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Photometry of the open cluster NGC 654

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Summary. Photoelectric *UBV* magnitudes have been determined for stars in the field of NGC 654. The reddening across the cluster varies from 0.74 to 1.16 mag. The true distance modulus is estimated to be 10.85 mag. The HR-diagram and the age of the cluster star have been discussed.

1 Introduction

The young open cluster NGC 654 (α = $01^h 40^m.6$, $\delta = +61° 38'.0$ (1950); $l^{II} = 129°.1$, $b^{II} = -0°.4$) in Cassiopeia, has been classified by Trumpler (1930) as of type I2p. In the cluster field, relative proper motions have been determined by Stone (1977) for 186 stars with an average standard error of ± 0.07 arcsec per century in each co-ordinate. Based on this proper motion study the membership probability (p) of these stars has been determined by Stone (1977). The distribution of these stars according to membership probability is shown in Table 1, which shows that 60 stars have their membership probability ⩾ 50 per cent. These 60 stars were considered as the cluster members. Out of these, photoelectric magnitudes and colours are available for 30 stars only (Pesch 1960; Hoag *et al.* 1961).

The present study is aimed at determining the *UBV* photoelectric magnitudes of the cluster members, reddening across the cluster, distance modulus to the cluster and age of the cluster stars.

2 Observations and reduction

The observations were carried out between 1977 October and 1978 November on the 104-cm Sampurnanand reflector of the Uttar Pradesh State Observatory. The methods of observation and instrumentation are the same as described earlier by us (Sagar & Joshi 1979). For standardizing the instrumental magnitudes the photoelectric sequence given by Pesch (1960) was used. Star number 68, which has constant light output within the errors of observations (i.e., ± 0.02 mag in *U, B* and *V* magnitudes), was used for the determination of atmospheric coefficients and the necessary extinction corrections were applied separately for each night. *UBV* magnitudes for the program stars were determined differentially, taking

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Table 1. Distribution of stars according to membership probability, p, determined by Stone (1977) in NGC 654.

Sl. no.	Probability of cluster membership, p, (per cent)	Number of stars present in the range of p
1.	0	103
2.	1 to 9	10
3.	10 to 15	6
4.	20 to 29	3
5.	30 to 39	1
6.	40 to 49	3
7.	50 to 59	3
8.	60 to 69	0
9.	70 to 79	5
10.	80 to 89	25
11.	90 to 99	27
Total number of stars		186

star number 68 as a standard. A minimum of two sets of observations, on different nights, were taken for each star and their average values are listed in Table 2.

3 Membership

Membership of the stars in the cluster field has been determined by Pesch (1960), McCuskey & Houk (1964) and Moffat (1972) on the basis of the photometric study and by Stone (1977) on the basis of the proper motion study. Following the discussions by Sanders (1976) on the above two methods of membership, we have based the cluster membership on the proper motion study only. We have divided the stars into two groups: (a) $1 \geq p > 50$; (b) $p \geq 50$.

Table 2. Photoelectric *UBV* magnitudes and colours of stars in NGC 654. Star number and corresponding membership probability, p, are taken from Stone (1977). The last nine stars, with *P* prefixed to the star number, are from Pesch (1960). stars with asterisked numbers belong to the photoelectric sequence by Pesch (1960). The adopted value of reddening, $E(B-V)$, is also given.

Star number	V (mag)	$(B-V)$ (mag)	$(U-B)$ (mag)	$E(B-V)$ (mag)	p (per cent)
5	12.22	0.83	0.48	0.86	92
7	13.65	0.76	−0.09		0
9	9.33	0.61	−0.20	0.80	92
10	13.47	0.74	0.05		10
11	13.81	0.63	0.06		5
13	13.97	0.62	−0.01	0.77	74
27	13.97	0.84	0.32		1
35	13.27	1.42	1.16		12
36	14.25	0.67	0.04	0.81	89
37	13.12	2.23	1.96	0.82	93
39	10.98	0.67	−0.06		29
40	14.11	0.73	−0.05		12
43	13.41	0.66	0.33		39
52	11.63	0.78	0.01	0.96	70
57	9.47	0.14	−0.23	0.25	90
58	13.08	0.72	0.3		3

Table 2 – *continued*

Star number	*V* (mag)	(*B*–*V*) (mag)	(*U*–*B*) (mag)	*E* (*B*–*V*) (mag)	*p* (per cent)
60	13.50	0.72	– 0.13	0.94	79
62	14.12	0.72	0.43	0.74	92
63	11.65	2.07	2.05		1
67*	12.38	0.49	0.35		0
68*	9.56	0.88	0.32	0.93	84
70	14.03	0.77	– 0.08	0.98	55
71*	12.64	0.68	– 0.10	0.88	93
72*	13.20	0.65	– 0.15	0.86	89
73*	11.54	1.27	0.83		0
74	13.94	0.98	0.12	1.18	82
76	13.05	0.80	– 0.03	1.00	90
78*	11.45	0.69	– 0.15	0.91	90
79	13.23	0.78	– 0.01	0.70	91
80	14.43	0.65	0.01	0.80	81
81	13.32	0.78	0.11	0.93	91
82*	14.32	0.80	0.02	0.99	79
84	13.61	0.61	0.02	0.74	86
85	13.34	0.65	– 0.17	0.86	89
86	13.18	0.73	– 0.03	0.91	87
88	11.71	0.63	– 0.19	0.85	88
89	13.22	0.90	0.10	1.08	90
90	12.22	0.67	– 0.23	0.91	89
94*	13.03	0.95	0.08	1.16	90
96	14.29	0.70	0.18	0.80	88
97	13.68	0.77	– 0.08	0.98	90
98	13.34	0.80	– 0.04	1.01	89
99	14.10	0.78	0.20		3
100	12.56	0.94	0.08	1.14	92
101	12.13	0.73	0.16		24
102	13.26	0.74	– 0.02	0.92	88
103	12.09	0.79	0.06	0.75	91
104	13.49	0.70	0.32	0.96	86
106	13.30	0.81	0.13	0.96	93
107	13.48	0.81	0.06		1
108	12.76	0.74	– 0.18	0.98	93
109	10.62	0.87	– 0.14	0.93	90
110	14.08	0.90	0.31		3
111*	7.32	1.24	0.94	0.85	86
112	14.00	0.76	– 0.03	0.83	84
113	13.48	0.72	– 0.13	0.94	89
114*	11.39	0.61	– 0.08	0.78	82
115	13.93	0.70	0.10	0.83	90
116	14.57	0.77	0.23	0.87	90
117	14.45	0.73	0.38	0.77	83
119	12.97	0.67	– 0.22	0.91	92
120	13.98	0.64	0.15		0
121	14.20	0.82	0.47		41
124*	12.36	0.57	– 0.21	0.78	92
125*	11.85	0.57	– 0.16	0.76	91
126	14.01	0.67	0.18	0.76	92
127	13.35	0.83	0.12	0.99	54
130	13.52	0.68	– 0.05	0.86	82
131	11.21	0.56	– 0.20	0.76	80
133	12.36	0.83	0.06	1.01	76
134	14.11	0.82	– 0.19	1.09	91

Table 2 – *continued*

Star number	V (mag)	$(B-V)$ (mag)	$(U-B)$ (mag)	$E(B-V)$ (mag)	p (per cent)
135	12.23	0.57	–0.17	0.76	93
137	10.86	1.38	1.37		0
141	13.96	0.81	0.06	0.98	87
143	13.94	0.71	–0.02	0.89	92
144	13.77	0.81	0.41		0
145	11.61	0.68	0.34		0
147	13.31	0.77	0.28	0.85	52
149	12.14	2.08	2.43		15
150	10.90	1.44	1.45		11
152	14.19	0.78	0.01		45
154	12.45	0.60	–0.02	0.75	81
161	9.87	0.20	0.01		48
163	11.95	0.41	0.45		4
170	11.72	2.01	1.61	0.83	80
174	13.46	0.76	0.04		29
181	10.58	0.66	–0.24		18
P8	14.46	1.48			
P25	15.01	1.01	–0.02		
P50	14.70	0.38	0.02		
P56	14.52	0.81	0.35		
P70	14.35	0.91	0.22		
P96	14.03	0.70	0.22		
PB	15.04	0.64			
PC	14.26	0.99			
PD	14.57	0.86			

Notes
(1) The photoelectric *UBV* values of star number 112 (p = 84 per cent) are taken from Hoag *et al.* (1961).
(2) For star numbers 37, 68, 97, 111, 130 and 170, the $E(B-V)$ value is taken from the nearest neighbouring star (see discussion in Section 4).

The number of stars in group (a) is 23 and in group (b) is 60. The median probability of group (a) is 11 per cent and of group (b) is 89 per cent. We can, therefore, statistically expect to find 20 field stars in group (a) and 6 field stars in group (b). From the above discussions, it is clear that most of the cluster members belong to group (b) and consequently, the cluster parameters are derived on the basis of these stars only.

4 Reddening

The $[V, (B-V)]$ colour–magnitude diagram (CMD) and the $(U-B)$ versus $(B-V)$ colour–colour diagram (CCD) of NGC 654 have been plotted in Figs 1 and 2 respectively. The scatter in these diagrams indicate non-uniform reddening across the cluster face, which is confirmed in the following manner.

We have fitted the intrinsic main sequence, given by Schmidt-Kaler (1965) on to the cluster CCD. We find that the mean value of the colour excess $E(B-V)$ is 0.94 mag. However, we find that the colour excess, as obtained by the sliding-fit method, varies from $E(B-V)_{min} = 0.74$ mag to $E(B-V)_{max} = 1.16$ mag, yielding $\Delta E(B-V) = E(B-V)_{max} - E(B-V)_{min} = 0.42$ mag and $\delta(B-V) = 0.36$ mag. $\delta(B-V)$ is the dispersion of the cluster main sequence in $(B-V)$ of a given spectral type in the colour–colour diagram of the clusters (Burki 1975).

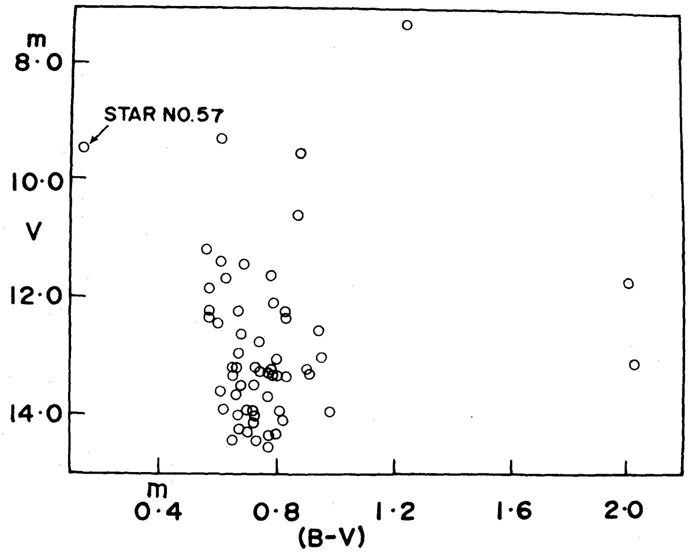

Figure 1. The *V*, (*B*–*V*) CMD of the cluster NGC 654.

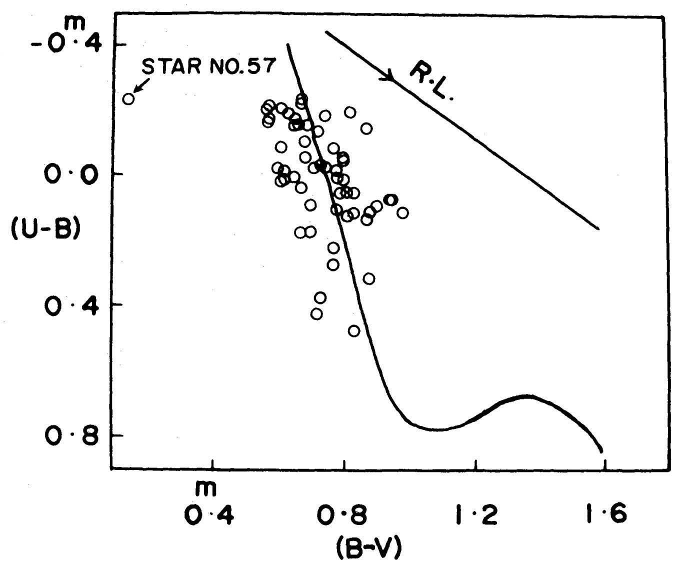

Figure 2. The (*U*–*B*), (*B*–*V*) CCD of NGC 654. The continuous curve represents the intrinsic MS, taken from Schmidt-Kaler (1965), fitted on to the mean position of the cluster CCD. The straight line represents the reddening line.

Based on the discussions by Burki (1975) on the values of $\Delta E(B-V)$ and $\delta(B-V)$, we infer that differential reddening is present across the cluster. Reddening across the cluster has also been found to be variable by various other investigators (Pesch 1960; McCuskey & Houk 1964; Moffat 1972; Stone 1977). In order to determine the spatial distribution of the differential reddening, we have divided the cluster field (i.e. $01^h41^m.9 > \alpha > 01^h38^m.4$; $61°42' > \delta > 61°24'$) into areas of 2×2 arcsec^2, as indicated in Table 3 and have determined the mean reddening across each box in the same way as described by us elsewhere (Sagar & Joshi 1978a, b, 1979). The maximum error in the $E(B-V)$ values listed in Table 3, is ± 0.05 mag.

Stone (1977) suggested that NGC 654, besides showing the usual central concentration of stars, is accompanied by an extension corona of members, which is in agreement with the

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Table 3. Variation of reddening across the cluster NGC 654. The average values of the reddening, $E(B-V)$, in areas of 2×2 arcmin^2 are indicated at appropriate places along with the number of stars used for this purpose, given in brackets. Coordinates are relative to $\alpha = 01^h\ 40^m$, $\delta = 61°\ 32'$ (1950) in arcmin.

$\Delta\delta$ \ $\Delta\alpha$	28 to 26	26 to 24	24 to 22	22 to 20	20 to 18	18 to 16	16 to 14	14 to 12	12 to 10	10 to 8	8 to 6	6 to 4	4 to 2	2 to 0	0 to −2	−2 to −4	−4 to −6	−6 to −8	−8 to −10	−10 to −12	−12 to −14	−14 to −16	−16 to −18	−18 to −20	−20 to −22	−22 to −24
8 to 10			0.85 (1)							1.14 (1)	1.16 (1)															
6 to 8	0.75 (1)			0.89 (1)	1.09 (1)		0.99 (1)	0.84 (2)	0.83 (1)	0.88 (7)	0.84 (7)	1.09 (2)									0.81 (1)					
4 to 6								0.80 (3)	0.84 (2)		0.92 (3)	0.91 (3)														
2 to 4					0.79 (3)			0.78 (1)																		0.86 (1)
0 to 2											0.86 (1)						0.96 (1)							0.77 (1)	0.80 (1)	
−2 to 0														0.74 (1)												
−4 to −2				0.98 (1)											0.94 (1)											
−6 to −4																										
−8 to −6					1.01 (1)																					

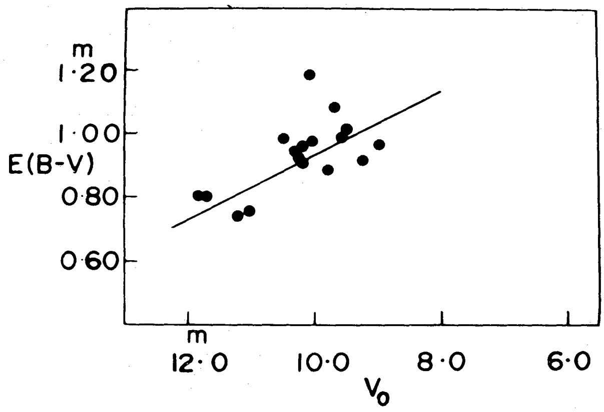

Figure 3. The $E(B-V)$, V_0 diagram of stars in the central region of NGC 654. The straight line is the best regression line.

findings of McCuskey & Houk (1964). We find that the reddening for stars in the coronal region is lower than that for the central region of the cluster, contrary to the findings of Moffat (1972). We observed that within the central region (i.e. $01^h 40^m.8 > \alpha > 01^h 40^m.2$; $61°39'.4 > \delta > 61°37'.8$) of the cluster, the value of $E(B-V)$ for each star depends upon its luminosity. In order to verify this, we have plotted $E(B-V)$ of each star against its intrinsic magnitude V_0 (Fig. 3) for stars lying in the central region of the cluster. Fig. 3 shows that the reddening increases approximately linearly with the luminosity of the star. The relation between reddening and luminosity as obtained by least-squares fit of a straight line can be expressed as:

$$E(B-V) = -0.10\,V_0 + 1.93.$$

This probably indicates that the bright stars of the cluster are surrounded by dust shell as in some other young clusters (Reddish 1967). In view of above, each star has been suitably dereddened for the following discussions, by applying the reddening corrections obtained from the Q-method as described by us elsewhere (Sagar & Joshi 1979). For six stars (Table 2) the reddening values are not available from the Q-method. For such stars we have adopted the reddening value of the nearest neighbouring star. The reddening value, $E(B-V)$, for each star thus estimated is listed in Table 2. From the standpoint of stellar evolution star number 57, which is situated at a large distance from the cluster centre, occupies a peculiar position in the CMD and CCD (Figs 1 and 2). For this star the reddening value $E(B-V)$, based on the Q-method, is 0.25 mag, which is very low compared to the average reddening value (0.94 mag) of the cluster. This shows that it can be a foreground star. However, the membership probability for this star is 90 per cent (Stone 1977). For group (b) stars the statistically expected number of field stars is six (see discussions in Section 3). Therefore, the possibility that star number 57 is a field star cannot be ruled out. However, in the subsequent discussions, we have not considered this star.

5 Distance

We have determined the intrinsic colours $(B-V)_0$ and $(U-B)_0$ and the V_0 magnitudes, of the member stars, using the individual values of $E(B-V)$, listed in Table 2, in the same way as described elsewhere (Sagar & Joshi 1979). The distance modulus to the cluster has been obtained by fitting the ZAMS given by Schmidt-Kaler (1965) on to the cluster main

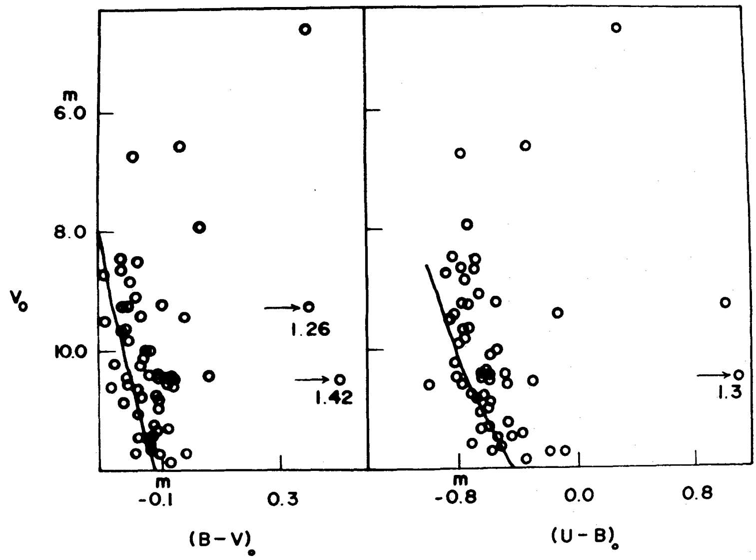

Figure 4. The intrinsic V_0, $(B-V)_0$ and V_0, $(U-B)_0$ CMD of NGC 654. The continuous lines represent the ZAMS, taken from Schmidt-Kaler (1965), fitted on to the cluster CMD.

sequence in the [V_0, $(B-V)_0$] and [V_0, $(U-B)_0$] diagrams (Fig. 4). To avoid the evolutionary effects, only the lower part of the main sequence has been used in distance modulus estimation. The two methods give respectively the distance modulus to be 11.90 and 11.80 mag. The average value thus obtained is 11.85 ± 0.1 mag implying that the distance to the cluster is 2.43 ± 0.23 Kpc. The distance to the cluster, determined by various other authors, ranges from 1.58 to 2.88 Kpc (Alter, Ruprecht & Vanÿsek 1970; Moffat 1972; Stone 1977) with a modal value of 2.4 Kpc.

6 HR-diagram of NGC 654

The HR-diagram of NGC 654 has been plotted in Fig. 5 for a true distance modulus of 11.85 mag after applying correction for variable reddening across the cluster as indicated in

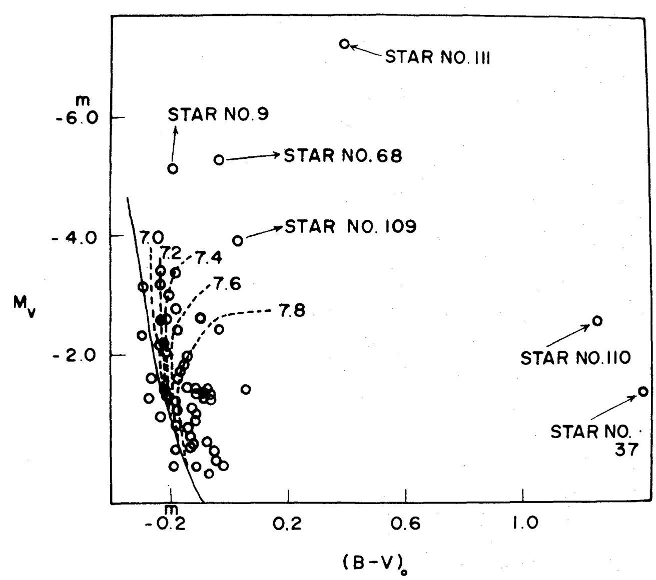

Figure 5. The HR-diagram of NGC 654. The solid curve is the ZAMS taken from Schmidt-Kaler (1965). Dashed curves are the isochrones for Population I (X = 0.70, Z = 0.03) taken from Hejlesen (1980). Ages in logarithmic scale are indicated alongside the respective isochrones.

Table 2. From the HR-diagram the following inferences can be drawn:

(i) Almost all the stars under discussion have reached the main sequence. The cluster sequence extends from $M_V = -3.4$ to -0.1 mag.

(ii) An evolutionary effect in the cluster stars is visible. The positions of stars 37 and 170, with membership probability $p = 82$ and 83 per cent respectively, indicate that these stars have reached red giant phase of stellar evolution.

(iii) The positions of the stars 9 and 109 in the HR-diagram indicate that these stars are blue supergiants of luminosity class Ib.

To determine the masses of yellow supergiants, Osmer (1972) has given the relation:

$$\log(m/m_\odot) = 0.25 - 0.32\, M_{\rm bol}.$$

Bolometric correction is zero for F5 supergiants (Parsons 1970). The mass of the supergiant star 111 is estimated to be about $16\, m_\odot$.

7 Age of the cluster stars

To determine the age of the cluster stars, we have used the isochrones for Population I ($X = 0.70$, $Z = 0.03$) given by Hejlesen (1980) after converting them from ($M_{\rm bol}$, $\log T_{\rm eff}$) plane to [M_V, $(B-V)_0$] plane by using the transformations given by Code (1975). From the fitting of the isochrones to the cluster HR-diagram (Fig. 5), we infer that the age of the cluster stars lies between $(1.6–6.3) \times 10^7$ yr.

We have also determined the cluster age based on the turn-off point using the method given by Sandage (1957). The $(B-V)_0^t$ value at the turn-off point is -0.22 mag. The corresponding age estimate comes out to be 3.1×10^7 yr.

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