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BVRI photometry of the Dipper Asterism region in M 67*

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Abstract. — We present Cousins *BVRI* magnitudes for stars in the M 67 'dipper asterism' region, based on observations carried out at the prime focus of the 2.3 m Vainu Bappu Telescope of the Vainu Bappu Observatory, Kavalur. The photometric system is calibrated using the photometric standards in the field and linear transformation relations are derived. Photometric results are reported for 37 stars in *BVRI* bands. Results are also presented for an additional set of 35 stars in only two or three of these bands. The photometric accuracy is better than 3% for magnitudes $B < 16$, $V, R < 17$ and $I < 14$, and is slightly poorer for the results presented beyond this limit.

Key words: clusters: open — clusters: M 67 — CCD photometry — photometric calibration

1. Introduction

The 2.3 m Vainu Bappu Telescope (VBT) at the Vainu Bappu Observatory (VBO), Kavalur, is equipped with two nearly identical CCD imaging systems — one jointly owned by TIFR Bombay and IUCAA Pune (A) and the other by IIA (B). The systems are equipped with a CCD dewar and controller obtained from Astromed Inc., Cambridge (UK). The chip in use in both the systems is GEC P8603 coated for enhanced ultraviolet sensitivity, and consists of 576 × 385 pixels each of 22 μm size. The data acquisition software in use was developed locally at IIA for both the controllers. Our observations were made using the combination of dewar A and controller B. Gain calibration of the system has been presented by Prabhu et al. (1992). The peak wavelengths and bandpasses of the coated, flat response filters used are

Filter	$\lambda_{\rm peak}$ Å	Bandpass Å
B	4400	1050
V	5425	1050
R	6550	1300
I	8150	1700

We present here photometric calibration of the CCD system A and Cousins *BVRI* photometry of stars in the 'dipper asterism' region of the open cluster M 67. This field has been used for photometric calibration by several workers (Schild 1983; Sagar & Pati 1989; Jones & Taylor 1990; Chevalier & Ilovaisky 1991, hereinafter CI; Mayya 1991; Bhat et al. 1992), and extensive photometry of stars in the central region of the cluster has been carried out by Gilliland et al. (1991, hereinafter GBD).

2. Observations

Two sets of data were obtained, one on 1991 April 16 and the other on 1992 March 30, at the prime focus of the VBT as part of a galaxy surface photometry programme. The total field covered by the CCD at the prime focus ($f/3.5$) is 5.7×3.8 arcmin^2. The 'dipper asterism' region was observed through *BVR* filters in April 1991 and through *BVRI* filters in March 1992. All observations were made when the cluster was close to the zenith, between hour angles $0^{\rm h}$–$1^{\rm h}$ at an airmass < 1.2. Since the skies were not of high photometric quality on both occasions, no attempts were made to obtain extinction coefficients. The details of observations are as follows: 1991 April 16 — 3 frames of exposure $64^{\rm s}$, $256^{\rm s}$ and $512^{\rm s}$ in B; 3 frames of $16^{\rm s}$, $64^{\rm s}$ and $256^{\rm s}$ in V and 2 frames of $16^{\rm s}$ and $64^{\rm s}$ in R. 1992 March 30 — 4 frames of $300^{\rm s}$, $200^{\rm s}$, $100^{\rm s}$ and $50^{\rm s}$ in B; 2 frames of $20^{\rm s}$ and $50^{\rm s}$ in V; 3 frames of $20^{\rm s}$, $10^{\rm s}$ and $5^{\rm s}$ in R and 4 frames of $20^{\rm s}$, $10^{\rm s}$, $5^{\rm s}$ and $2^{\rm s}$ in I. For flat-field corrections, twilight sky flats as well as dome flats were obtained in April 1991, whereas only twilight sky flats were obtained in March 1992. The average seeing during observations was ~ 2.5 arcsec.

*Based on observations using Vainu Bappu Telescope, VBO, Kavalur

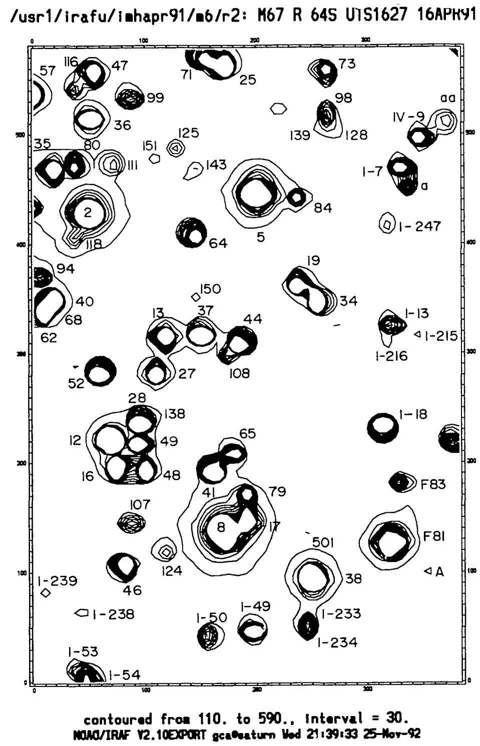

Fig. 1. a) The region of M 67 observed in 1991. North is at top and east to the left. The chart is prepared using an R band image

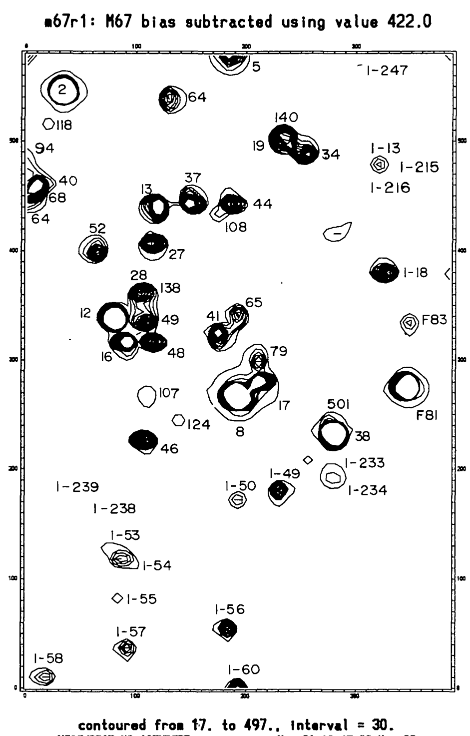

Fig. 1. b) The region of M 67 observed in 1992. North is at top and east to the left. the chart is prepared using an R band image

Figures 1a and 1b show the observed region with stars numbered for identification following GBD when available, and otherwise from Racine (1971) or Eggen & Sandage (1964).

3. Data reduction and photometric calibration

Bias subtraction for the 1991 data was effected using the overscan region of the frame. The 1992 frames, which were obtained using a new version of data acquisition software, do not have an overscan region. Hence several zero-exposure bias frames were obtained during the night. The average value of the bias frame obtained close to the time of M 67 observations was used to subtract a constant bias value. Likewise, bias values for flat-field frames were obtained from the closest frames.

In the 1991 data, twilight sky flats were found to be of a better quality than the dome flats. Hence only the sky flats were used in flat-fielding. An average of 4 and 2 flat frames was used for the B and V filters, respectively. Only one good flat was available for the R filter. All flats suffer from a slow variation across the chip due to short exposure times. The flat-fielding error is estimated to be $\sim 3\%$ between the centre of the frame and the edge. For the 1992 observations, flat-fielding in each filter was done using an average flat frame obtained by combining 6 flat frames in B, 4 in V and 5 each in R and I filters. Each of these frames was obtained with sufficiently long exposure time. The accuracy of flat-fielding was found to be $\sim 1-2\%$. The IRAF[1] CCDRED task was used for initial reductions.

Magnitudes of the stars were obtained using the DAOPHOT task in IRAF following the standard procedure (Gilliland 1992; Stetson 1987), using a value of 4 for the CCD gain (number of photons per ADU) and 10 for the read out noise estimates of the system (Prabhu et al. 1992). The instrumental magnitudes in each of the filters are given by

$-2.5\log(\mathrm{ADU}) + 23.0$,

where ADU represents the integrated counts per second within the PSF of the star. The magnitudes obtained from different frames of the same filter are averaged.

3.1. The transformation equations

The observed magnitudes and colours, uncorrected for extinction, v_i, $(b-v)_i$, $(v-r)_i$, $(r-i)_i$ are transformed into the Johnson-Cousins $BVRI$ system by fitting equations of the form

$$B-V = \alpha_{b-v} + \beta_{b-v}(b-v)_i \quad (1)$$

$$V-R = \alpha_{v-r} + \beta_{v-r}(v-r)_i \quad (2)$$

[1]IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities, Inc. (AURA) under cooperative agreement with the National Science Foundation

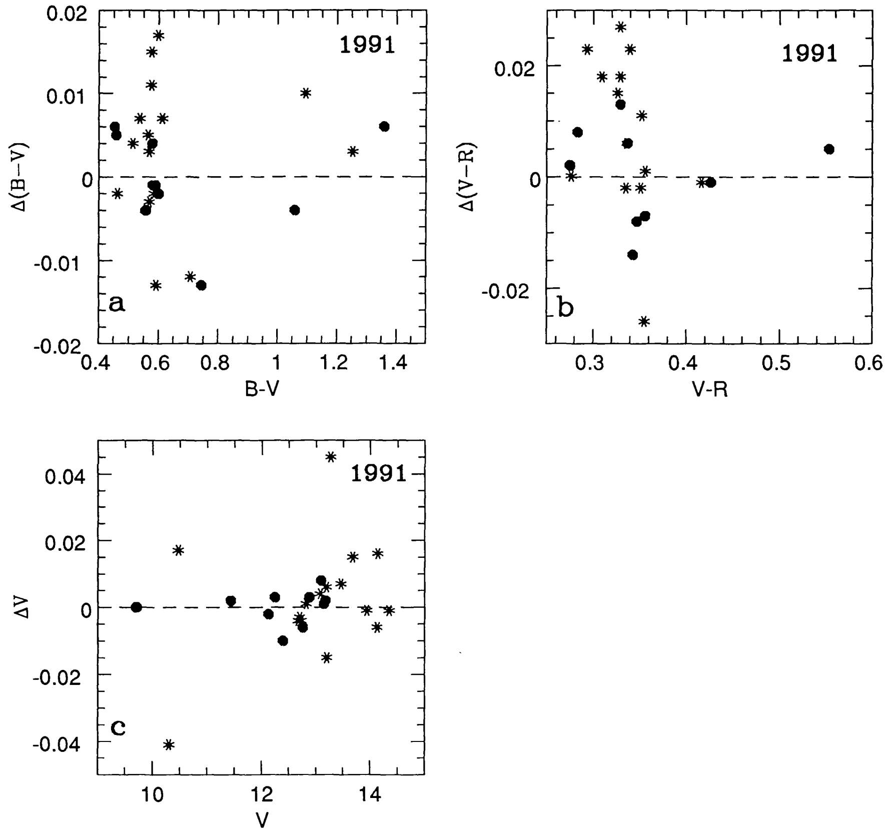

Fig. 2. The difference (computed−standard) plotted against the standard values for a) $B-V$, b) $V-R$ colours and c) V magnitude for the 1991 data. Filled circles represent the stars used for calibrating the system, and the asterisks other stars in common with Chevalier & Ilovaisky (1991)

$$R - I = \alpha_{r-i} + \beta_{r-i}(r-i)_i \quad (3)$$

$$V - v_i = \alpha_{bv} + \beta_{bv}(B-V)_i \quad (4)$$

$$V - v_i = \alpha_{vr} + \beta_{vr}(V-R)_i \, . \quad (5)$$

The standard *BVRI* magnitudes were taken from CI. The primary calibrators of CI were used, with two additional stars G17 and G46 for which the photometry of Chevalier & Ilovaisky agrees well with that of Joner & Taylor (1990). This addition was done primarily because two of the calibrators, F81 and G37, were not available in the 1991 frames; these stars were, however, used in 1992. G17 magnitudes are slightly affected by its bright neighbour G8. However, the contamination was not severe except for the I band. This star was not used for $R-I$ transformation. The coefficients α and β were estimated from a linear, least-squares regression analysis using the program SIXLIN of Isobe et al. (1990). It was assumed that all the errors lie in instrumental colours and magnitudes. Table 1 lists the transformation coefficients together with their standard error, the standard error of the fit ($\sigma_{\rm f}$) and the regression coefficient (r). It is apparent from the table that the errors of the photometry are $\sim 1\%$ over the range of magnitude and colours spanned by the calibrators.

The residuals are shown in Figs 2 and 3 as the difference between the calculated value and the standard value for all the stars in common between the present work and that of CI. There are a few instances where the difference exceeds 3%. These stars merit further observations as they could possibly be variable.

Table 1. Transformation coefficients to Johnson-Cousins system

	α		β		$\sigma_{\rm f}$		r	
	1991	1992	1991	1992	1991	1992	1991	1992
$B-V$	-1.211 ± 0.013	-1.359 ± 0.014	1.310 ± 0.009	1.354 ± 0.008	0.006	0.010	0.9999	0.9998
$V-R$	-0.735 ± 0.024	-0.770 ± 0.011	1.053 ± 0.022	1.087 ± 0.011	0.009	0.005	0.9973	0.9998
$R-I$		0.071 ± 0.004		1.052 ± 0.009		0.008		0.9994
$(V-v_i)_{bv}$	-1.959 ± 0.003	-2.213 ± 0.012	0.087 ± 0.003	0.079 ± 0.017	0.006	0.013	0.9871	0.9493
$(V-v_i)_{vr}$	-1.972 ± 0.003	-2.219 ± 0.015	0.183 ± 0.006	0.154 ± 0.038	0.006	0.014	0.9877	0.9450

4. Results

Using the calibration in Table 1, all the stars extracted by NSTAR of DAOPHOT were converted to Cousins *BVRI* magnitudes. Some stars had to be dropped because they could not be extracted in two adjacent bands. Further, stars with $B > 17$, $V, R > 19$ mag had photometric errors $> 5\%$ and were hence dropped. The images of 1992 had

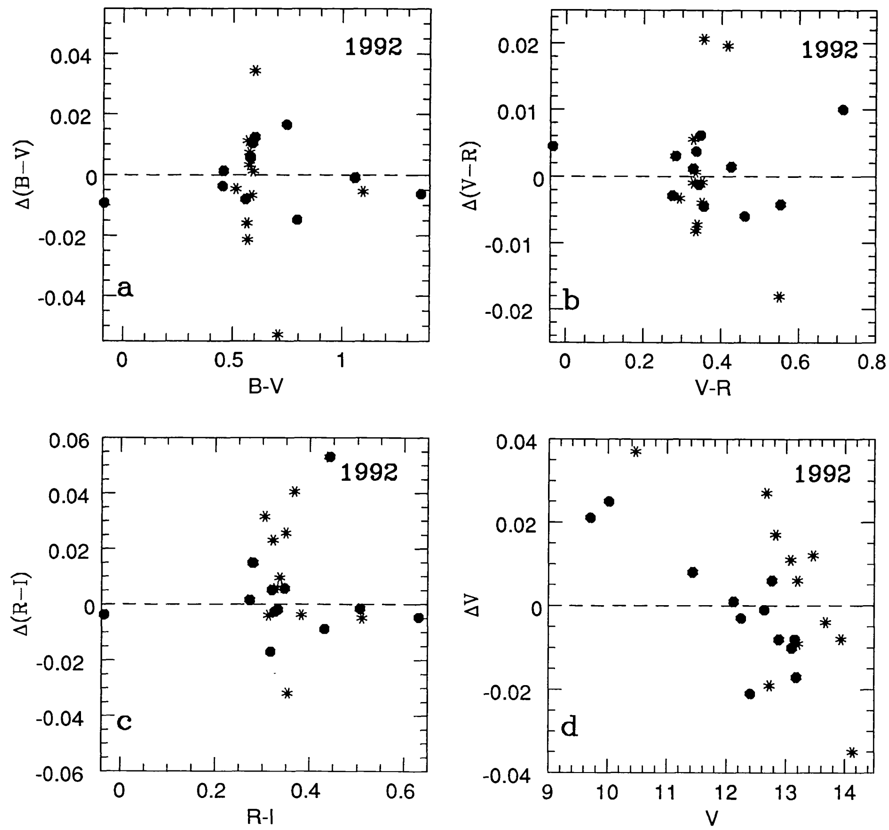

Fig. 3. The difference (computed−standard) plotted against the standard values for a) $B-V$, b) $V-R$, c) $R-I$ colours and d) V magnitude for the 1992 data. Filled circles represent the stars used for calibrating the system, and the asterisks other stars in common with Chevalier & Ilovaisky (1991)

not reached as faint limits as in 1991. Hence the limit of I band photometry was only about 16 mag. Thus between the two years, we have *BVRI* photometry for 37 stars in all. In addition, 14 stars have *BVR* photometry, 13 stars have *VR* photometry, 5 stars have *VRI* photometry and 3 stars have *BV* photometry.

All the results are presented in Table 2, which also lists the V magnitudes of stars from GBD and CI for comparison.

A comparison with the photometry of CI and GBD shows that our photometry is accurate to 1% for calibration stars, and better than 3% for all stars in common with CI. The difference between our magnitudes and GBD reaches 5% occasionally, particularly for fainter stars. The stars which differ by more than 5%, as also stars which differ by more than 7% between our two measurements were examined in detail. Of these, our measurements of G84 agrees with CI who have noted the difference from GBD. G124 is consistently fainter by 0.055 mag compared to the value of GBD. G128 is also fainter by a similar amount. I-50 shows significant difference between 1991 and 1992. The results on I-233 and I-234 could have larger errors since these stars are very close to each other.

5. Conclusions

BVRI magnitudes of stars in the 'dipper asterism' region of the open cluster M 67 is presented. Photometric transformation equations for calibration of the system to standard Johnson-Cousins *BVRI* bands are also obtained using standards in the field. The system is found to be stable upto 0.03 mag during 1991–1992. The typical residual rms scatter of measured quantities, and hence the accuracy of photometry is 0.01 mag for calibrators, and typical errors for other stars are better than 0.03 mag at least upto $V = 16$ mag, and generally to fainter limits in VR bands. The star G84 was at similar brightness between 1990 (CI) and 1991, at a brightness different from 1988 (GBD). The stars G84, G124, G128 and I-50 could be variables and further monitoring is required to establish their variability.

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Table 2. Magnitudes and colours of stars in M 67

Ident	V		$B-V$		$V-R$		$R-I$	V	
	1991	1992	1991	1992	1991	1992	1992	GBD	CI
G2	10.482	10.428	1.083	1.099		0.568	0.516	10.49	10.465
G5	10.260		1.250					10.30	10.301
G8	9.702	9.691	1.353	1.353		0.714	0.636	9.70	9.702
G12	11.435	11.424	1.061	1.058	0.562	0.557	0.508	11.45	11.432
G13	12.122	12.123	0.453	0.457	0.294	0.280	0.272	12.14	12.124
G16	12.248	12.250	0.575	0.573	0.319	0.341	0.329	12.27	12.247
G17	12.387	12.415	0.757	0.732	0.422	0.421	0.388	12.40	12.397
G19	12.667	12.644	0.509	0.518	0.319	0.296	0.273	12.67	12.671
G25	12.620		0.603		0.359			12.66	
G27	12.759	12.759	0.561	0.565	0.343	0.327	0.315	12.78	12.765
G28	12.887	12.892	0.448	0.457	0.277	0.278	0.265	12.91	12.884
G34	12.821	12.803	0.564	0.568	0.349	0.330	0.300	12.83	12.820
G35	12.848		0.544		0.330			12.85	
G36	12.691		0.543		0.343			12.72	12.693
G37	12.597	12.636	0.800	0.810	0.482	0.466	0.440	12.63	12.636
G38	11.042	11.039	0.396	0.380	0.239	0.231	0.259	11.09	
G40	12.876	12.816	0.776	0.770	0.460	0.428	0.423	12.85	
G41	12.720	12.743	0.565	0.557	0.344	0.344	0.324	12.73	12.724
G44	13.081	13.066	0.559	0.580	0.355	0.324	0.318	13.09	13.077
G46	13.104	13.106	0.601	0.587	0.350	0.361	0.342	13.10	13.096
G47	13.307		0.465		0.279			13.30	13.262
G48	13.150	13.155	0.581	0.575	0.366	0.333	0.334	13.16	13.147
G49	13.176	13.191	0.590	0.579	0.329	0.344	0.324	13.20	13.174
G52	13.198	13.194	0.586	0.591	0.335	0.432	0.323	13.22	13.192
G57	13.257		0.573					13.27	
G62	13.518	13.464	0.635	0.640	0.374	0.351	0.362	13.48	
G64	13.685	13.674	0.571	0.589	0.362	0.346	0.342	13.70	13.670
G65	13.933	13.941	0.605	0.591	0.366	0.353	0.327	13.94	13.933
G68	13.792	13.750	0.585	0.596	0.365	0.338	0.351	13.77	
G73	14.122		0.605		0.358			14.14	14.128
G79	14.147	14.167	0.719	0.760	0.415	0.396	0.386	14.14	14.132
G80	14.378		0.851		0.502			14.32	
G84	14.342		0.529		0.332			14.21	14.343
G94	15.017		0.750					14.95	
G98	15.382		0.835		0.438			15.38	
G99	15.266		0.762		0.473			15.23	
G107	15.861	15.837	1.012	0.969	0.587	0.591	0.587	15.84	
G108	15.820	15.774	1.087	1.086		0.575	0.561	15.80	
G111	15.774		0.869		0.535			15.74	
G116	16.267				0.569			16.24	
G118	16.457				0.611			16.41	
G123	16.936				0.595			16.89	
G124	16.626	16.620			0.675	0.708	0.680	16.57	
G128	17.443				0.759			17.38	
G138	17.745	17.844			0.856	0.931	0.922	17.78	
G139	17.746				0.818			17.66	
G140	17.988				0.849			17.94	
G143	17.997				0.829			17.98	
G151	18.685				0.898			18.67	
G501	12.787		0.547		0.297			12.76	
F81		9.995		−0.145		−0.038	−0.030		10.022
F83	13.184	13.208	0.581	0.564	0.351	0.355	0.327		13.199
I-13	15.148	15.118	0.755	0.771	0.462	0.431	0.421		
I-18	15.074	15.097	0.878	0.856	0.497	0.504	0.439		
I-49	13.466	13.446	0.567	0.572	0.329	0.334	0.338		13.458
I-50	15.414	15.341	0.892	0.816	0.536	0.519	0.554		
I-53	16.413	16.378			0.627	0.586	0.553		
I-54	14.179	14.184	0.636	0.668	0.368	0.387	0.372		
I-55		16.699				0.683	0.543		
I-56		13.401		0.565		0.316	0.337		
I-57		14.491		0.654		0.375	0.350		
I-58		14.693		0.738		0.434	0.419		
I-70	13.884		0.584		0.342				
I-213	18.122				0.651				
I-216	17.820				0.877				
I-233	15.705	15.716	0.850	0.862	0.481	0.506	0.404		
I-234	15.328	15.267	0.776	0.778	0.507	0.387	0.430		
I-238	17.484				0.445				
I-239	18.488				0.893				
I-247	16.722	16.687			0.442	0.421	0.423		
IV-9	13.767		0.590		0.333				
a	14.873		0.724		0.405				
aa	16.007		1.055		0.626				
A	18.361				0.526				

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