes & Philip 1984).

2. CCD PHOTOMETRY

In the 1980's CCD photometers became available at KPNO and CTIO and time was requested for the BHB star program. First a RCA chip, which had an effective size of 322 x 511 pixels, giving an area on the sky of about 4 x 2.8 minutes of arc a 0.9-m telescope, was used. Only a portion of a cluster could be observed in one frame and this meant only a few BHB stars could be measured at one time. The RCA chips were not very sensitive in the ultraviolet and in most of the clusters on the program c_1 indices could not be calculated. The gains in using the RCA chips were that stars as faint as $V = 17$ could be measured in y, b and v with internal probable errors under +0.01 mag. Stars closer to the cluster center were identified and measured. Frames in the globular clusters M4, M22, M55 and M92 were processed at DAO and reported in Philip (1988). In each of the color-magnitude diagrams a tight distribution of points was found as a lower envelope, curving from the right to the lower left. Above this relation were found other points, about 0.2 mag or brighter. In Figure 1. a combined diagram of BHB stars in the four globular clusters is shown. The dotted line indicates the lower envelope. The rms errors of the measures of y and $(b - y)$ were of the order of +0.01 mag so a difference of 0.2 is significant. In Figure 2 a set of Sweigart (1987) evolutionary horizontal-branch tracks are shown. For a Y of 0.3 and Z of 0.01 it can be seen that, no matter what the mass, stars begin on the ZAHB and then move along it towards the blue. Depending on the mass of the star, the track then turns up and to the right and the star begins its way towards the asymptotic giant branch. Orthogonal tick marks indicate intervals of 10^7 years.

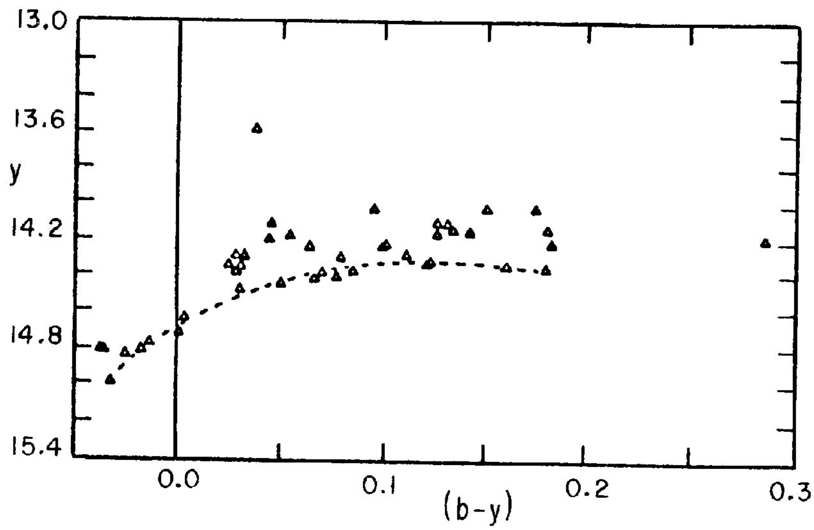

Fig. 1. Combined CM diagrams for four clusters.

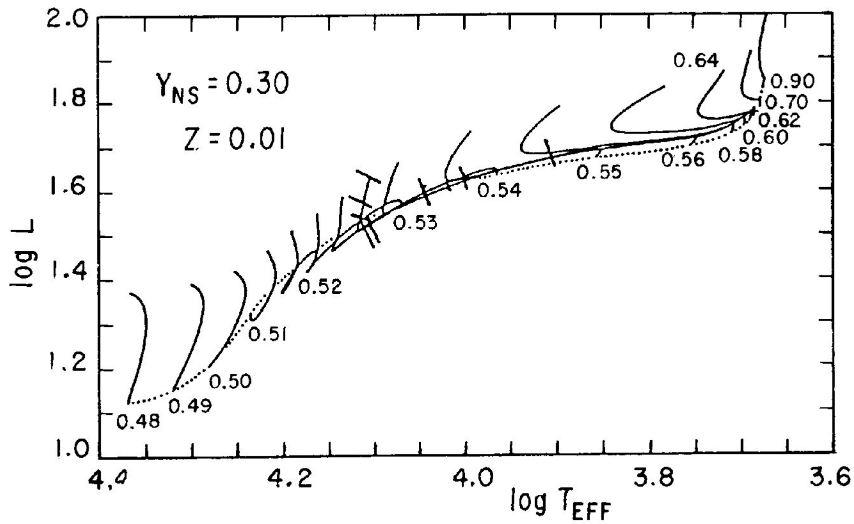

Fig. 2. Sweigart (1987) evolutionary tracks.

The main problem with the observations made with the RCA chip is one of statistics. There are not a sufficient number of BHB stars in the cluster frames taken with the RCA chip to make a firm indication of the distribution of stars on the horizontal branch. The best case is that of M22 where there were twelve BHB stars which separated into two clear groups. With the new chips now available, frames taken of globular clusters will include of the order of 100 BHB stars and definitive studies of the BHB star distribution will be possible.

2.1. NGC 1904

NGC 1904 is a southern globular cluster which is near the galactic anticenter. It was first investigated by Stetson & Harris (1977) who did *UBV* photometry of stars down to a $V = 16.5$ mag and *BV* photometry to $V = 17.0$ mag. The cluster is in an intermediate latitude field, has a small amount of interstellar reddening ([E$(B-V) = 0.01$]) and has a small contamination from field stars. The Color-Magnitude diagram for NGC 1904 is very like that of M13 Sandage (1977). Four-color CCD frames were obtained in y, b and v in a field that included the center and eastern edge of the cluster. About 30 BHB stars were located, making this cluster the one with the greatest number of stars in one frame obtained with the RCA chip in the current program.

The frames were reduced at the Dominion Astrophysical Observatory using Peter Stetson's program ALLSTAR to compute the y, b and v magnitudes. First the FIND program was used to compile a list of all the stars on the frame that could be measured. Then about two dozen, well separated stars, were selected as "PSF" stars and their three-dimensional profiles were calculated in the "PSF" routine which then formed the mean PSF profile used to measure all the stars on the FIND list. The y magnitudes were fit to the V magnitudes and the $(b-y)$ colors were fit to $0.7(B-V)$ colors of Stetson Ĥarris (1977). Figure 3 shows the $(b-y), y$ diagram for NGC 1904. On the right side the giant and asymptotic giant branches can be seen. To the left a strong horizontal branch extends from $y = 16$ to $y = 18$. Below the HB there are ten points that fall in the region $17 < y < 18$ and $0 < (b-y) < 0.3$. Each of these stars were checked on the original frames and they are each single stars and not located in the most crowded central regions of the cluster. It is possible that these stars are blue stragglers. This diagram resembles the diagram in Stetson & Harris (1977), which also has points falling below the HB. The Stetson-Harris diagram also shows a slanting lower envelope and then points that scatter above, 0.2 to 0.4 mag brighter than the lower envelope.

Figures 4 and 5 show a $(b-y), y$ and $(b-y), m_1$ diagrams for stars on the horizontal branch. Solid triangles represent BHB stars on the lower envelope. Crosses represent those more luminous stars, above the HB. Solid squares represent the stars falling below the HB. In each of the figures the points tend to fall together in groups. In the $(b-y), m_1$ diagram stars on the lower envelope in Figure 4 fall fairly close to a linear relation, sloping from the upper left to the lower right of the diagram. The stars redder than $(b-y) = 0$ fall in a region above the ZAMS (represented by the curved line at the bottom of the diagram). Eight of the ten stars represented by squares fall together in a group, close to the ZAMS relation, but with a different slope. Two stars (squares) have smaller m_1 indices. With frames containing 100 or more BHB stars, the distribution of points in the $(b-y), m_1$ diagram can be mapped more completely.

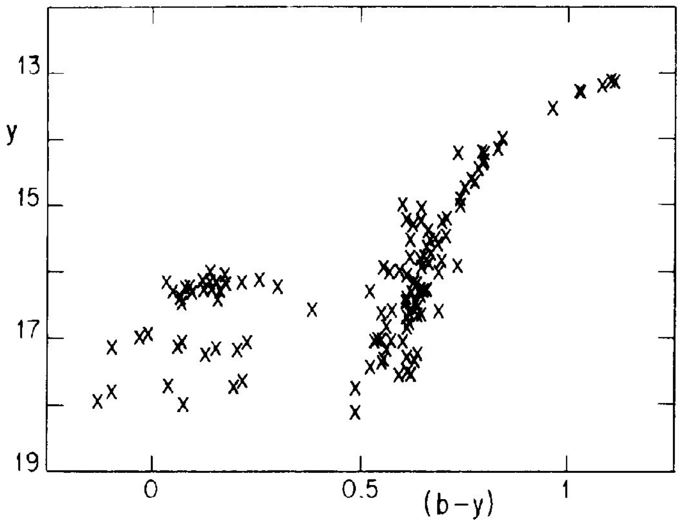

Fig. 3. CM diagram for NGC 1904.

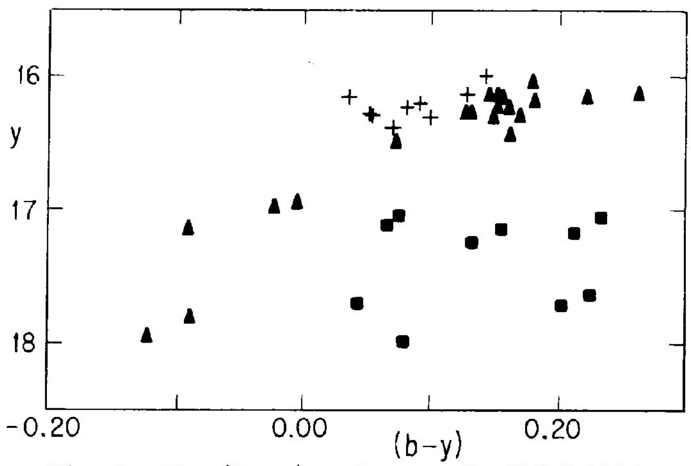

Fig. 4. The $(b-y), y$ diagram for NGC 1904.

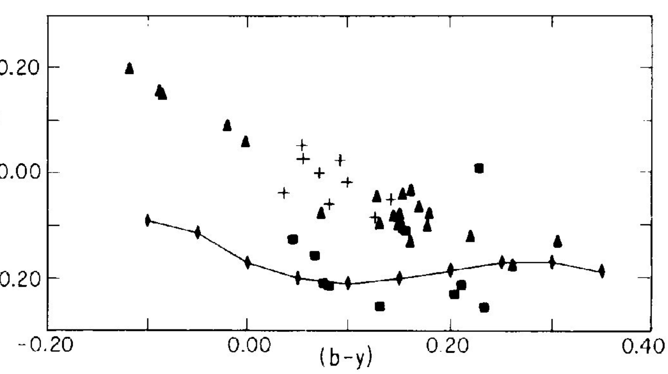

Fig. 5. The $(b-y), m_1$ diagram for NGC 1904.

2.2. M92

A set of *uvby* frames has been taken of M92 with the 2k × 2k Tek chip. The area covered was 17 arcmin^2 which allows all the stars in the cluster to be measured. Accurate u magnitudes were obtained and c_1 indices can be calculated for all the stars. Over 100 BHB stars have been detected (previously known BHB stars and many new BHB stars near the cluster center). I am especially interested to see how the natural groups distribute in the $(b-y), c_1$ diagram; if the frames are measured to the limit over 8000 stars can be identified. On a preliminary reduction session at DAO a catalog of 2000 stars was produced. On the next trip to DAO, ALLSTAR will be run to obtain the maximum number of stars. These new measures will be plotted to test the ability of *uvby* photometry to discriminate among stars of different evolutionary ages on the horizontal branch. With over 100 stars available this will be a significant test. Additional time will be requested to observe other globular clusters with strong blue horizontal branches.

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DISCUSSION

Herbig: Are those very high points on one of your globular cluster color-magnitude diagrams the so-called "ultraviolet-bright" stars? If so, what is the current evolutionary interpretation of such stars?

Philip: Probably the points that fall very high in the color-magnitude diagram are uv-bright stars, I believe such stars, found in many globular clusters, have evolved up the AGB and are now in a horizontal track across the H-R diagram. But such stars are very blue and I am not sure these stars are blue enough. It would help to have the u magnitude, which was not available from the RCA CCD chip.

Carrasco: From your diagrams it is apparent that there are too many stars lying above the zero age HB, that could be accounted for by the isochrone of the evolutionary tracks. Perhaps we should look for other physical parameters to account for that.

Philip: As I said in my talk, the combined diagram was the result of a statistically small sample and thus I do not expect it to show correct relationships in all aspects. For example, when I analyzed the first frame from M92 there were two stars possibly on the lower track and four stars on the upper track. However, with a sample of only six stars this result does not have much statistical significance. What has more significance are the plots for NGC 1904 in which there are 29 stars on the horizontal branch. Nineteen of these stars fall on the lower track and nine fall on the upper track so 31% of the stars fall above and 69% fall below. A very recent preprint from Yale (Koopmann et al. 1994, ApJ, 423, 380) shows in their Fig. 4 a standard model horizontal branch (similar to the Sweigart models). Between $(B-V)_0$ colors of 0 and 0.4 there are about 130 model points which separate into two groups. About 36% of the points fall in the upper group, a percentage close to that found in NGC 1904. Currently I am working on 2K × 2K frames of M92 which cover 17 minutes of arc across and include the entire cluster. Over 100 horizontal-branch stars have been found and when their distribution in the four-color CM diagrams is determined this will give the best statistical result found so far in this investigation.

Roman: In respect to the stars above the narrow sequence in the y vs. $(b-y)$ diagram. a) Can these stars be explained as binaries? b) If they result from evolution would you expect to have stars of different colors (and therefore, different masses) evolved from the "main horizontal branch sequence" by the same amount at a given time as shown on one of your diagrams?

Philip: I do not think these stars are binaries. I know of no report in the literature of an early-type binary in Population II, in a cluster or in the field. This does not mean they do not exist, but seems to indicate the numbers must be small. Eary-type stars of all masses in the ZAHB fall on the same ZAHB relation. At the turn-around point evolution speeds up. Depending on the mass, the turn-around point occurs at a different place in the $\log L - \log T_{eff}$ diagram. Thus you end up with a scatter of points above the lower relation.

Crawford: I (and others) will be interested in how uniform the PSF and the photometric indices are over the field of the Tek CCD chip.

Philip: My preliminary data from the Tek chip showed no serious problem with the PSF across the chip, so I used one average of the approximately 30 PSF stars used.

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