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Integrated parameters of open clusters

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Summary. Integrated magnitudes and colours of population I synthetic clusters have been derived using the theoretical evolutionary tracks given by Stothers and Iben and an age-dependent initial mass function (IMF) obtained from the data of Tarrab. A comparison of the theoretically obtained integrated parameters with the observational data of open clusters in the Milky Way and clusters in the LMC has also been made. It is found that the observed dependences show a better agreement with the theoretical dependences obtained in the present work than the theoretical dependences obtained by earlier authors (Dixon, Ford & Robertson; Searle, Sargent & Bagnuolo; Barbaro & Bertelli and Chiosi, Bertelli & Bressan). It is also concluded that the clusters in the LMC in general show a mean reddening of $E(B-V) \simeq 0.12$ mag.

1 Introduction

Open clusters have been used to trace the structure of our Galaxy because several important parameters are more accurately measurable for open clusters than for single stars. With the increasing knowledge of some known physical parameters of open clusters, such as integrated magnitude and colours, age, metallicity and IMF, it has been possible to find solutions to some problems related to our Galaxy and to the nearby galaxies. The study of integrated parameters of star clusters as a function of their age is important for broad improvements in the theories of stellar evolution.

The studies related to the observed dependences of integrated parameters of open clusters have been carried out by several authors (Sagar, Joshi & Sinvhal 1983; Spassova & Baev 1985, and references therein). The integrated magnitude and colours for synthetic clusters have been derived by Dixon *et al.* (1972), Searle *et al.* (1973), Barbaro & Bertelli (1977) and Chiosi *et al.* (1986) with the purpose of comparing the results with the observed dependences of integrated parameters of open clusters and testing the theoretical evolutionary background on which the predicted dependencies are based.

In Figs 1–5 we have plotted the theoretical dependences derived by different authors along with the observed dependences for open clusters. The observed integrated parameters have been taken from Sagar *et al.* (1983) and also from Table 2 of the present study in the subsequent sections. Figs 1–5 manifest that:

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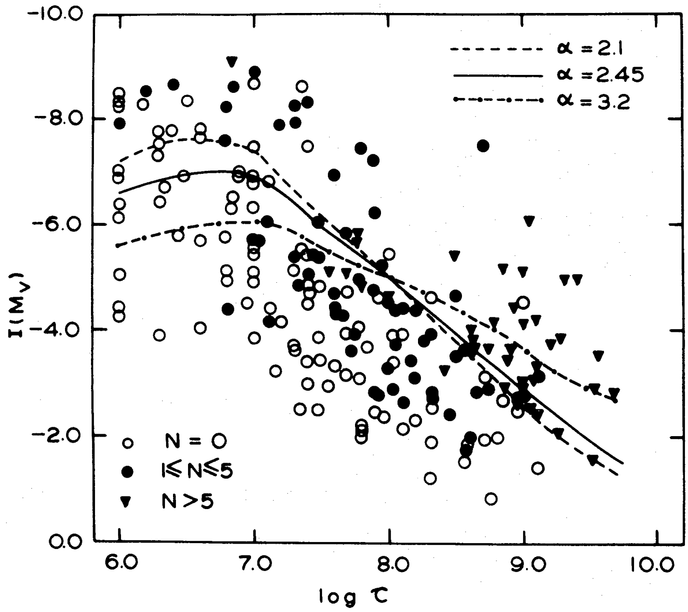

Figure 1. The $I(M_v)$-log age diagram. N is the number of red giants/supergiants in the open clusters. Curves represent theoretical dependences predicted by the model of Searle *et al.* (1983).

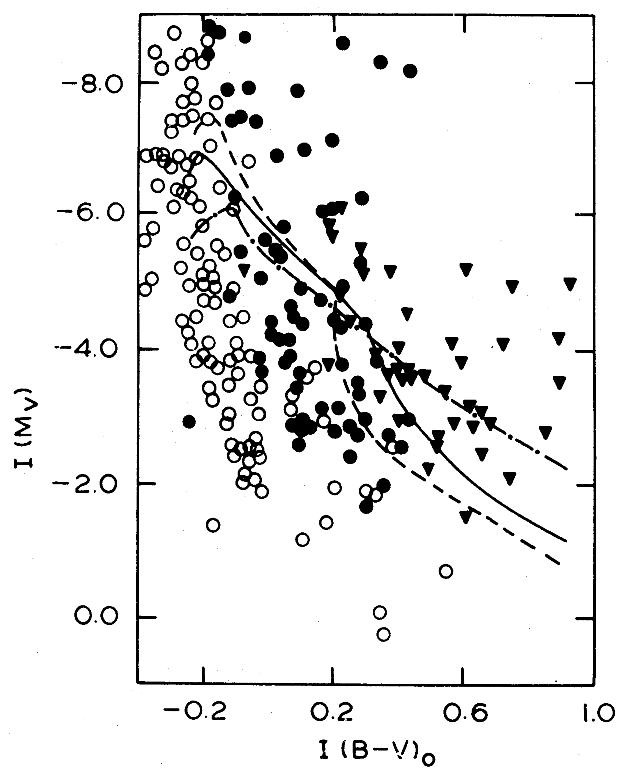

Figure 2. The $I(M_v)$-$I(B-V)_0$ diagram. The curves and symbols are the same as in Fig. 1.

(i) Except for $I(M_v)-\log \tau$ and $I(M_v)-I(B-V)_0$ dependences, the theoretically predicted dependences (Searle *et al.* 1973) agree fairly well with the observed dependences for the clusters having evolved stars. Similar conclusions have also been drawn by Spassova & Baev (1985). Elson & Fall (1985) have reported that, unlike the relation between colour and age, the relation between luminosity and age depends strongly on IMF.

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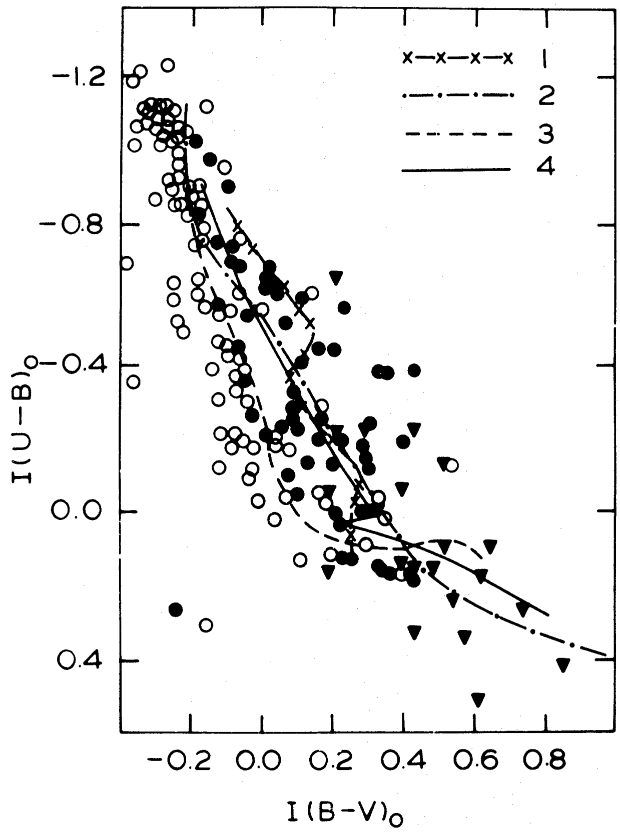

Figure 3. The $I(U-B)_0$–$I(B-V)_0$ diagram. The symbols are the same as in Fig. 1. The curves represent the theoretical dependences predicted by the models. (1) Dixon *et al.* (1972); (2) Searle *et al.* (1973) for $\alpha=2.45$; (3) Barbaro & Bertelli (1977) for the main sequence stars only and (4) Barbaro & Bertelli (1977) for the whole cluster.

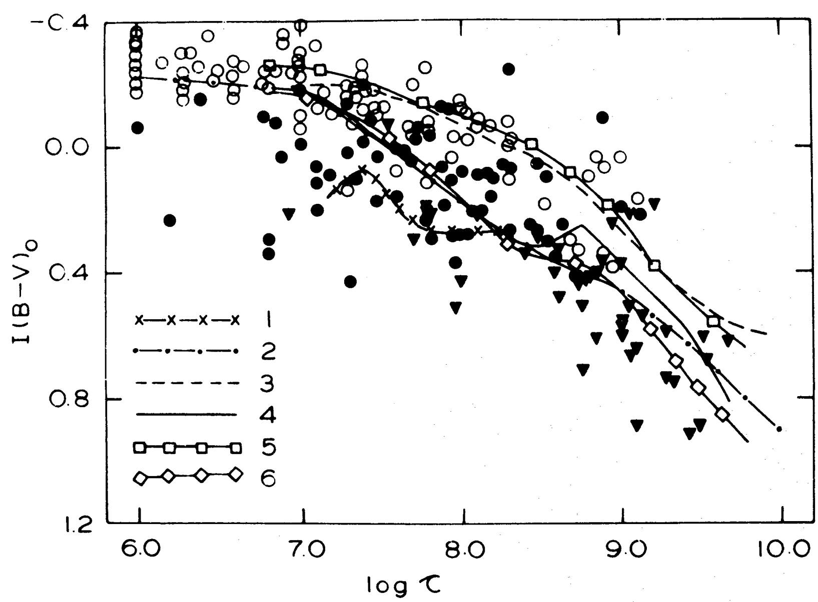

Figure 4. The $I(B-V)_0$–log age diagram. The symbols are the same as in Fig. 1. The curves represent the theoretical dependences predicted by the models. (1) Dixon *et al.* (1972); (2) Searle *et al.* (1973) for $\alpha=2.45$; (3) Barbaro & Bertelli (1977) for main sequence stars only; (4) Barbaro & Bertelli (1977) for the whole cluster; (5) Chiosi *et al.* for main sequence stars only and (6) Chiosi *et al.* for the whole cluster.

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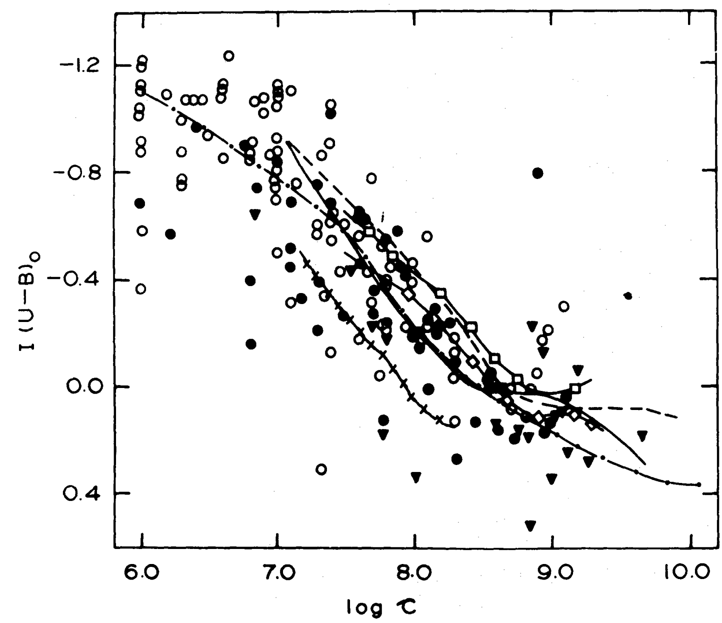

Figure 5. The $I(U-B)_0$–log age diagram. The curves and symbols are the same as in Figs 4 and 1, respectively.

(ii) The integrated $I(U-B)_0$ colours predicted by Barbaro & Bertelli (1977) are bluer than the observed ones. The $I(B-V)_0$ colours derived by Searle *et al.* (1973) and Barbaro & Bertelli (1977) do not follow the trend for the clusters consisting of evolved stars and having age $\geqslant 10^9$ yr.

(iii) $I(B-V)_0$ and $I(U-B)_0$ colours derived by Dixon *et al.* (1972) are redder in comparison to the observed integrated colours.

(iv) The $I(U-B)_0$ colours obtained from the model of Chiosi *et al.* (1986) are bluer than the observed colours.

The integrated magnitudes and colours of the synthetic clusters have been derived by all the authors using theoretical evolutionary tracks for specified chemical composition and assuming a constant IMF for all the synthetic clusters, irrespective of their age. However, the universality of IMF of open clusters in the Milky Way does not seem to be a valid assumption. Recently Stecklum (1985) has concluded that the IMF is a function of the age of the cluster and the steepness of the IMF of open clusters increases with increasing age. Freeman (1977) has concluded that the LMC clusters also indicate a large range of IMF, $0.2 \leqslant x \leqslant 2.5$ with a median value closer to the lower end.

Therefore, in the light of the above discussions, it was considered meaningful to derive the integrated magnitude and colours for synthetic clusters of different ages, taking into account that the IMF is a function of age, and then to compare the results with the observed integrated parameters of the open clusters.

2 Integrated parameters of synthetic star clusters

To calculate the integrated *UBV* magnitudes for star clusters of various ages, we have used the theoretical evolutionary tracks given by Stothers (1963) and Iben (1965, 1966a,b,c, 1967). For a given age the mass range of component stars in a synthetic cluster has been determined according to the following assumptions:

(i) For old clusters (up to the age of 5×10^9 yr) the lower mass limit, M_L, is not a relevant parameter, since the contribution to the integrated *UBV* magnitudes from dwarfs of late

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Table 1. The integrated magnitudes and colours of synthetic star clusters as a function of their age.

log τ	Main sequence			Whole cluster		
	$I(M_V)$	$I(B-V)_0$	$I(U-B)_0$	$I(M_V)$	$I(B-V)_0$	$I(U-B)_0$
6.8	−6.70	−0.28	−0.97	−9.85	−0.15	−1.05
7.0	−5.95	−0.24	−0.87	−7.85	−0.05	−0.85
7.3	−4.90	−0.19	−0.71	−6.35	0.00	−0.65
7.7	−3.65	−0.10	−0.43	−5.00	0.13	−0.30
8.0	−3.05	−0.01	−0.26	−4.20	0.20	−0.10
8.3	−2.75	0.04	−0.15	−3.58	0.28	0.02
8.7	−2.30	0.13	0.00	−2.85	0.35	0.10
8.9	−1.95	0.24	0.06	−2.60	0.42	0.18
9.3	−1.05	0.41	0.07	−2.25	0.60	0.20
9.5	0.60	0.46	0.07	−2.20	0.75	0.25

types is almost negligible (Barbaro & Bertelli 1977). In this case we have taken $M_L = 1\ M_\odot$.

(ii) Since in the present study we have computed the integrated colours and magnitudes of synthetic clusters older than 5×10^6 yr and at this age the stars having masses greater than 30 $M_\odot$ have already completed their evolution, the upper mass limit has been taken as $M_U = 30\ M_\odot$.

To convert the theoretical (Luminosity–T_{eff}) diagram into the colour–magnitude diagram, the luminosity–temperature points were classified into luminosity classes. The values of bolometric corrections, $(B-V)$ and $(U-B)$ colours were read out for each point from table 1 of Sagar *et al.* (1986) as a function of T_{eff} and luminosity class. The U, B and V magnitudes were calculated for each point from the values of $\log L$, BC, $B-V$ and $U-B$.

The integrated magnitudes for synthetic clusters have been obtained by summing the magnitudes of their component stars. Following the method adopted by Searle *et al.* (1973), if $\phi(m)$ is the number of stars in the cluster, at the time of its formation, in the mass range $m \rightarrow m + dm$ and $M_V(m, \tau)$ is the visual magnitude of one star of mass m and age τ, then the integrated magnitude of the cluster is expressed as

$$I(M_V)(\tau) = \sum_i M_V(m_i, \tau)\, \phi(m_i)\, \Delta m_i, \tag{1}$$

The mass function has been assumed to be

$$\phi(m) \propto m^{-x} \tag{2}$$

where x is the initial mass function (IMF) which has been considered to be dependent on the age of the cluster. The age dependence of the IMF has been obtained using the data of Tarrab (1982) and can be expressed as

$$x = 0.5 \log \tau - 2.4. \tag{3}$$

The integrated colours have been computed using the following expressions:

$$I(B-V) = 2.5 \log[I(M_V)/I(M_B)] \text{ and} \tag{4}$$

$$I(U-B) = 2.5 \log[I(M_B)/I(M_U)], \tag{5}$$

where $I(M_U)$, $I(M_B)$ and $I(M_V)$ are the integrated magnitudes in the U, B and V colours, respectively. The integrated magnitudes and colours, thus obtained as a function of age, are given in Table 1.

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Table 2. Integrated parameters of open clusters.

Name	$(m-M)$ mag	$E(B-V)$ mag	$\log \tau$	Integrated absolute values $I(M_V)$ mag	$I(B-V)_0$ mag	$I(U-B)_0$ mag	References
NGC 129	13.00	0.61	7.69	−5.78	0.05	–	26
NGC 869	13.48	0.56	7.00	−8.86	−0.18	−0.83	51
NGC 884	13.68	0.56	6.84	−9.11	0.21	−0.65	51
NGC 1245	12.65	0.28	9.04	−6.05	0.22	–	45
NGC 1502	11.90	0.74	7.30	−5.12	−0.19	–	45
NGC 1605	15.85	1.19	8.10	−3.90	−0.09	−0.55	7, 17
NGC 1907	12.10	0.47	8.64	−2.79	0.25	–	45
NGC 1912	11.47	0.24	7.36	−4.85	0.10	–	45
NGC 1960	11.17	0.22	7.40	−4.87	−0.17	–	45
NGC 2099	11.55	0.34	8.48	−5.35	0.29	–	45
NGC 2204	13.40	0.08	9.40	−4.96	0.92	0.70·	25, 31
NGC 2215	10.28	0.10	8.55	−1.68	0.30	0.00	5, 7
NGC 2244	12.48	0.46	6.48	−6.91	−0.22	–	39
NGC 2287	9.03	0.01	7.80	−4.78	0.22	−0.20	15, 22
NGC 2301	9.49	0.03	7.99	−3.32	0.28	−0.19	51
NGC 2324	12.63	0.11	8.82	−3.61	0.41	0.18	6, 7
NGC 2362	11.33	0.11	7.40	−7.46	−0.26	−0.90	6, 7
NGC 2384	13.50	0.31	6.00	−6.09	−0.29	−1.01	30
NGC 2422	8.64	0.08	7.89	−2.84	0.07	–	45
NGC 2447	10.38	0.06	7.99	−4.53	0.43	0.33	4, 7
NGC 2451	8.07	0.11	7.56	−5.10	−0.07	−0.44	18, 43, 71, 72, 73
NGC 2477	11.00	0.30	8.85	−5.15	0.61	0·.51	28, 29, 50
NGC 2506	12.76	0.05	9.26	−3.78	0.59	–	9
NGC 2547	8.43	0.06	7.83	−3.63	−0.09	−0.44	12
NGC 2910	10.75	0.09	7.60	−3.34	0.08	−0.17	6, 7
NGC 3293	12.94	0.31	7.40	−8.36	−0.19	−1.02	33, 62
NGC 3330	11.25	0.18	7.70	−3.91	−0.04	−0.31	5, 7
NGC 4103	12.00	0.30	7.35	−5.47	−0.16	0.31	70
NGC 4755	12.62	0.38	6.85	−8.64	−0.08	−0.74	13, 44, 49
NGC 5460	9.88	0.14	8.03	−3.86	−0.10	–	45
NGC 5662	10.00	0.32	7.80	−4.38	0.30	−0.24	32
NGC 6067	12.46	0.32	7.89	−7.16	0.19	–	55, 67, 68
NGC 6192	10.55	0.26	8.95	−2.65	0.52	−0.13	37
NGC 6383	11.65	0.35	6.65	−6.27	−0.27	−1.23*	2
NGC 6405	8.75	0.15	7.71	−3.65	−0.03	−0.27	2
NGC 6451	9.00	0.08	7.80	−0.73	0.53	−0.13	7, 54
NGC 6475	7.08	0.06	8.16	−3.44	0.09	−0.29	45
NGC 6520	12.03	0.31	9.00	−4.51	0.04	−0.20	7, 54
NGC 6664	12.95	0.75	7.70	−5.06	0.30	−0.23	3, 47
NGC 6705	12.45	0.40	7.78	−5.65	0.20	–	45
NGC 6913	13.42	0.78	6.30	−7.30	−0.30	−0.87	36
NGC 7243	10.12	0.24	7.72	−3.91	−0.05	−0.36	51
NGC 7762	11.97	0.79	8.90	−3.62	0.36	–	45
NGC 7788	12.74	0.28	7.20	−4.14	−0.10	–	45
NGC 7790	14.36	0.52	7.89	−4.76	−0.12	−0.57	27, 38
Basel 4	15.85	0.65	7.10	−6.03	0.20	−0.44	7, 53
Basel 5	10.67	0.39	9.10	−1.38	0.17	−0.29	7, 53
Basel 20	15.50	0.84	–	−6.75	−0.25	−0.63	56
Be 19	14.70	0.40	9.50	−1.50	0.60	–	10
Be 28	17.00	0.95	7.80	−7.42	−0.04	−0.54	8
Be 96	15.65	0.68	–	−6.20	−0.23	−1.04	14
Cr 121	9.09	0.03	6.20	−8.56	0.23	−0.56	16, 19

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Table 2. – *continued*

Name	*(m – M)* mag	*E(B – V)* mag	log τ	Integrated absolute values $I(M_V)$ mag	$I(B-V)_0$ mag	$I(U-B)_0$ mag	References
Cr 299	12.00	0.40	–	–2.91	0.17	–0.05	57
CV Mon	13.60	0.77	–	–3.80	0.33	0.15	48, 58
IC 348	9.31	0.47	7.00	–5.59	–0.39	–0.74	52
IC 2714	11.75	0.46	8.30	–4.59	–0.01	–0.03	6, 7
IC 4996	13.40	0.72	6.90	–6.96	–0.36	–1.01	1, 64
IC 5146	11.35	0.45	6.30	–3.90	–0.20	–	24, 69
King 8	14.80	0.68	8.90	–3.08	0.07	–0.04	11
King 12	13.95	0.60	7.00	–4.90	–0.20	–0.88	41
King 21	14.30	0.89	7.00	–4.90	–0.39	–0.69	42
Ru 36	12.11	0.15	8.30	–1.86	–0.02	–0.11	46, 66
Ru 77	16.00	0.79	–	–6.07	–0.21	–0.82	56
Ru 78	15.00	0.75	–	–6.23	0.29	0.00	56
Ru 83	13.50	0.57	–	–3.03	–0.03	–0.09	56
Ru 97	13.70	0.21	9.00	–5.13	0.38	0.71	40, 65
Stock 2	8.36	0.30	8.00	–4.46	0.08	–	45
Stock 14	13.00	0.26	6.80	–8.25	0.34	–0.39	59
Stock 16	12.90	0.49	6.60	–5.72	–0.27	–1.07	61
Mar 50	14.28	0.86	7.00	–5.48	–0.26	–0.92	63
Pismis 16	13.43	0.60	6.80	–4.42	0.30	–0.12	56
Tombough 1	11.31	0.27	8.90	–7.48	–0.09	–0.79	60
Tr 10	8.45	0.05	7.68	–3.15	–0.06	–0.42	34
Tr 14	13.00	0.50	7.00	–7.45	–0.30	–1.08	21
Tr 15	13.54	0.48	6.78	–7.50	–0.10	–0.90	23
Tr 16	13.82	0.49	7.00	–8.67	–0.29	–1.12	20
Tr 22	12.85	0.56	8.04	–4.39	0.22	–0.20	32
Tr 24	12.16	0.38	6.00	–8.33	–0.20	–0.87	35
Tr 31	11.35	0.43	9.10	–3.09	0.22	0.04	7, 54

* $I(U-B)_0$ is uncertain.

Notes: (1) For NGC 1605, 6451, 6520, Basel 4, 5, 20, Cr 299, Ru 77, 78, 83, Pismis 16 and Tr 31 original data were in the RGU system. These have been converted into the *UBV* system using the transformations given by Buser (1978). (2) For NGC 2215, 2447, 2910, 3330, IC 2714 original data were in the U_cBV system. These have been converted into the *UBV* system using the transformations given by Cousins & Stoy (1962). (3) If the reddening, distance and age estimates for the clusters are not available in the reference mentioned then these values have been taken from the catalogue of Lyngå (1983).

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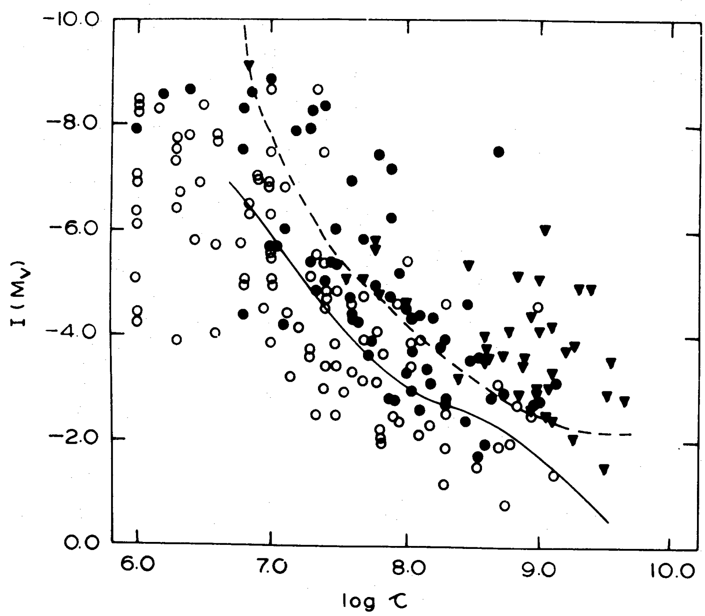

Figure 6. The $I(M_V)$–log age diagram along with the theoretical dependences obtained in the present work. The dashed curve represents the theoretical curve calculated for the whole cluster and the continuous curve represents the curve calculated for the main sequence part of the cluster.

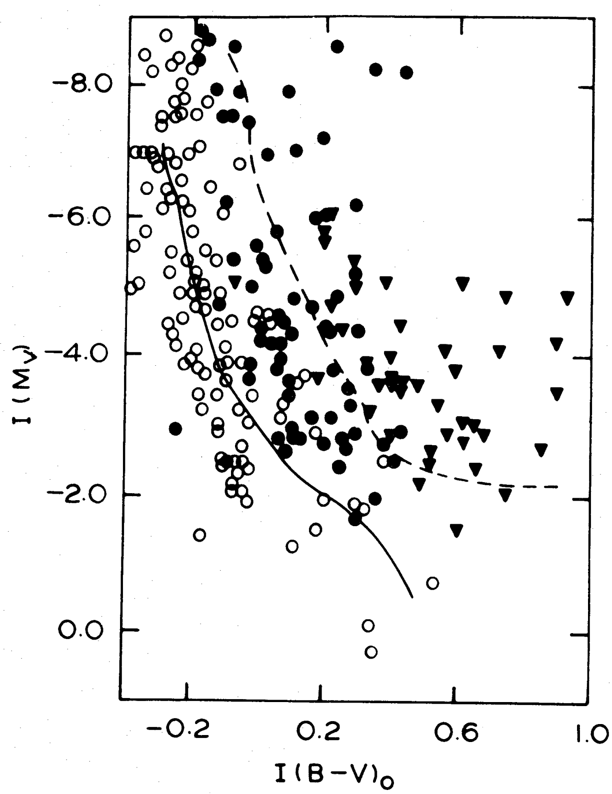

Figure 7. The $I(M_V)$–$I(B-V)_0$ diagram. The curves and symbols are the same as in Figs 6 and 1, respectively.

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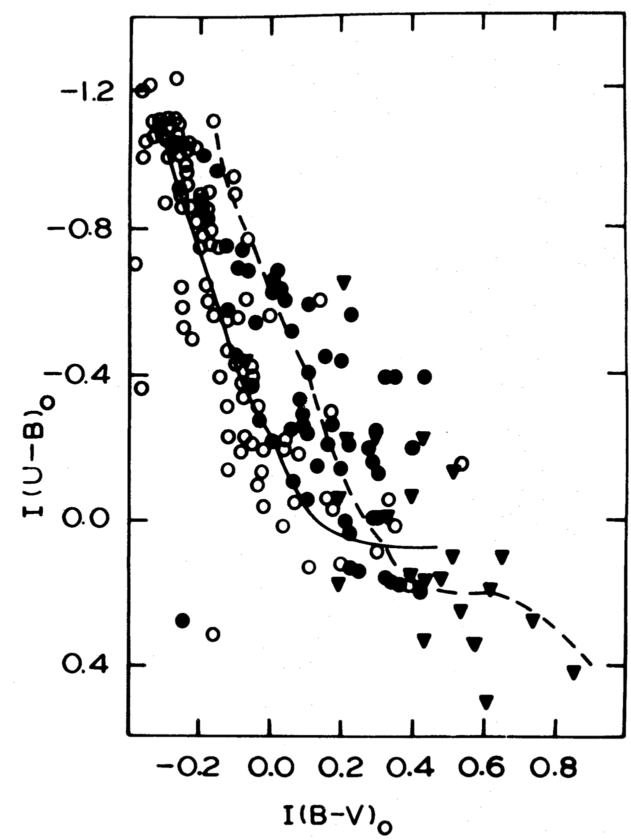

Figure 8. The $I(U-B)_0$–$I(B-V)_0$ diagram. The curves and symbols are the same as in Figs 6 and 1, respectively.

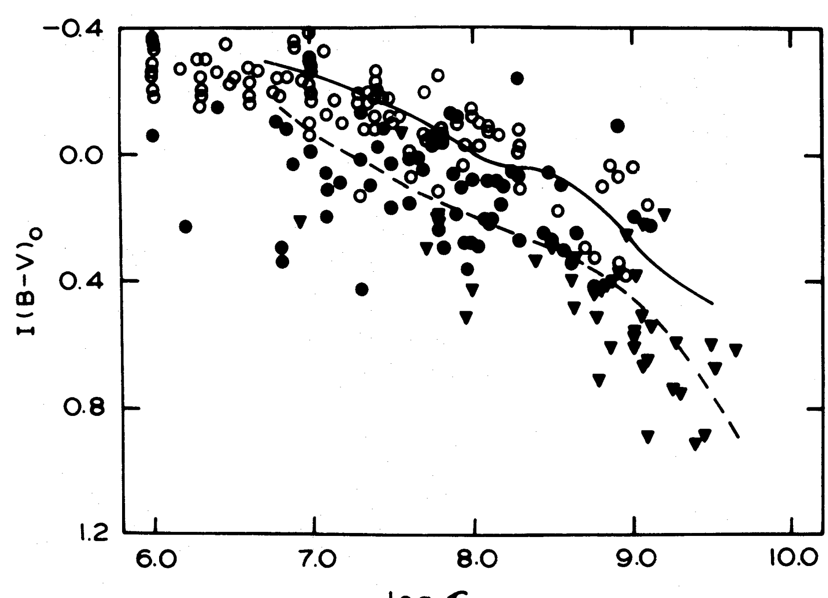

Figure 9. The $I(B-V)_0$–log age diagram. The curves and symbols are the same as in Figs 6 and 1, respectively.

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3 Comparison with the observed integrated parameters

Observed integrated parameters for the 142 open clusters have been taken from Sagar *et al.* (1983). Integrated parameters for 79 open clusters have been obtained using the method of Sagar *et al.* (1983) and these are given in Table 2. A maximum error of ± 0.5 mag in $I(M_V)$ and ± 0.2 mag in integrated colours has been estimated by Sagar *et al.* (1983). The ages of those clusters, for which no age is given in the catalogue of Sagar *et al.* (1983), have been taken from the catalogue of Lyngå (1983).

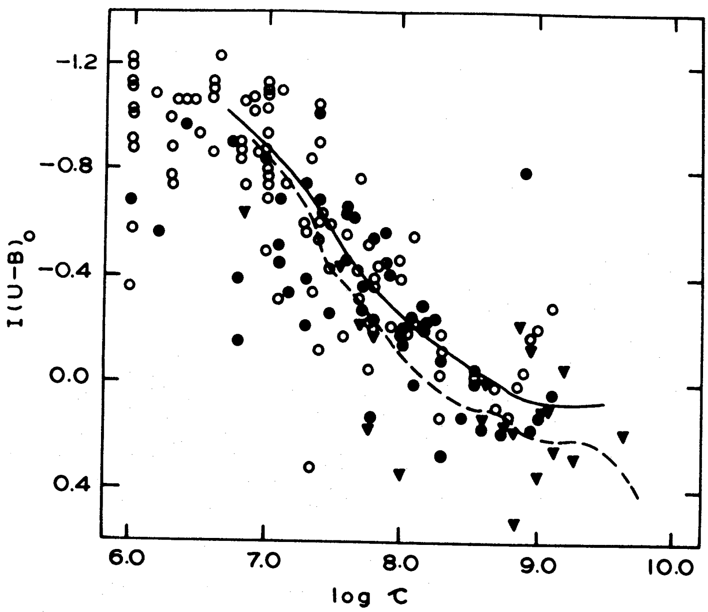

Figure 10. The $I(U-B)_0$–log age diagram. The curves and symbols are same as in Figs 6 and 1, respectively.

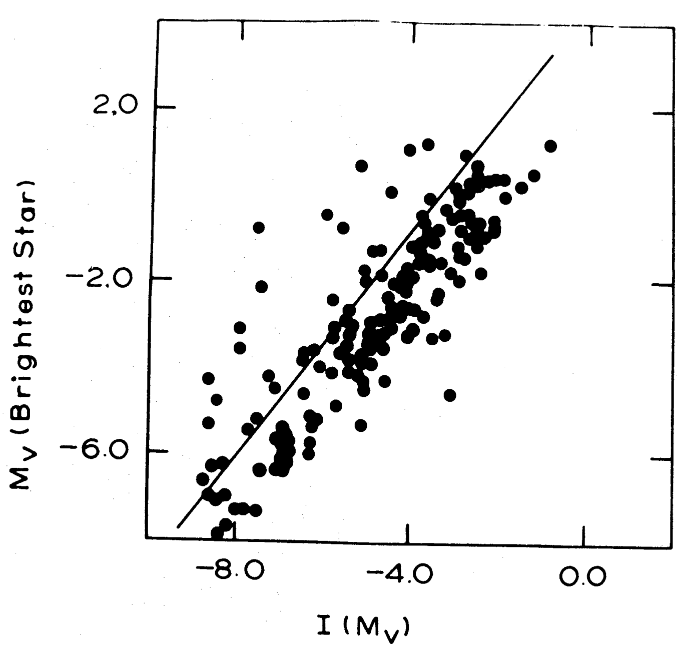

Figure 11. The M_v (brightest star) – $I(M_v)$ diagram. The solid curve represents the theoretical curve.

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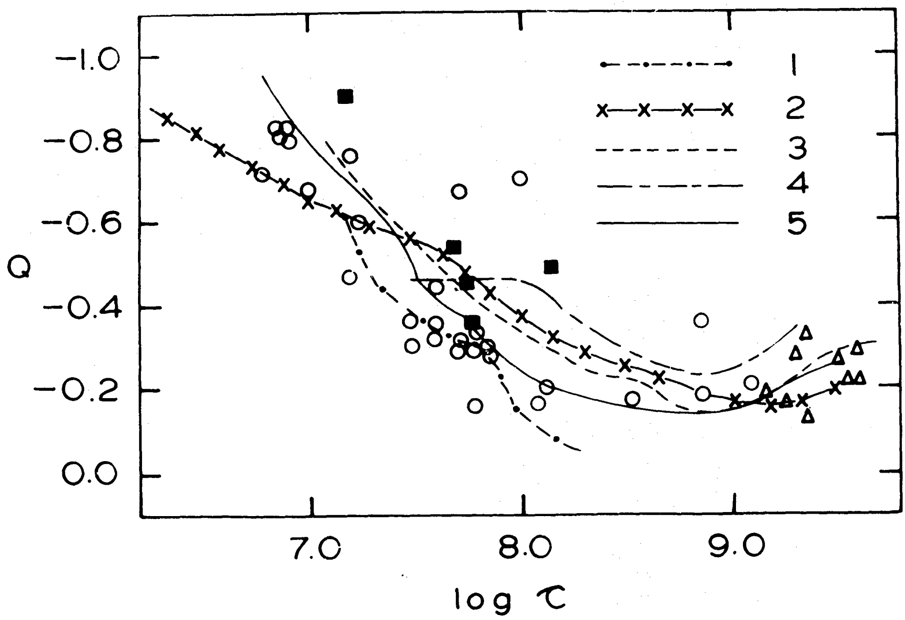

Figure 12. The Q–log age relation for the clusters in the LMC. The curves represent theoretical dependences. (1) Dixon *et al.* (1972); (2) Searle *et al.* (1973) for $\alpha = 2.45$; (3) Barbaro & Bertelli (1977); (4) Chiosi *et al.* (1986) and (5) present work. The ages of the clusters have been taken from Mould & Aaronson (1982) – triangles, Hodge (1983) – circles and Alcaino & Liller (1980) – squares.

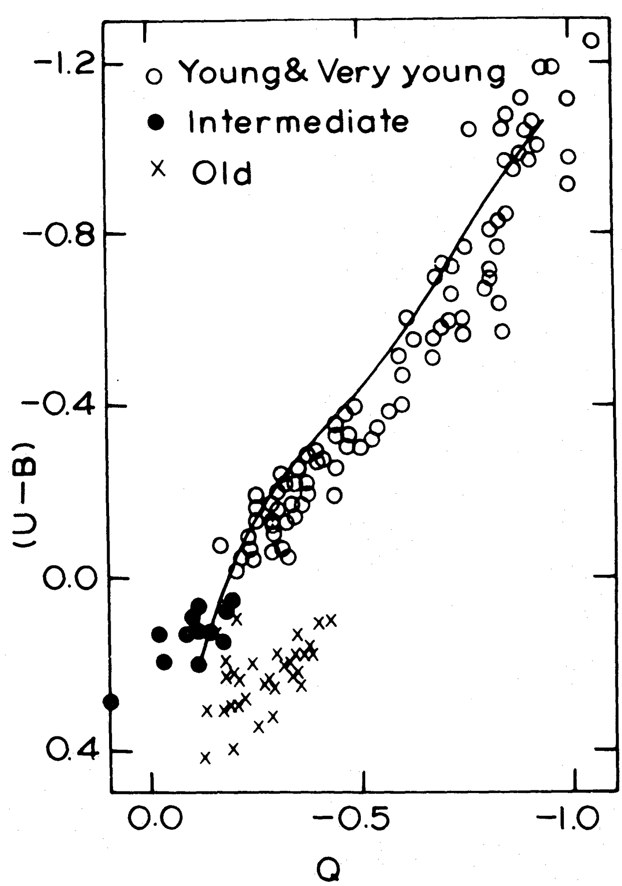

Figure 13. The $(U-B)$–Q diagram for the clusters in the LMC along with the theoretical dependences obtained in the present study.

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The observed dependences have been compared with the theoretical dependences obtained in the present study in Figs 6–11. Figs 6–11 manifest that the theoretical dependences obtained in the present study show significantly better agreement with the observed dependences than the theoretical dependences derived by earlier authors (Dixon, Ford, & Robertson 1972; Searle *et al.* 1973; Barbaro & Bertelli 1977; Chiosi *et al.* 1986). However, the use of the theoretical dependences shown in these figures, to derive the properties of individual clusters, may be subject to substantial error, as is apparent from the large scatter in the observed points.

4 Present model and clusters in the LMC

The rich star clusters in the Magellanic Clouds are very useful in studies of stellar evolution. The clusters in the LMC have large masses and appearances like globular clusters but in all other respects these clusters resemble the open cluster in our Galaxy. Their ages range from 10^6 to 10^{10} yr and most of the clusters in the LMC are members of disc populations (Freeman, Illingworth & Oemler 1983).

The work of van den Bergh (1981) provides a large collection of integrated magnitudes and colours for the clusters in the Magellanic Clouds. However, one can not directly use these data for comparison with the theoretical models because of the lack of reddening corrections. Assuming that the following relation holds between the colour excesses for the clusters in the Magellanic Clouds

$$E(U-B)=0.72\,E(B-V), \tag{6}$$

we have used the reddening free parameter, Q, defined by the relations

$$Q=(U-B)-0.72\,(B-V)=(U-B)_0-0.72(B-V)_0. \tag{7}$$

In Fig. 12 we have compared the observed Q–age dependence for the clusters in the Magellanic Clouds with the present model and also with the theoretical models given by Dixon *et al.* (1972), Searle *et al.* (1973), Barbaro & Bertelli (1977) and Chiosi *et al.* (1986). The values of the reddening free parameter, Q, have been taken from van den Bergh (1981) and the ages for the clusters have been taken from the studies of Mould & Aaronson (1982), Hodge (1983) and Alcaino & Liller (1986). Fig. 12 shows that present theoretical dependence is in fairly good agreement with the observed Q–age dependence for LMC clusters, whereas none of the other models completely explains the observed dependence.

In Fig. 13 we have plotted the $(U-B)$ colours against the Q-parameter for the clusters in the LMC along with the theoretical curve based on the present work. Fig. 13 indicates that the clusters in the LMC in general show a mean reddening $E(B-V)\simeq 0.12$ mag, whereas van den Bergh (1968), using a true colour line in the $[(U-B), (B-V)]$ diagram obtained by Gray (1965), has obtained a mean reddening $E(B-V)=0.20\pm 0.05$ mag for younger clusters and $E(B-V)=0.06\pm 0.01$ mag for older clusters. However, Efremov (1978) has pointed out that if the true colour line given by Gray (1965) is used to determine colour excesses for the cluster in the Magellanic Clouds then the colour excesses obtained for the youngest clusters will be considerably exaggerated. Colour excesses obtained for individual clusters in the LMC using the present model are in good agreement with those obtained by Efremov (1978).

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