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Study of the extremely young open cluster NGC 6530

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Summary. Photoelectric magnitudes and colours in the *UBV* system have been determined for 101 stars in the field of NGC 6530. The interstellar reddening across the cluster varies from 0.25 to 0.48 mag, with an average value of 0.35 mag. The distance modulus to the cluster is estimated at 11.3 mag and an age of 2×10^6 yr is ascribed. The cluster luminosity function is compared with the general luminosity function and the initial luminosity function. Star numbers 304 and 338 are in the early stages of their evolution while star numbers 171, 284 and 338 are probably variables.

1 Introduction

The extremely young cluster NGC 6530 ($\alpha = 18^h 01^m.7$, $\delta = -24° 20'.0$ (1950); $l^{II} = 3°.06$, $b^{II} = -1°.36$) in Sagittarius is associated with the Lagoon nebula, M8. Based on proper-motion studies, 88 stars in the field of the cluster have a membership probability of not less than 50 per cent of which for 73 stars the probability exceeds 60 per cent. Even so, the possibility of some non-members having been included in the discussion cannot be ruled out (van Altena & Jones 1972). Out of these, photoelectric magnitudes and colours are available for only 41 stars (Walker 1957), while for the remaining 47 stars, only photographic *V* magnitudes are known within error limits of ± 0.1 mag (van Altena & Jones 1972).

The *UBV* photometry on NGC 6530 is aimed at determining the photoelectric magnitudes and colours for the member stars, reddening across the cluster, distance modulus to the cluster and age of the cluster stars.

2 Observations and reductions

The observations were carried out between 1975 May and 1976 June on the 104-cm Sampurnanand reflector of the Uttar Pradesh State Observatory. The methods of observation and instrumentation are the same as described by Joshi, Sagar & Pandey (1975). For standardizing the instrumental magnitudes, we have used the photoelectric sequences given by Walker (1957). The observations have been made at zenith distances generally not exceeding 60 deg. A minimum of two sets of observations, on different nights, were taken for each star and the average values were taken.

Table 1. Photoelectric magnitudes and colours of stars in NGC 6530. The stars with asterisked serial numbers belong to the photoelectric sequence by Walker (1957). The adopted reddening value $E(B-V)$ for the member stars is also given.

Serial number	Star number by van Altena & Jones	V	$(B-V)$	$(U-B)$	$E(B-V)$	Membership probability p (per cent)
1	2	3 (mag)	4 (mag)	5 (mag)	6 (mag)	7
1	28	8.68	0.01	−0.77	0.27	72
2	30	12.43	0.20	−0.10	0.28	64
3	35	12.28	0.23	0.10	0.25	76
4	45	13.12	0.68	0.22	0.28	85
5	47	12.72	0.42	0.18	0.25	65
6	53	11.47	1.13	−0.02	0.26	78
7	72	13.51	0.57	0.19	0.25	50
8	73	12.36	0.65	−0.02	0.28	72
9	74	12.82	0.29	0.25	0.28	70
10	79	12.80	1.50	0.81	0.25	69
11	91	12.66	0.54	−0.11	0.33	78
12	92	12.05	1.28	1.06	0.38	85
13	93	11.69	0.39	−0.22	0.25	83
14	94	11.86	0.24	−0.26	0.38	80
15	97	10.94	1.24	0.79		45
16	100	11.92	1.25	1.18	0.26	59
17	107	10.01	0.16	−0.54	0.43	86
18	113	12.15	0.29	−0.46	0.43	78
19	114	12.78	0.37	−0.17	0.43	77
20	120	12.08	0.28	−0.12	0.43	62
21	130	13.67	0.61	0.25		0
22	132	11.33	0.22	−0.31		41
23*	133	11.60	0.17	−0.37	0.37	57
24	135	12.20	0.27	0.07	0.27	50
25	137	13.75	0.67	0.04	0.37	79
26	138	11.95	0.17	−0.25	0.33	77
27	140	10.78	0.25	−0.48		48
28	141	13.26	1.14	0.64		34
29	142	12.72	0.22	0.11	0.27	69
30	146	11.43	0.09	−0.34	0.29	86
31*	147	11.65	0.22	−0.32	0.33	62
32	149	11.93	0.19	−0.26	0.37	64
33	150	12.95	0.66	0.24	0.33	79
34	152	10.51	0.11	−0.59	0.33	84
35	154	13.44	0.77	0.50	0.29	52
36	155	11.69	0.30	−0.32	0.37	52
37	157	12.25	0.52	0.25	0.27	68
38*	161	9.18	0.04	−0.75	0.33	84
39	163	12.28	0.24	0.05	0.29	76
40	165	11.63	0.19	−0.22	0.37	60
41	171	11.89	0.30	0.01	0.29	85
42	173	13.12	0.73	0.21	0.37	78
43*	176	9.03	0.10	−0.71	0.33	86
44*	177	11.59	0.27	0.02	0.33	62
45	180	9.86	0.18	−0.65	0.36	81
46	181	12.50	0.50	0.20	0.36	61
47*	182	8.93	0.09	−0.65	0.36	75
48*	184	9.66	0.07	−0.66	0.36	81
49	187	11.49	0.19	−0.45	0.36	70

Table 1. *Continued.*

Serial number	Star number by van Altena & Jones	V	$(B-V)$	$(U-B)$	$E(B-V)$	Membership probability p (per cent)
1	2	3 (mag)	4 (mag)	5 (mag)	6 (mag)	7
50	189	13.07	1.48	1.07	0.26	61
51	190	11.68	0.20	−0.29		48
52*	192	10.14	0.11	−0.65	0.36	79
53	193	7.42	0.16	−0.76		1
54	194	11.87	0.45	0.03	0.36	86
55	195	12.69	0.36	0.01	0.36	74
56*	197	10.45	0.15	−0.61	0.36	83
57	201	8.24	0.08	−0.70		48
58*	202	10.69	0.10	−0.56	0.36	86
59*	203	12.01	0.50	0.25	0.33	83
60*	204	9.56	0.06	−0.78	0.36	85
61	207	13.08	0.36	0.12	0.30	66
62*	210	10.49	0.13	−0.61	0.36	75
63	211	11.72	0.17	−0.47	0.36	59
64	212	12.44	0.29	−0.22	0.36	70
65*	215	9.75	0.16	−0.58	0.36	77
66	216	11.91	0.23	−0.41	0.36	79
67*	223	8.63	0.02	−0.79	0.36	84
68	228	12.18	0.23	−0.14	0.36	55
69	229	11.31	0.16	−0.58	0.36	77
70	230	10.81	0.09	−0.52	0.36	50
71*	235	10.54	0.17	−0.48	0.35	56
72	238	12.76	0.85	0.29		37
73	239	12.62	0.28	0.03	0.35	58
74	240	11.22	0.16	−0.49	0.44	70
75	242	13.67	1.18	0.55	0.44	85
76	245	12.02	0.33	−0.33	0.44	79
77	246	11.32	0.34	0.07	0.44	52
78	247	11.51	0.28	−0.40	0.48	81
79	250	11.72	0.28	−0.45	0.44	86
80	256	10.81	0.25	−0.45	0.44	71
81	259	11.61	0.41	−0.24	0.43	84
82	261	12.25	1.47	0.69	0.26	74
83	266	11.84	0.22	−0.48	0.43	80
84	269	12.52	0.68	0.25	0.26	82
85	275	13.01	0.44	0.28	0.25	70
86	284	13.22	0.68	−0.10	0.25	52
87	296	13.35	0.61	0.09	0.25	83
88	298	12.69	0.43	0.11	0.25	63
89	301	11.98	1.37	1.05		37
90	304	9.89	2.32	2.17	0.25	73
91	306	13.44	1.31	0.73	0.25	81
92	309	11.73	0.87	0.43		33
93	315	13.13	0.83	0.21		35
94	317	11.99	0.85	0.03	0.25	85
95	330	10.82	0.86	0.14		45
96	332	13.47	0.78	0.06	0.25	80
97	336	13.15	0.62	0.04	0.25	78
98	338	10.27	2.45	2.44	0.25	69
99	353	12.28	0.38	0.25	0.25	50
100	360	12.20	0.81	0.18	0.25	74
101	361	12.85	0.53	0.00	0.25	58

The computed standard deviations of our observations are 0.02 mag in *V*, *B* and *U* filters.

3 Membership

Walker (1957) had reported cluster membership on the basis of a *UBV* photoelectric photometric study. We have based cluster membership in NGC 6530 on van Altena & Jones' (1972) proper-motion study alone – following our earlier practice in Tr-1 (Joshi & Sagar 1977). Only stars having membership probability not less than 50 per cent are considered here in further discussions and the cluster parameters are derived only on the basis of these stars. The apparent standard *V* magnitudes and the $(B-V)$, $(U-B)$ colours of the stars observed in the cluster field are listed in Table 1, along with the membership probability as given by van Altena & Jones. The reddening value $E(B-V)$ for the 88 member stars (i.e. those with membership probability exceeding 50 per cent) is also given.

4 Reddening

The interstellar reddening was determined from the colour–colour diagram of the cluster, after adopting the slope of reddening line to be 0.72. The values of the colour excesses, $E(B-V)$ and $E(U-B)$, thus obtained, are 0.35 and 0.25 mag respectively. Alongside, using the observed values of $(U-B)$ and $(B-V)$ colours for stars of spectral types earlier than A0 and lying on the zero-age main sequence (ZAMS), the colour excesses are calculated in the manner described earlier (Sagar 1976). The results obtained are $E(B-V) = 0.35$ mag and $E(U-B) = 0.25$ mag, which are identical to the ones obtained from colour–colour diagram (Fig. 1).

Considering the association of the cluster with an emission nebulosity (Walker 1957), it is reasonable to attribute the spread of points on the colour–colour diagram to differential reddening across the cluster (*cf.* Turner 1973). To determine this, we have divided the cluster field within the region $17^h 59^m 17^s < \alpha < 18^h 02^m 17^s, -24° 28' 50'' < \delta < -24° 08' 50''$ into areas of 25 arcmin^2 each, as indicated in Table 2. In each area, the reddening is determined by considering stars of spectral types earlier than A0, lying on the ZAMS and using the observed values of $(B-V)$ and $(U-B)$ colours, and the average value of the reddening

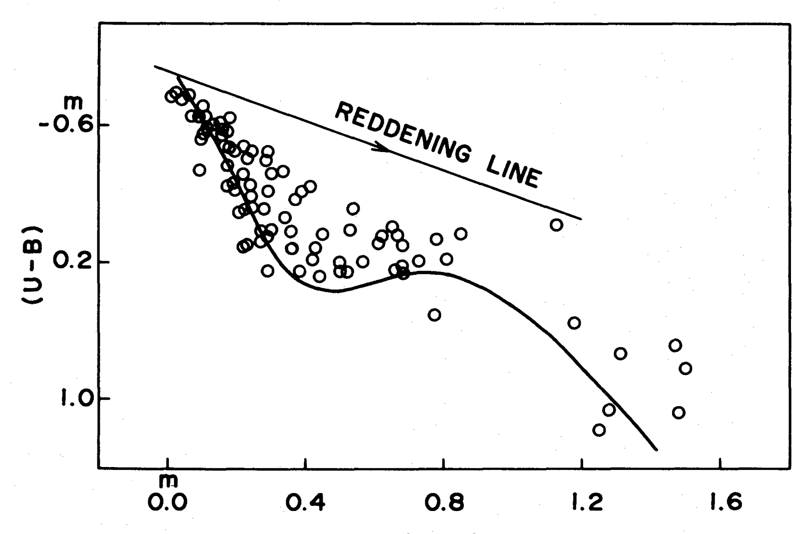

Figure 1. The colour–colour diagram of the open cluster NGC 6530.

Table 2. Variation of reddening across the cluster NGC 6530. The average value of the reddening, $E(B-V)$, in areas 5 × 5 arcmin is indicated in the appropriate boxes with the number of stars used for the determination of reddening given in brackets.

δ α	−24° 28′ 50″– −24° 23′ 50″	−24° 23′ 50″– −24° 18′ 50″	−24° 18′ 50″– −24° 13′ 50″	−24° 13′ 50″– −24° 08′ 50″
h m s	(mag)	(mag)	(mag)	(mag)
17 59 17– 17 59 37			0.27 (1)	
17 59 37– 17 59 57		0.25 (1)	0.28 (1)	
17 59 57– 18 00 17	0.28 (1)			
18 00 17– 18 00 37				0.38 (1)
18 00 37– 18 00 57	0.33 (1)	0.43 (3)		
18 00 57– 18 01 17	0.37 (3)	0.33 (6)	0.29 (3)	0.27 (2)
18 01 17– 18 01 37	0.36 (4)	0.36 (13)		
18 01 37– 18 01 57	0.44 (3)	0.48 (1)	0.35 (2)	
18 01 57– 18 02 17			0.43 (1)	

found in the area is indicated in the appropriate box in Table 2. Outside the region considered, no member star has yet reached the ZAMS, and as such it is not possible to calculate the reddening for the rest of the cluster field. The two member stars, number 304 and 338, are not plotted on the colour–colour diagram due to their relatively very high values of colour indices as compared to the rest of the member stars.

From Table 2, it is clear that the reddening is variable across the cluster from 0.25 to 0.48 mag and that the obscuration generally increases as one goes from west to east across the cluster and, less generally so, as one goes from north to south.

In view of the above the individual stars have been suitably dereddened in the discussions to follow, by applying corrections based on Table 2, if available. Otherwise, for stars belonging to regions for which reddening values have not available from Table 2, the same has been estimated on the basis of the nebulosity present on the photograph given in Walker's (1957) paper and visually comparing it with the nebulosity of the areas of known reddening.

5 Distance

The distance modulus to the cluster is obtained by fitting the cluster main sequence, in the $(V, B-V)$ colour–magnitude diagram (Fig. 2) and the $(V, U-B)$ colour–magnitude diagram (Fig. 3) to the standard ZAMS. Walker (1957) noted that a large number of cluster stars are spectroscopic binaries. We have, therefore, placed the ZAMS on the lower edge of the observed cluster main sequence. The value of the uncorrected distance modulus obtained in this way is 12.35 ± 0.1 mag. Taking the ratio of total to selective absorption, $R = 3.0$, the value of corrected distance modulus, $(m-M)_0 = 11.3 \pm 0.1$mag, implying that the cluster lies

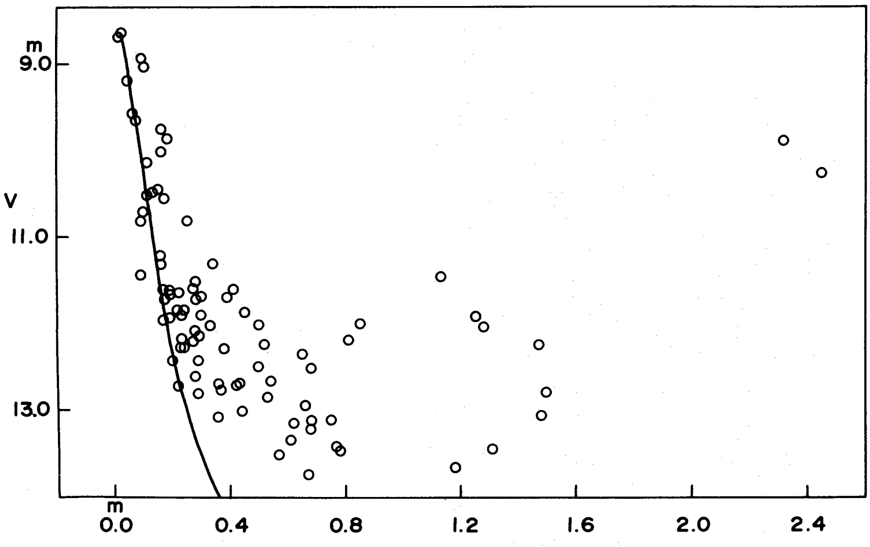

Figure 2. The $(V, B-V)$ colour–magnitude diagram of NGC 6530. The solid line represents the ZAMS fitted to the observations of members of NGC 6530.

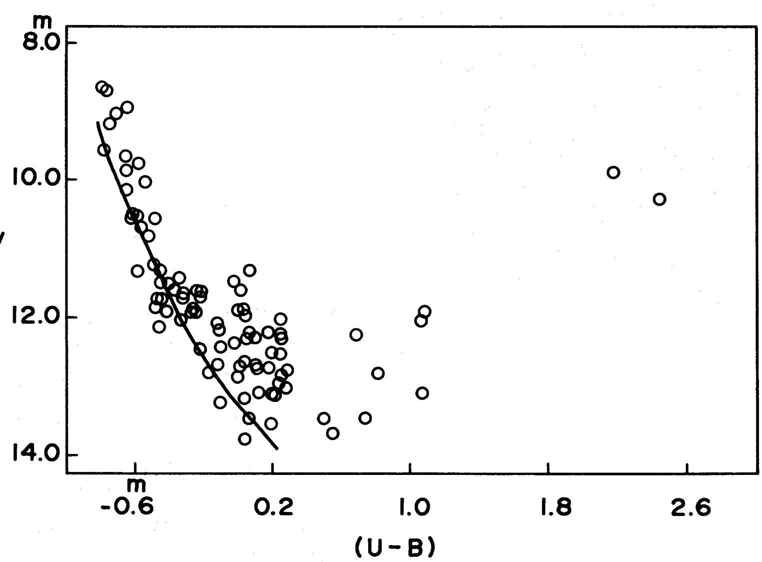

Figure 3. The $(V, U-B)$ colour–magnitude diagram of NGC 6530. The solid line represents the ZAMS fitted to the observations of members of NGC 6530.

somewhere between 1700 and 1900 pc from the Sun. For the same cluster, a distance of 1600 to 1800 pc has been determined by van Altena & Jones (1972) and of 1400 to 2000 pc by Walker (1957).

6 H–R diagram and age

The H–R diagram of NGC 6530 is plotted in Fig. 4 for a corrected distance modulus of 11.30 mag and applying a variable reddening across the cluster as indicated in Table 1. The values of absolute magnitudes and intrinsic colours are obtained using the relations:

$$M_V = m - 11.30 - 3E(B-V);$$

and

$$(B-V)_0 = (B-V) - E(B-V).$$

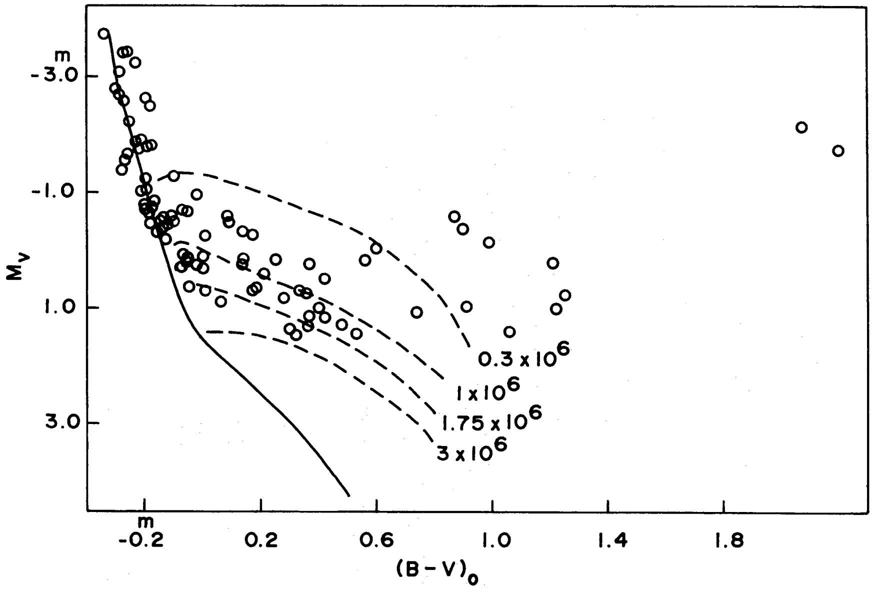

Figure 4. H–R diagram of NGC 6530. The solid line represents the ZAMS and the dotted lines represent the theoretical gravitational isochrones used by Iben & Talbot (1966), after converting from the ($\log L$, $\log T_e$) plane to the [M_V, $(B-V)_0$] plane for the cases 0.3, 1, 1.75 and 3 Myr.

From the H–R diagram the following inferences can be drawn:

(1) Stars having $(B-V)_0$ colour redder than -0.05 mag have perhaps not yet reached the ZAMS. On inspection of the cluster field we find that all the cluster members in the region $18^h 02^m.3 < \alpha < 18^h 03^m.7$ and $-24°38'.3 < \delta < -24°6'.0$ belong to this part of the H–R diagram.

(2) No cluster member has moved off the ZAMS.

(3) The H–R diagram can be divided into four regions according to the $(B-V)_0$ colour: $(B-V)_0 \leqslant -0.05$ mag; -0.05 mag $< (B-V)_0 < 0.60$ mag, 0.75 mag $< (B-V)_0 < 1.25$ mag and 2.05 mag $< (B-V)_0 < 2.2$ mag.

Stars in region 1 have reached the hydrogen-burning phase, while stars in the other regions are still under gravitational contraction. The gap between regions 2 and 3 and the distribution of stars on both the side of the gap in the H–R diagram of NGC 6530 (Fig. 4) can be explained on the basis of the convective episode in protostars, prior to reaching the ZAMS (Larson 1972).

The theoretical gravitational isochrones used by Iben & Talbot (1966), after converting from the ($\log L$, $\log T_e$) plane to the [M_V, $(B-V)_0$] plane, are plotted in Fig. 4. The method of the above transformation is similar to that described by Ulrich (1971). In view of the absence of a turnoff point in the H–R diagram of the cluster and based on the fitting of the theoretical time-constant loci in the H–R diagram of the member stars, it is clear that rather than assign a unique age to the cluster it would be preferable to set a lower limit of 2×10^6 yr for the age of the cluster and to say that, on present evidence, stars of the cluster have continued to evolve until as recently as 0.25 Myr. This is in agreement with the suggestion of Iben & Talbot (1966) and also with the age of 2×10^6 yr, determined by van Altena & Jones (1972).

Star numbers 304 and 338, with respective membership probability of 73 and 69 per cent, appear to be objects of interest. On the assumption of a uniform reddening, $E(B-V) = 0.35$ mag, across the cluster, van Altena & Jones (1972) have estimated them to be of absolute magnitudes -2.4 and -2.1 mag respectively and Parthasarathy (1974) ascribes them to be late-type giants on the basis of ultra-low dispersion slitless spectra. On evolutionary grounds this result is against the age of the cluster being 2×10^6 yr. The very young age assigned to the cluster can be consistent with the above stars being apparently red only if they are either heavily reddened B Stars (*cf.* Parthasarathy 1974) or are in the early stages of their evolution assuming their position in the H–R diagram or are field stars. The Q values for star numbers 304 and 338 are 0.50 and 0.68 respectively, indicating that they are not heavily reddened B stars. This is further supported by the photograph of the region in Walker's paper, where both these stars lie just outside the east boundary of the photograph and it is indicated that the stars are not heavily reddened. We are thus left with the other two alternatives. Spectroscopic study may help in understanding the nature of these stars. If these are young objects, further study of these stars is extremely important from the point of view of stellar evolution in the early stages.

Studies by Strom, Strom & Yost (1971), Strom *et al.* (1972a, b), Breger (1972) and Jones (1972) have suggested the existence of circumstellar shells around the contracting stars and

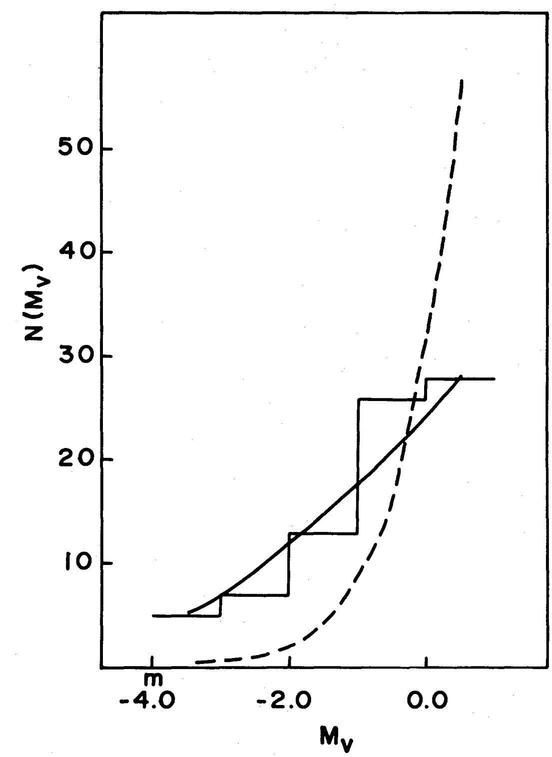

Figure 5. The histogram is the luminosity function of the cluster NGC 6530. The broken line represents the general luminosity function, $\phi(M_V)$ and the continuous line the initial luminosity function $\psi(M_V)$.

Table 3. Luminosity function for NGC 6530.

M_V	Observed number of stars	$\phi(M_V)$	$\psi(M_V)$
−3.99 – −3.00 mag	5	0.3	5.5
−2.99 – −2.00 mag	7	1.1	9.5
−1.99 – −1.00 mag	13	4.1	14.8
−0.99 – 0.00 mag	26	16.6	21.0
0.01 – 1.00 mag	28	56.9	28.2
1.01 – 2.00 mag	9	—	—
Total	88	79.0	79.0

have shown that such shells can account for some of the scatter in the H–R diagram, about the mean theoretical gravitational isochrones. Such an effect is also found in the theoretical model for the young stars by Larson (1972). The observational support of Larson's model is given by Kuhi (1974), on the basis of the energy distribution. According to Larson's calculations, the computed times for the onset of visibility of the stellar core for low-mass stars (i.e. $M < 2M_\odot$) increase with mass and are 2.8, 5.0, 8.7 and 12×10^5 yr for 0.25, 0.5, 1.0 and $1.5 M_\odot$ respectively. Thus for a cluster that is 10^6 yr old, the $1.5 M_\odot$ stars will have just become visible. On this ground, considering their location on the H–R diagram it is very likely that star numbers 304 and 338 have their masses around $1.5 M_\odot$.

Integrated magnitude and colours for the cluster have been computed using the method by Gray (1965) and the values obtained are $I(M_V) = -6.4$ mag, $I(B-V)_0 = -0.15$ mag and $I(U-B)_0 = -0.74$ mag.

7 Variables in the cluster

The magnitudes determined for star numbers 171, 284 and 338, on different nights, show a large difference, as compared to the photometric errors, which suggest that these stars may be variables. Further study of these stars is in progress.

8 Luminosity function

The observed, general and initial luminosity functions for NGC 6530 are calculated in the same manner as described by Sandage (1957). They are listed in Table 3 and are plotted in Fig. 5, which indicates that $\psi(M_V)$ is a considerably better approximation to the cluster luminosity function than $\phi(M_V)$. The poor fit of $\phi(M_V)$ to the cluster luminosity function at both ends shows that the cluster stars are younger than field stars and are well segregated from field stars. Walker (1957) has compared the luminosity function of NGC 6530 with those of NGC 2264 and the Orion Nebula cluster and found the luminosity functions to be similar.

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