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Photometric performance of the CCD detector at the Kavalur 102 cm reflector

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Abstract. A CCD detector system built around the Thomson TH 7882 chip has recently been acquired for use at the 102 cm telescope at the Vainu Bappu Observatory (VBO). The chip has a coating for enhanced ultraviolet sensitivity, making it a viable system for two-dimensional imaging in the wavelength range of $\sim$ 0.3–1 μm. Observations of stars in open cluster M67 standard field were carried out on two nights with U, B, V, R filters to evaluate the performance of the system. The use of this chip for standard astronomical photometry, to our knowledge, has not been reported earlier.

Key words : CCD detector — stellar photometry

1. Introduction

A charge coupled device (CCD) detector system was recently commissioned for use on the 102 cm telescope at the Vainu Bappu Observatory (VBO) in Kavalur. A detailed description of the system and its characteristics has been given elsewhere (Pati 1988). The system uses the Thomson-CSF TH 7882 CCD chip coated for enhanced sensitivity to ultraviolet radiation. The evaluation of the performance of this chip in astronomical photometry has not been reported anywhere. Observations with an intent to evaluate the photometric calibration of the system were carried out in 1988 March and the results obtained are presented here.

2. Selection of standard sequences

The photometric calibration of any detector system requires observations of standard stars with known accurate photometric magnitudes. Such standards are available in the E-regions (see Graham 1982; Menzies & Laing 1985 and references therein) as well as in the equatorial region (see Landolt 1983; Cousins 1984 and references therein). The advantage of using these standards is the high accuracy of a few thousandths of a magnitude and the large range in colour spanned by the different stars; the disadvantage is that single stars do not tell much about the chip as a whole and are wasteful in terms of observing time.

An alternative is to observe fields which have several accurately measured stars within the area of the sky projected onto the CCD chip, preferably spanning a large range in colours and a relatively small range in magnitudes, so that the zero points and the colour equations can be determined from a small number of exposures. Such fields have been set up recently by Schild (1983), Christian *et al.* (1985) and Stobie *et al.* (1985) among others. Except in the field set up by Schild (1983), the stars are mostly faint, not well-suited for initial system calibration for a telescope of 1m aperture; also, in some fields, the range in colour of the stars is limited. Consequently, for this work the region measured by Schild (1983) in the open cluster M67 (NGC 2682 ≡ C0848 + 119) was chosen. This field contains standard stars in the brightness range $9.6 < V < 13.3$ and colour range $-0.1 < (B - V) < 1.4$, with photometric accuracies at the 1 % level.

3. Observations

The observations were carried out on the nights of 1988 March 17 and 18 with the CCD dewar mounted directly after the offset guiding unit at the f/13 Cassegrain focus of the 102 cm reflector. The pixel size of 23 μm^2 corresponds to 0.357 arcsec square on the sky (image scale 15.56 arcsec mm^{-1}); the chip size of 384 by 576 pixels covers an area on the sky of 137 arcsec by 206 arcsec. The observations were carried out with the CCD chip at a temperature of -120 ± 1 C. There were no detectable bad columns or hot spots on the chip as seen from displays of dark, bias and object frames.

Since filters optimized for the CCD chip were not yet available, existing Schott glass filter combinations used for *U*, *B*, *V*, *R* photometry with the EMI 9658 photomultiplier tube were used. The filter combinations as prescribed by Fernie (1974) are :

Standard band	*Filter combination*
U	UG–1, 2mm + BG–18, 2mm
B	BG–12, 4mm + BG–18, 2mm + GG–4, 1mm
V	GG–14, 3mm + BG–18, 2mm
R	OG–550, 2mm + RG–6, 1mm

The details of observation of the M67 standard field are given in table 1. In addition, six bias frames spread over the entire observing time, five dark frames with exposure times ranging between 10 to 300 s and three sets of flat-field exposures (each set through four filters), two on 1988 March 18 and one on 1988 March 17 were taken. The flat-field exposures were made on the twilight sky after sunset and before sunrise with the ambient brightness allowing exposures ranging between 2 and 30 s. These exposures were good enough to produce significant counts per pixel without recording faint stars in the field. The

Table 1. Observational details of M 67 field

	Filter	Exposure, s	Frames
1988 March 17			
	V	20	1
	V	40	1
	R	20	1
	R	10	1
	R	5	1
	B	20	1
	B	40	1
	B	120	1
1988 March 18			
	V	10	1
	V	20	5
	B	40	1
	B	80	5
	R	10	5
	U	300	1
	U	900	5

average seeing during the observations was judged to be in the range 1.5 to 2 arcsec.

4. Reduction of the data

Since the method of reduction is important in determining the final accuracy obtained, we outline it in some detail. The average counts per pixel in the bias frames were about 340 (ADUs — analog to digital units) with a variation of less than 0.5 % over the two nights. The average counts per pixel for the dark frames had the same value as for the bias with no dependence on exposure time. The above considerations exclude the occurrence of cosmic ray events which were removed during subsequent steps in the reduction procedure. To perform bias and dark subtraction, a constant value of 340 was subtracted from all flat-field and object exposures. The dark counts were not subtracted since they did not show significant excess over bias and no variation from pixel to pixel. Especially since the stellar photometry program used here fits a local sky background, this procedure has been found to be satisfactory.

The flat field exposures were then cleaned and smoothed to remove sharp events such as the ones caused by cosmic rays, and then normalized. The two sets of flat field exposures of March 18 were averaged. This processing ensures that less noise is introduced into the data in the process of flat-fielding and improves the accuracy in the estimation of magnitudes for faint stars. The object exposures through a given filter were divided by the normalized flat field taken through the same filter. The evenness of response of the chip both overall and pixel-to-pixel (see Pati 1988) enabled object frames to be flattened to better than 2 to 4 % in *U*, *B*, *V* and *R*. None of the image frames showed any evidence of fringing.

The next step in the procedure entailed the fitting of the stellar intensity profile using a two-dimensional, iterative, linearized least squares technique and a Gaussian profile with the intensity distributions in two dimensions being given by

$$I(x, y) = I_0 \exp\left[-\left\{\left(\frac{x - x_0}{R_x}\right)^2 + \left(\frac{y - y_0}{R_y}\right)^2\right\}\right] + \text{constant},$$

where I_0, R_x, and R_y are the parameters of the Gaussian; and the constant is the local value of the sky. x_0 and y_0 are the positions of Gaussian maximum. In uncrowded fields the error in stellar photometry can be considerably reduced if the stars used to establish the parameters of the Gaussian profile have a high signal-to-noise ratio in the wings. We, therefore, fitted the profile to the sum of several bright stars in each frame, each scaled to the same value at maximum. The resulting profile parameters were then used for all the stars in the frame. Compared to the procedure involving the fitting of individual profiles for each star, the procedure used here yielded more accurate magnitudes, especially for the fainter stars.

In the general case, the instrumental magnitudes for different exposures of the same field would be different depending on atmospheric extinction and exposure time. In the subsequent procedure, the mean difference in magnitude for all stars chosen for a given frame vis-a-vis a reference frame taken close to the zenith (air mass = 1.003) was calculated. This difference was subtracted out and a similar process employed for all frames for a given filter. The average instrumental magnitude over all frames for a given filter were then determined with the zero point being that for the reference frame. It was thus not necessary to obtain atmospheric extinction corrections for individual frames as well as to correct the instrumental magnitudes for exposure time. This procedure is especially useful when the sky is not of uniform photometric quality throughout the night, as was the case during our observing run.

The above photometric reductions were effected using the STARLINK software package running on the VAX 11/780 system at VBO. The procedures requiring display and interaction with the image frames were done outside the STARLINK package, using the COMTAL Vision One image display station.

5. Colour equations

The colour equations were derived using 11 stars in the field for which Schild (1983) gives B, V and R magnitudes with an accuracy of 0.01 to 0.02 mag. $(U-B)$ magnitudes for these stars are taken from Eggen & Sandage (1964) and have an accuracy of 0.03 to 0.04 mag. The differences in magnitudes and colours in the sense standard minus instrumental are plotted versus the $(B-V)$, $(V-R)$ and $(U-B)$ colours in figures 1 and 2. Using a linear, least squares regression, the following relations were derived:

$$U - u_1 = 0.04\ (\pm 0.036)\ (U - B) - 9.76\ (\pm 0.020)$$

$$B - b_1 = -\ 0.04\ (\pm 0.030)\ (B - V) - 10.53\ (\pm 0.022)$$

$$V - v_1 = 0.04\ (\pm 0.021)\ (B - V) - 10.17\ (\pm 0.015)$$

$$R - r_1 = 0.57\ (\pm 0.028)\ (V - R) - 9.56\ (\pm 0.01)$$

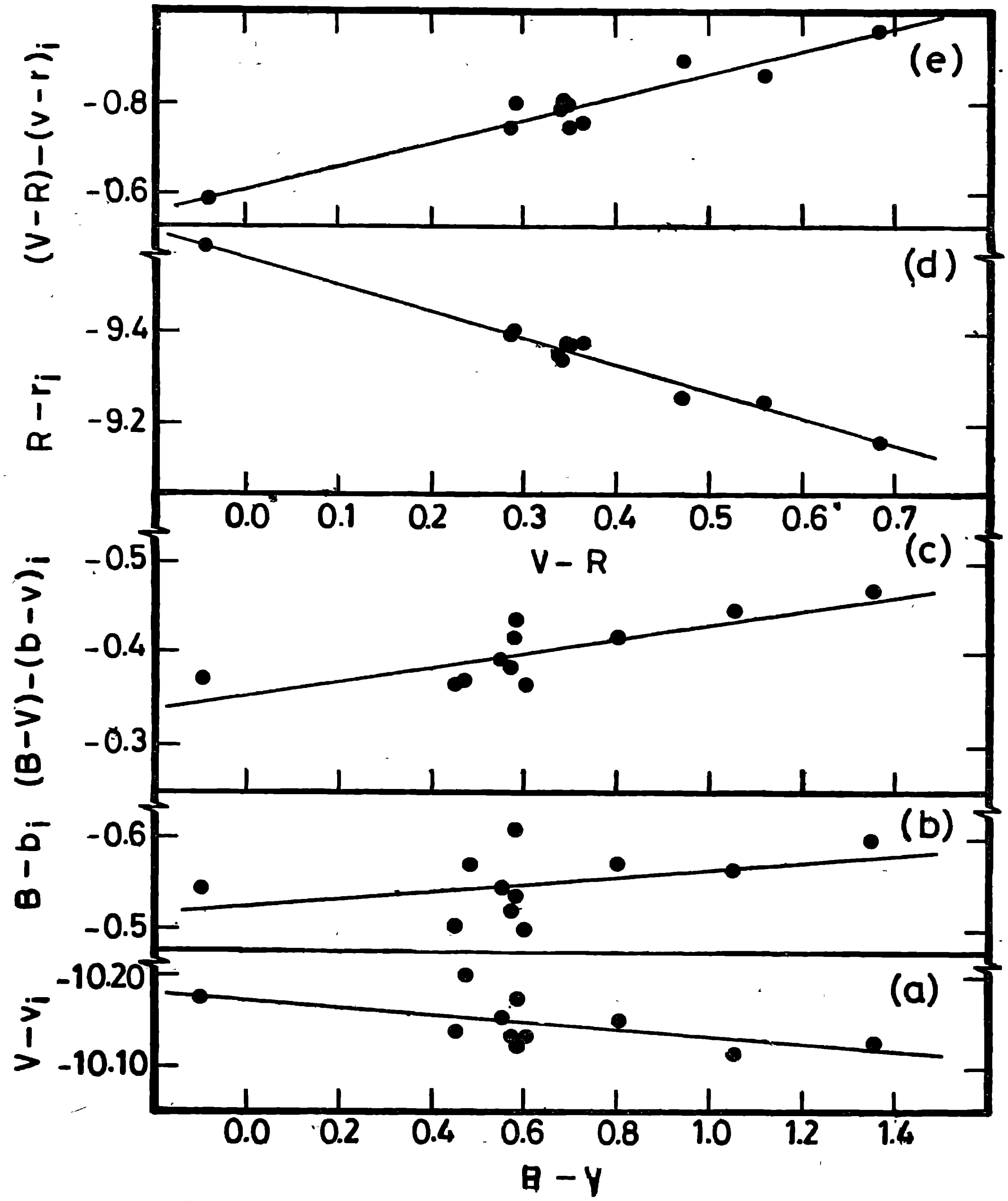

Figure 1. Plots of $V - v_{\text{i}}$; $B - b_{\text{i}}$; and $(B - V) - (b - v)_{\text{i}}$ against $(B - V)$ are shown in (a), (b) and (c) while those of $(R - r_{\text{i}})$ and $(V - R) - (v - r)_{\text{i}}$ against $(V - R)$ are shown in (d) and (e).

for U, B, V and R magnitudes; and

$$(U - B) = 1.08\,(\pm 0.027)\,(u - b)_{\text{i}} + 0.85\,(\pm 0.026)$$
$$(B - V) = 0.93\,(\pm 0.018)\,(b - v)_{\text{i}} - 0.33\,(\pm 0.015)$$
$$(V - R) = 0.67\,(\pm 0.022)\,(v - r)_{\text{i}} - 0.41\,(\pm 0.019)$$

for $(U - B)$, $(B - V)$ and $(V - R)$ colours.

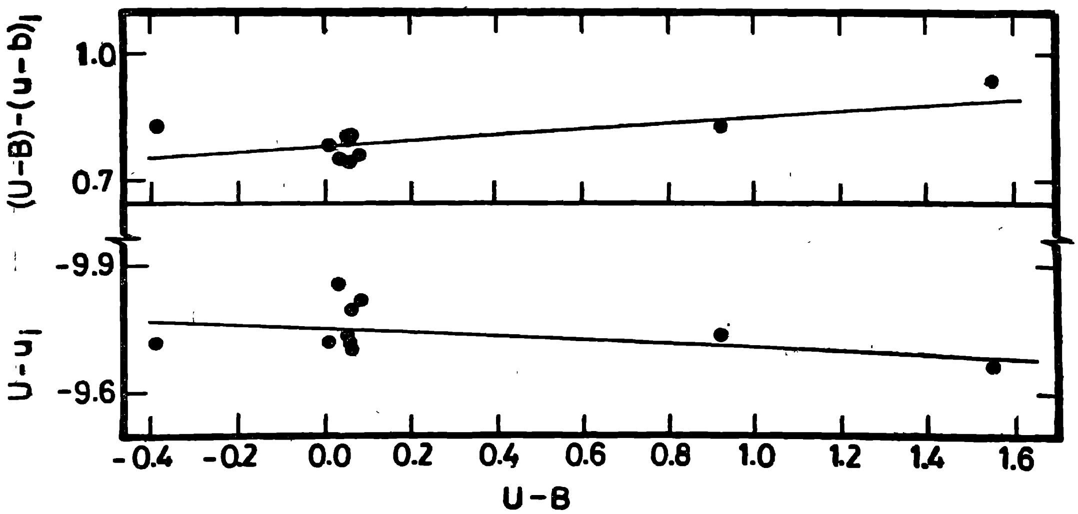

Figure 2. Plots of $U - u_l$ and $(U - B) - (u - b)_l$ against $(U - B)$.

6. Accuracy of the results

We list in table 2 the derived *U, B, V, R* magnitudes for all stars in the M 67 field using the transformations given above. The residuals in magnitudes between values derived here and those given by Schild (1983) and Eggen & Sandage (1964) are plotted in figure 3 as a function of brightness and colour. There is no systematic dependence on either colour or magnitude. The standard deviations in magnitudes and colours are

$$\begin{aligned} V &; \ 0.323 \text{ mag} \\ (B - V) &; \ 0.021 \text{ mag} \\ (U - B) &; \ 0.037 \text{ mag} \\ (V - R) &; \ 0.020 \text{ mag.} \end{aligned}$$

Table 2. Derived *U, B, V, R* magnitudes

Star number Present	Schild (1983)	*V* (mag)	$(B - V)$ (mag)	$(U - B)$ (mag)	$(V - R)$ (mag)
1		13.13	0.58	0.99	0.58
2		13.28	0.59	0.00	0.38
3	135	11.46	1.06	0.96	0.54
4	134	12.27	0.56	0.06	0.34
5	128	13.15	0.60	0.05	0.32
6	129	13.20	0.57	0.07	0.33
7	130	12.92	0.43	0.03	0.27
8	127	12.82	0.55	0.12	0.35
9	124	12.20	0.45	0.14	0.31
10	117	12.69	0.81	0.41	0.50
11	106	13.13	0.62	0.09	0.35
12		13.96	0.56	0.25	0.34
13		12.74	0.59	0.05	0.33
14	108	9.71	1.37	1.52	0.68
15		12.41	0.71	0.22	0.41
16		14.19	0.79	0.16	0.40
17		13.23	0.60	0.03	0.35
18	81	10.01	−0.07	−0.44	−0.08

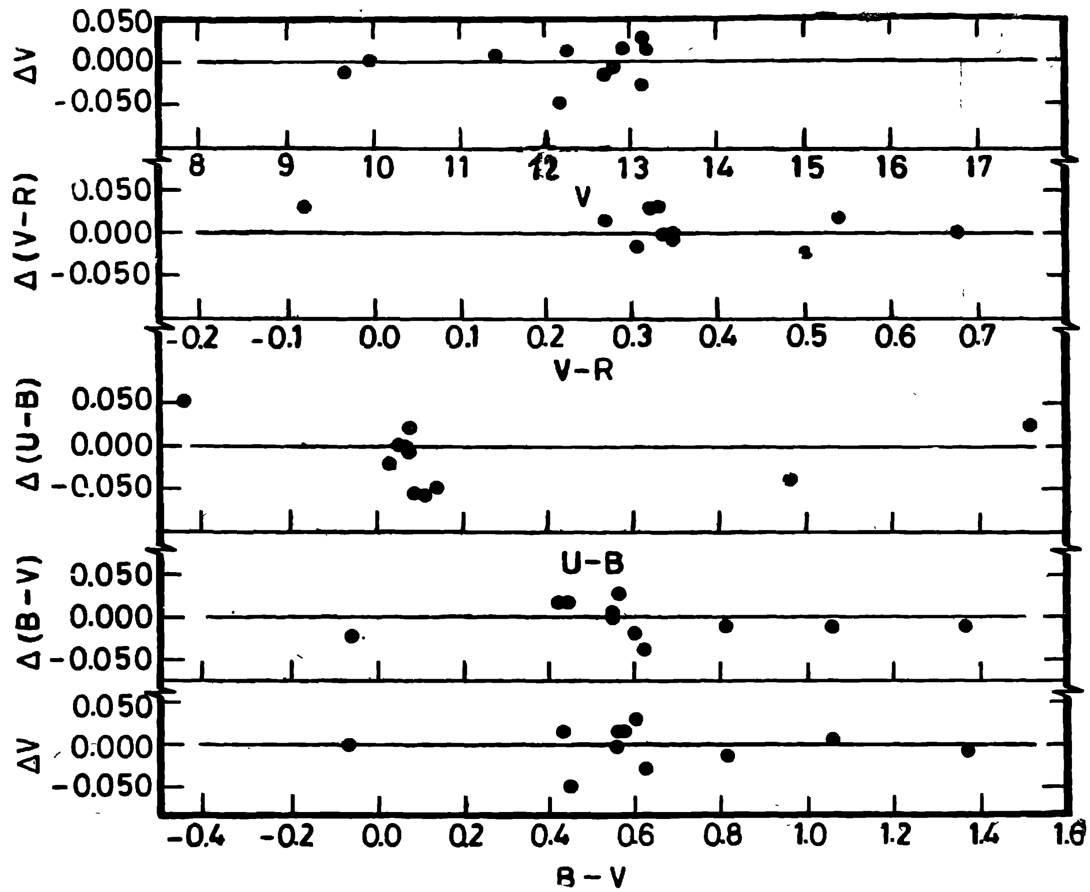

Figure 3. The differences Δ between standard values and present measurements are plotted against magnitude and colours.

7. Summary and discussion

The observations reported above show that the *U*, *B*, *V*, *R* instrumental magnitudes can be calibrated with an accuracy of about 3%. The transformation coefficients indicate that the filter combinations in the *U*, *B* and *V* bands together with the response of the Thomson chip, closely reproduce the standard Johnson-Morgan *U*, *B*, *V* system. The filter combination for the R filter however gives an overall response significantly different from the Kron-Cousins R band.

The response functions of photomultipliers of a given type are more or less the same and filter combinations yielding standard photometric responses are available in the literature (e.g. Johnson & Morgan 1953; Fernie 1974). In the case of CCD chips, the responses can vary widely from manufacturer to manufacturer and also from chip to chip. The response of a given chip may also change with time (see Oke *et al.* 1988). The suitability of the filter-chip combination for photometry in some standard system can be established as attempted here. A set of filters with bandpasses that reproduce the Johnson-Morgan *U*, *B*, *V* and Kron-Cousins *R*, *I* systems more closely are being acquired.

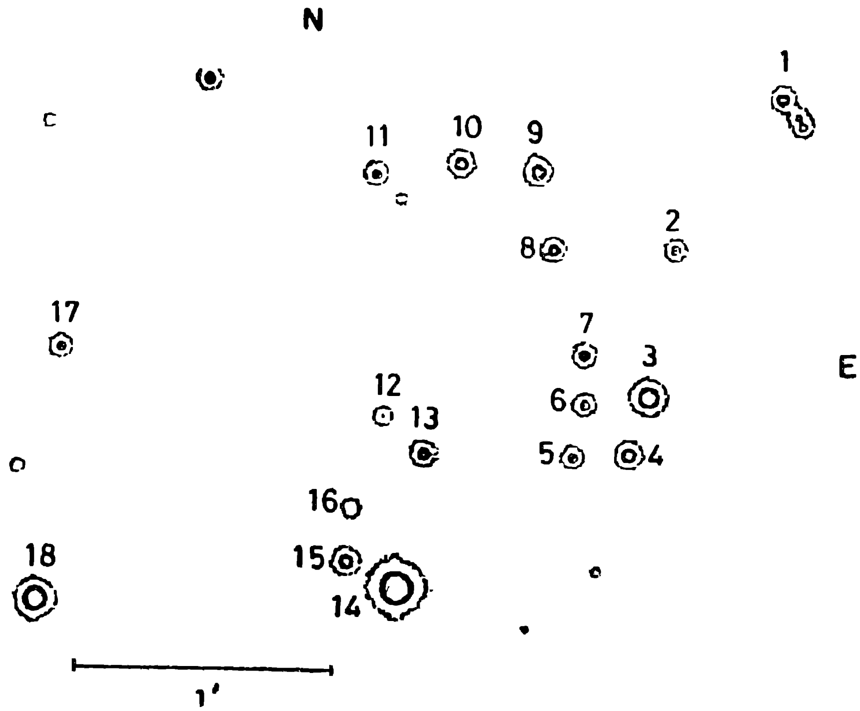

Figure 4. Identification chart of the measured stars.

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