Extended Strömgren Photometry with CCD's

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Abstract

CCD's have made possible the extension of intermediate-band photometric systems, including the Strömgren *uvby* system, to larger, fainter and cooler stars, with successful applications in old disk and globular clusters. Some of the applications in globular clusters demonstrate the ability to remove foreground stars from photometric diagrams and have enabled a re-evaluation of the evolutionary correction needed for distance modulus determination for metal-poor stars. We have developed an additional index based on measurement of the Ca II H and K lines which retains sensitivity to metallicity changes for extremely metal-poor stars. Finally, we are testing the utility of CCD Hβ photometry in the unusual and old open cluster Melotte 66.

1. Introduction

Despite its enormous success, the Strömgren photometric system has suffered from a few limitations. The spectral range for which the system was originally developed and calibrated did not extend to cooler stars and therefore excluded much of the galaxy's history. Both theoretical models (Gustaffson & Bell 1979) and empirical applications (Eggen 1978) have shown that this restriction is unnecessary, and that *uvby* indices can yield useful information for G and K stars.

Narrower filters had also restricted *uvby* studies to relatively bright stars as well; in fact, rather few open clusters with turnoffs in the F-star range, well within the original realm of calibration, were accessible with phototubes as detectors. CCD's have eliminated this restriction and the Strömgren *uvby* system has been applied to fainter, cooler and more metal-poor stars with considerable success.

At halo metallicities, a different limitation is encountered which afflicts most photometric indices of metal abundance based on weak lines, a reduction of sensitivity to declining abundances below [Fe/H] ~ -2.0. We have ameliorated this problem by the introduction of a new index, *hk*, which retains sensitivity to metallicity changes below -3.0. The index is a color difference analogous to the m_1 index, with a 90Å bandpass which covers the Calcium II H and K lines replacing the v filter where most of the iron lines are clustered. We have described the system with a set of standards (Anthony-Twarog, Laird, Payne and Twarog 1991) and demonstrated its applicability to metal-poor red giants in Twarog and Anthony-Twarog (1991)

Extension of the Strömgren system by use of CCD's is not without some pain, however. Development of suitable standards for fainter and cooler programs has

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lagged. Most of our applications of CCD-Strömgren photometry have exploited the large dynamic range and high internal precision afforded by advanced detectors. We have happily encountered no evident difficulty with image structure in using filters even as narrow as the Hβ narrow filter.

2. Applications to Globular Clusters

CCD technology has brought the main sequences of globulars within the reach of intermediate-band photometric systems, permitting some membership discrimination for stars which may be too faint, crowded or numerous to permit proper motion studies or radial-velocity measures. NGC 6397 has provided the first, and one of the best proving grounds for Strömgren applications. In the second CCD-Strömgren study directed at this relatively nearby cluster, Anthony-Twarog, Twarog and Suntzeff (1992) surveyed six fields in the cluster with the original intent to confirm additional photometric main sequence binary candidates suggested by Anthony-Twarog (1987). In this application, the photometric reduction code *DoPhot* was used (Mateo and Schechter 1990). For the main sequence as well as for the giant branch, the m_1 index provides sufficient discrimination of cluster members from foreground stars to permit unusually clean color-magnitude diagrams (see Figures 3, 5 and 6 of Anthony-Twarog et al. 1992). The issue of possible main sequence binaries remains unresolved, however; the statistical incidence of photometric binary candidates is too close to the expectation for chance superposition of stellar images, and these faint weak-lined stars have proven too difficult for direct radial-velocity measurement.

ω Centauri has provided a very different set of challenges to the CCD-Strömgren system. Begun several years ago as a masters' thesis, Krishna Mukherjee's study of this famously inhomogeneous cluster was designed to measure the dispersion of heavy elements among the main sequence stars. For this application, internal precision was considered more important than the accuracy of the external calibration. We followed our usual practice of **not** averaging CCD frames prior to processing or reduction. Our software uses the positional correlation between frames to match and average measurements for each star in each color before index construction. Any small zero-point shifts between similar frames can be removed this way, and the errors constructed reflect the realistic repeatability of measurement for each star. We "rediscovered" one variable dwarf Cepheid by sifting through our set of stars with anomalously large standard deviations. By comparing our assessment of measurement errors in $b - y$ and m_1 for upper main sequence stars, 0.015 and 0.017 respectively, we were able to show that the intrinsic dispersions in both these indices imply an intrinsic spread in iron-peak elements of 0.7 to 1.0 dex, entirely consistent with results from studies of the cluster's evolved stars (Mukherjee, Anthony-Twarog and Twarog 1992).

One unanticipated result from the ω Centauri study emerged from the upper main sequence surface gravity indices, which were initially scrutinized to see any discernible evidence for an age spread among the turnoff stars (none was found). Figure 6c of Mukherjee et al. (1992) shows the progression of c_1 values along the upper 1.5 mag of the nearly vertical turnoff, with the expected increase in c_1 for more evolved stars. The Strömgren system permits the determination of individual distance moduli, based on the difference δc between a star's c_1 value and the ZAMS value for its temperature; the absolute magnitude for the star's temperature is then corrected by an amount $f\delta c$. ω Cen has provided the first high-quality determination of f for metal-poor F stars, and the implied value of 8 differs from values derived in disk clusters. The temperature-dependent characterization of f derived by Nissen, Twarog and Crawford (1987) has been verified in model computations by Bell (1988) for solar and slightly metal-poor compositions, but predicts a value of 12 for F stars at the turnoff color of ω Cen. Interestingly, Allen, Schuster and Poveda (1991) noted in their analysis of photometric parallaxes for halo stars based on $uvby\mathrm{H}\beta$ data, that their derived absolute magnitudes for subdwarfs are too bright, equivalent to use of evolutionary corrections based on overly large f values.

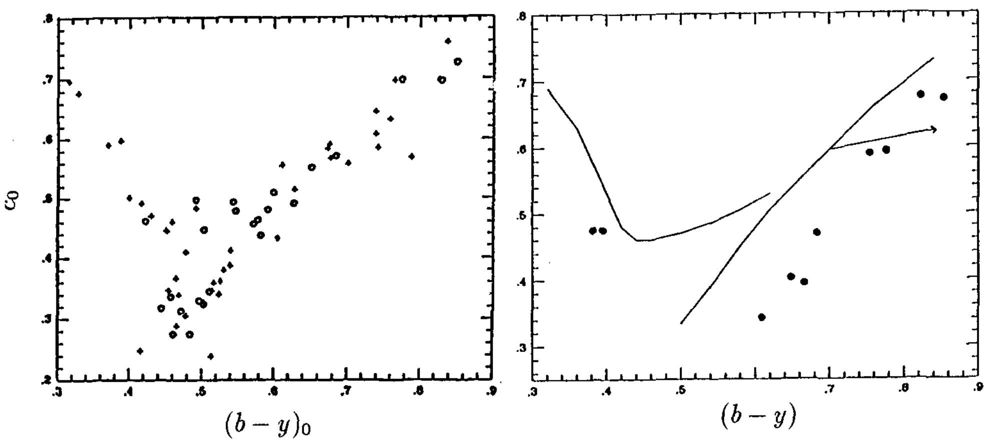

Figure 1 On the left, c_0 and $(b-y)_0$ values for field metal-poor giants. Circles indicate stars with [Fe/H] < -2.0. The right-hand panel shows a comparable diagram for photoelectric data in the cluster NGC 6397. The vector shows the shift direction for the field star sequence for $\mathrm{E}(b-y) = 0.10$

Many of these applications in globular clusters are anchored with photoelectric photometry, and until recently, our *Ca* filter data was entirely photoelectric. In the course of photoelectric observations with the the *uvbyCa* system of the widely scattered metal poor red giant sample, we noted a peculiar morphology in the $c_1, b-y$ diagram for field metal-poor giants. Figure 1a shows the reddening-corrected values for a large sample of giants, with photometric values from Twarog and Anthony-Twarog (1991). Stars with spectroscopically determined [Fe/H] values < -2.0 are noted with circles, while more metal-rich stars are noted with crosses. The implication of a metallicity-independent pseudo-HR diagram for halo giants provided one

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strong motivation to extend our Strömgren studies to globular clusters, with uniformly determined reddenings the expected payoff.

The typically perverse result, at least for NGC 6397 where our photoelectric indices are reliably tied to our larger field star system, is that cluster $c_1, b-y$ diagrams may well be different from the field! In Figure 1b we have reproduced the field star $c_1, b-y$ relation with the photoelectric data obtained for giants in NGC 6397. The reddening vector indicates the direction of shift for a value of $E(b-y) = 0.10$, smaller than the likely value of 0.14 for the cluster. The cluster stars evidently define a steeper relation than the field giants, and the two bluer AGB stars would lie far off the reddening-adjusted field star sequence.

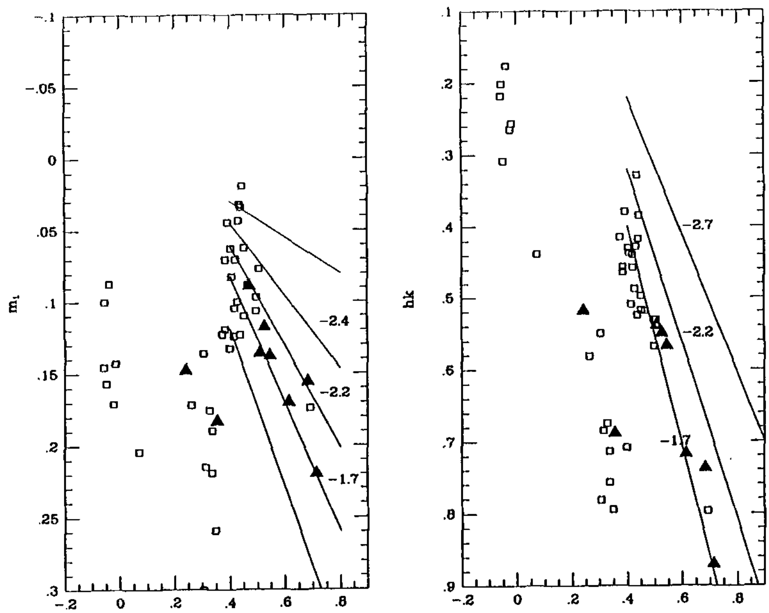

Figure 2 Metallicity indices m_1 and hk versus $b-y$ for giants in NGC 6397. Dark symbols represent results of photoelectric photometry, while the remaining points are from one CCD field in the cluster. In both diagrams, reddening corrections consistent with $E(b-y) = 0.14$ have been applied to the data. The linear sequences have been developed from observations of field stars with well-determined abundances, and are labeled with [Fe/H] values.

While we have not yet resolved this fascinating discrepancy, we have pursued CCD extensions in this and other globular clusters. Results from one field in NGC 6397 are presented here. We have found that the *hk* index not only provides superior metallicity information for the giants but provides cleaner membership discrimination as well. Figure 2 shows companion diagrams of the metallicity indices m_1 and hk as functions of $b-y$ color. The photoelectric data in the cluster are echoed here with darkened symbols and have been used to provide a provisional calibration of the CCD data. The linear sequences are isometallicity sequences based on data for

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field stars with spectroscopic abundance determinations and indicate a metallicity of -1.85 ± 0.10 for the cluster, based on the photoelectric data alone. The CCD sample is dominated by more faint giants, clustered near $(b-y)_0 \sim 0.4$. The brightest giant in this sample appears to conform to the appropriate isometallicity relation. Apart from horizontal branch stars in the upper left part of the $hk, b-y$ diagram, most of the other stars appear to be non-members.

3. Hβ Photometry in Melotte 66

The class of very old disk clusters is an exceedingly small one, and Melotte 66 has always appeared to be one of the most interesting. In photographic studies (Hawarden 1976; Anthony-Twarog, Twarog and McClure 1979) as well as more contemporary CCD surveys (Kaluzny and Shara 1988) the main sequence and giant branch display a width reminiscent of the chemically inhomogeneous globular cluster ω Centauri, although to a lesser extent. In spite a fairly large reddening (E$(B-V) \sim 0.14$ to 0.17), previous studies indicated that the breadth of the sequences is not due entirely to variable reddening. We have confirmed this is in a definitive and novel manner by one of the first large applications of Hβ photometry with CCD's.

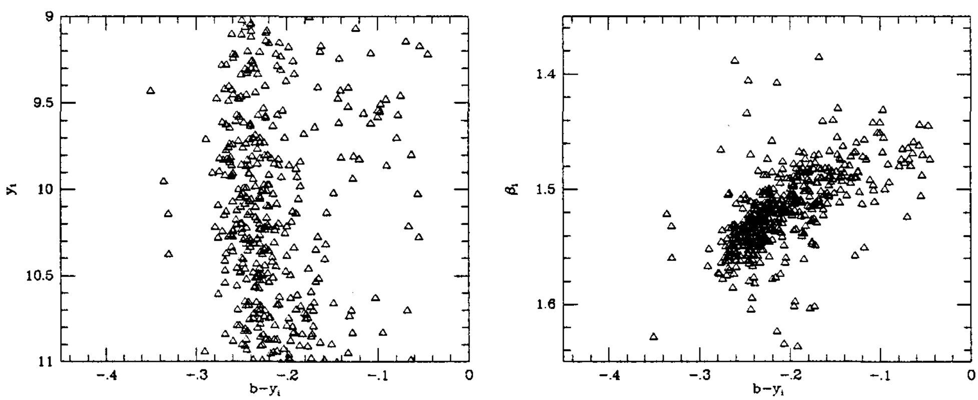

Figure 3 On the left, an instrumental color-magnitude diagram for Melotte 66 covering the turnoff region from $V \sim 16.5$ to 18.5. The right-hand panel shows the correlation between instrumental indices β_i and $b-y$ for the same sample.

Figure 3a shows a portion of the instrumental color-magnitude diagram, y_i versus $(b-y)_i$. The corresponding cmd with β as the temperature index is nearly indistinguishable over this nearly vertical stretch near the turnoff. Measurement errors in both indices for this range of magnitudes are about 0.01. There is a striking correlation between β_i and $(b-y)_i$, showing clearly that within the considerable breadth of this upper main sequence, **redder** stars are in fact **cooler** stars; if variable reddening

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were the cause of the main sequence width, no correlation would be expected. There is no obvious correlation between temperature indices β or $b - y$ and the metallicity index, so we cannot yet describe a cause for this sizeable temperature range at the turnoff of this very old cluster.

We want to acknowledge Stephen Shawl's collaboration on the Melotte 66 project, and to indicate our very large debt to the several students at the University of Kansas who have cheerfully assisted in data reductions over the past few years, especially Jackie Milingo, Marian Sheeran and Robert Stewart. We have depended heavily on photometric codes developed by Peter Stetson (DAOPHOT) and by Paul Schechter with Mario Mateo (DoPhot), and we can't thank them enough.

References:

Allen, C., Schuster, W.J., Poveda, A., 1991, Astron. Astrophys., **244**, 280.

Anthony-Twarog, B.J., 1987, Astron. J., **93**, 1454.

Anthony-Twarog, B.J., Laird, J. B., Payne, D.M., Twarog, B.A., 1991, Astron. J., **101**, 1902.

Anthony-Twarog, B.J., Twarog, B.A., McClure, R.D., 1979, Astrophys. J., **233**, 188.

Anthony-Twarog, B.J., Twarog, B.A., Suntzeff, N.B., 1992, Astron. J., **103**, 1264.

Bell, R. A., 1988 Astron. J., **95**, 1984.

Eggen, O.J., 1978, Astrophys. J., **221**, 881.

Gustafsson, G., Bell, R.A., 1979, Astron. Astrophys., **74**, 313.

Hawarden, T.G., 1976, MNRAS, **174**, 471.

Kaluzny, J., Shara, M.M., 1988, Astron. J., 95, 785.

Mateo, M., Schechter, P., 1990, *Proceedings of the First ESO Workshop on Data Analysis.*

Mukherjee, K.M., Anthony-Twarog, B.J., Twarog, B. A., 1992, PASP, in press.

Nissen, P.E., Twarog, B.A., Crawford, D.L., 1987, Astron. J., **93**, 634.

Twarog, B.A., Anthony-Twarog, B.J., 1991, Astron. J., **101**, 237.

Discussion

E.F. Milone: *Your colour-magnitude diagram of NGC 6397, where you showed a variable blue straggler, had a circle around two stars. Are they the two blue stragglers?*

Anthony-Twarog: We recovered one variable blue straggler, E39, an AI Velorum star, and also discovered one additional non-variable blue straggler.

W. Tobin: *Do you have any experience as to whether interference filters are sufficiently uniform for there to be no transformation problems as a function of location on the chip?*

Anthony-Twarog: I don't, and I'm not sure that it would be determinable given the standards which have been available.

T.J. Kreidl: *I've done Strömgren photometry of some open clusters and compared the photometry with published photoelectric photometry. I have seen no obvious, systematic, deviations. One should be cautious, however, that the filters are of the highest possible quality to ensure minimal variations over the field.*

A.T. Young: *I would like to make a further comment on interference filter variations. Laboratory measurements show a spatial variation of a few Å in a centimetre or so. I would recommend placing a filter at a pupil image, rather than near the field image.*

R. Florentin-Nielsen: *If you put the filter in the pupil plane, you will have a field dependance of the bandpass due to the fact the angle of incidence of light onto the filter will be different between the different position in the field. It may be safer to just have the filter a fair distance in front of the CCD and map the throughput effects.*

Anthony-Twarog: The angular effects can be kept small by using a large filter and pupil image. Conservation of throughput then ensures small angular effects.