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Integrated photometric characteristics of galactic open star clusters

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Abstract. Integrated $UBVRI$ photometric parameters of 140 galactic open clusters have been computed. Integrated $I(V-R)_0$ and $I(V-I)_0$ colours as well as integrated parameters for 71 star clusters have been obtained for the first time. These, in combination with published data, altogether 352 objects, are used to study the integrated photometric characteristics of the galactic open clusters. The $I(M_V)$ values range from -9.0 to -1.0 mag corresponding to a range in total mass of the star clusters from $\sim$25 to 4×10^4 $M_\odot$. The integrated colours have a relatively narrow range, e.g., $I(B-V)_0$ varies from -0.4 to 1.2 mag. The scatter in integrated colours at a given integrated magnitude can be understood in terms of differences in fraction of red giants/supergiants in the clusters. The observed integrated magnitudes and colours agree with the synthetic ones, except the dependences of $I(V-R)_0$ and $I(V-I)_0$ colours for clusters younger than $\sim$100 Myrs and also of the integrated magnitudes of oldest clusters. The large sample provides the most accurate age dependence of integrated magnitudes and colours determined so far. The luminosity function of the $I(M_V)$ has a peak around -3.5 mag and its slope indicates that only $\sim$1% of the open clusters in the galactic disc are brighter than $I(M_V) = -11$ mag. No variation has been found of integrated magnitude with galactocentric distance and metallicity.

Key words. galaxies – open clusters – integrated photometry – star formation

1. Introduction

Star clusters in a galaxy play an important role in understanding the processes of star formation and stellar evolution in the galaxy as well as galactic structure and evolution. The physical quantities required for such studies are best determined from the observations of individual cluster members. Unfortunately, such observations are not possible in the case of extra-galactic clusters because ground based optical telescopes can not resolve member stars that are separated by less than 1 arcsec. Even with the Hubble Space Telescope, where resolution is improved to 0.1 arcsec, all cluster members cannot be observed in galaxies like M 31, M 33 etc. On the other hand, in such cases integrated photometric parameters can still be observable and, in fact, integrated colours and spectra will remain for long time to come the only way to investigate the evolutionary history of stellar systems beyond the local group of galaxies. To interpret these parameters in terms of age, stellar content, metallicity etc. of the extra-galactic star clusters, it is necessary to study the integrated photometric parameters of those star clusters of our galaxy where observations of individual cluster members provide these parameters. Without understanding these integrated parameters, it may not be possible to study the observations of integrated light of star clusters of other galaxies, wherein it is not practical even to visually separate out the open clusters from the globulars. Integrated light characteristics of star clusters are thus very important.

Based on the observations of individual stars of a galactic star cluster, integrated photometric parameters have been estimated by several authors (Gray 1965, 1967; Schmidt-Kaler 1967; Piskunov 1972, 1974; Sagar et al. 1983; Spassova & Baev 1985; Pandey et al. 1989; Battinelli et al. 1994 and references therein). The luminosity distribution of integrated magnitudes of galactic clusters have been discussed in detail by van den Bergh & Lafontaine (1984). Spassova & Baev (1985) and Bhatt et al. (1991) have also obtained the integrated luminosity function. The slope of the luminosity function obtained by Bhatt et al. (1991) is steeper than that of van den Bergh & Lafontaine (1984).

Out of over 1200 open star clusters in our galaxy, reliable integrated photometric parameters are available only for about 200 objects. During the last decade multicolour CCD photometric data have been

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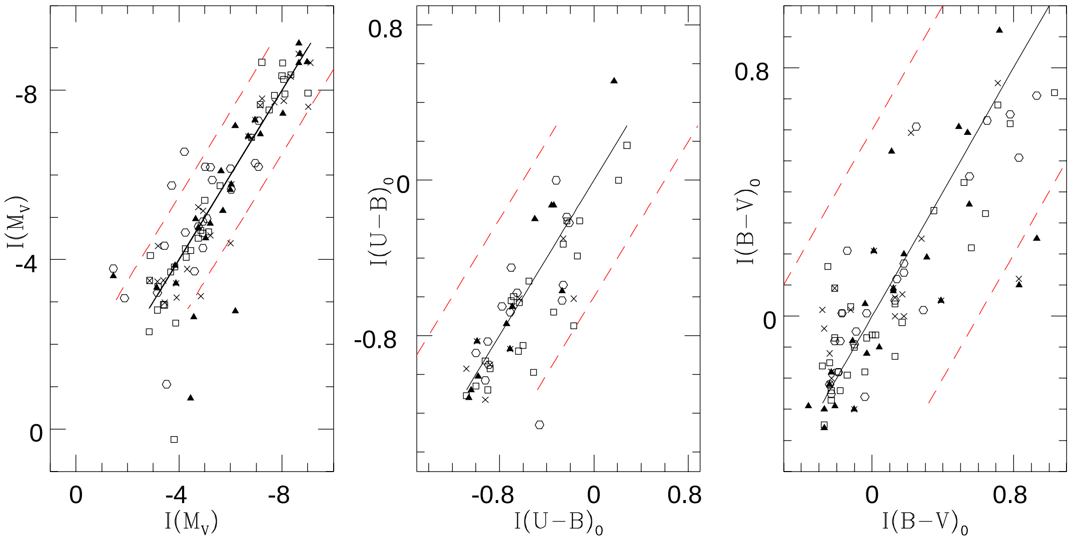

Fig. 1. Comparison of the integrated magnitudes $I(M_V)$ and $I(B-V)_0$, $I(U-B)_0$ colours obtained in this work with those given by Sagar et al. (1983) (squares), Pandey et al. (1989) (triangles), Spassova & Baev (1985) (crosses), and Battinelli et al. (1994) (hexagons). The solid line represents a slope of unity. The dashed lines represent 3σ uncertainties in the estimation of parameters.

obtained for a number of unstudied clusters. Mermilliod (1995) maintains a data base WEBDA (`http://obswww.unige.ch/webda`) for open star clusters. In order to re-investigate the luminosity function studies we have calculated integrated magnitudes and colours of 140 clusters in the $UBVRI$ passbands using the method given by Gray (1965). These in combination with earlier estimates provide integrated photometric parameters for 352 star clusters. The sample has been used to study the integrated luminosity function as well as various photometric properties of integrated light. The data and reduction procedures along with accuracy of parameters are described in the next section.

2. The data and their comparison

The UBV Johnson and RI Cousins CCD data of the open clusters have been taken from the WEBDA data base. To calculate the integrated parameters of the clusters, the photometric membership criterion has been used to reduce the effects of field star contamination. For this purpose, we fitted the theoretical isochrones by Bertelli et al. (1994) to the cluster sequence in the colour-magnitude diagram. The isochrones were brightened by 0.75 mag to take into account the maximum effects of binaries present in the cluster. This accounts for the broadening of the main-sequence which may also be due to other reasons, e.g., the photometric errors, internal reddening and spread in metallicity. The stars lying along the cluster sequence were considered members and used to compute the integrated parameters. Wherever CCD data for the bright stars were not available, the photoelectric data for these stars were taken from the data base. Altogether integrated parameters of 140 clusters were determined. The integrated parameters of 71 star clusters have been computed for the first time. The following relation was used to compute integrated magnitudes in $UBVRI$ passbands

$$I(m) = -2.5\ \log\left[\sum_i (10^{-0.4m_i})\right], \qquad (1)$$

where m_i is the magnitude of the ith member star in a passband. In order to account for un-observed faint stars we followed the method suggested by Battinelli et al. (1994). The integrated apparent colours of the clusters are determined as:

$$I(B-V) = I(B) - I(V) \qquad (2)$$

$$I(U-B) = I(U) - I(B) \qquad (3)$$

$$I(V-R) = I(V) - I(R) \qquad (4)$$

$$I(V-I) = I(V) - I(I). \qquad (5)$$

The apparent integrated magnitudes and colours, thus obtained, are converted to intrinsic ones and are listed in Table 1 along with the used distance and $E(B-V)$ values taken from the data base. The colour excesses $E(U-B)$, $E(U-V)$, $E(V-R)$ and $E(V-I)$ have been calculated from $E(B-V)$ using the relations $E(U-B) = 0.72E(B-V)+0.05E(B-V)^2$; $E(U-V) = 1.72E(B-V)$; $E(V-R) = 0.60E(B-V)$ and $E(V-I) = 1.25E(B-V)$. The possible source of errors in determination of the integrated parameters are same as described by Sagar et al. (1983). The uncertainty in integrated absolute magnitude could be ±0.5 mag and in colours it could be ±0.2 mag. Battinelli et al. (1994) have also reported the same order of uncertainty in their estimation of integrated parameters.

Figure 1 shows a comparison of the present integrated values with those available in the literature, where the solid line has a slope of unity. It indicates that the integrated magnitudes $I(M_V)$ are, in general ($\sim$92% lies

Table 1. Integrated parameters of the open clusters. The distance modulus $(m-M)$, $E(B-V)$ and log(age) are taken from data base.

				Integrated Absolute values				
Name of cluster	$(m-M)$ (mag)	$E(B-V)$ (mag)	$\log t$ (t in years)	$I(M_V)$ (mag)	$I(U-V)_0$ (mag)	$I(B-V)_0$ (mag)	$I(V-R)_0$ (mag)	$I(V-I)_0$ (mag)
1	2	3	4	5	6	7	8	9
NGC 129	12.71	0.55	7.76	−6.03	−0.25	0.39	–	–
NGC 146	13.61	0.49	7.60	−4.88	−0.75	−0.07	–	–
NGC 188	11.41	0.09	9.82	−2.86	–	1.13	0.7	1.39
NGC 381	11.27	0.34	8.47	−2.98	−0.31	0.11	–	–
NGC 433	14.58	0.86	7.50	−4.60	−0.36	−0.09	–	–
NGC 436	13.88	0.48	7.78	−5.21	−0.14	0.04	–	0.13
NGC 457	13.77	0.48	7.15	−9.01	−0.04	0.13	–	−0.11
NGC 581	13.16	0.44	7.13	−6.82	−0.75	−0.12	–	−0.10
NGC 637	14.12	0.70	6.96	−5.47	−1.13	−0.28	–	–
NGC 654	14.64	0.85	7.08	−7.71	−0.47	−0.21	–	–
NGC 659	14.00	0.64	7.63	−5.00	−0.26	−0.14	–	–
NGC 663	14.42	0.82	7.13	−8.02	−0.74	−0.14	–	–
NGC 869	13.48	0.58	7.10	−8.65	−1.22	−0.23	–	–
NGC 884	13.83	0.58	7.15	−8.65	−0.68	0.01	–	–
NGC 1039	8.82	0.10	8.26	−3.19	–	0.17	–	–
NGC 1193	13.55	0.12	9.90	−3.00	–	1.06	–	–
NGC 1245	13.07	0.31	9.16	−3.60	–	0.63	–	–
NGC 1750	10.08	0.34	8.30	−3.46	−0.40	0.04	0.05	0.13
NGC 1798	14.75	0.51	9.15	−4.86	0.97	0.82	–	1.14
NGC 1893	14.51	0.49	7.00	−7.63	−0.79	−0.19	–	–
NGC 1907	12.24	0.43	8.61	−6.19	–	0.93	–	–
NGC 1912	11.07	0.26	8.48	−5.22	–	0.83	–	0.32
NGC 1931	13.40	0.58	7.13	−3.15	−1.02	−0.20	−0.05	−0.07
NGC 2112	11.12	0.50	9.48	−1.88	–	0.65	–	–
NGC 2158	14.51	0.49	9.27	−2.81	–	0.61	–	–
NGC 2168	10.44	0.25	8.00	−4.93	−0.10	0.13	–	0.06
NGC 2192	13.36	0.20	9.04	−3.53	0.59	0.49	–	0.54
NGC 2204	13.44	0.08	9.27	−4.65	–	0.72	–	1.10
NGC 2243	13.17	0.03	9.49	−2.67	–	0.23	–	0.78
NGC 2244	12.61	0.48	6.80	−6.69	−1.07	−0.24	–	–
NGC 2264	9.57	0.06	6.99	−5.29	−1.27	−0.27	−0.11	−0.24
NGC 2266	12.98	0.10	8.86	−3.83	1.02	0.62	–	–
NGC 2355	12.10	0.12	8.85	−3.67	0.81	0.59	–	0.64
NGC 2383	12.33	0.27	7.61	−3.18	–	−0.05	0.04	0.08
NGC 2384	12.95	0.29	6.92	−5.63	–	−0.21	−0.22	−0.01
NGC 2420	12.02	0.02	9.32	−3.44	–	0.71	–	–

within 3σ), in fair agreement barring some points that deviate considerably from the relation. The difference is mainly due to the difference in the values of distance modulus used. The $I(U-B)_0$ and $I(B-V)_0$ colours are also in fair agreement (∼97% lies within 3σ) barring a few points which show large deviation.

3. Comparison of integrated parameters with theoretical models

In the present work we have calculated integrated photometric parameters for 140 clusters. The integrated photometric data along with age estimates for another 162 clusters are taken from Sagar et al. (1983) and Pandey et al. (1989). When age estimates are not available in these catalogues they are taken from the catalogue of Mermilliod (1995). As a comparison of these observed integrated parameters with those obtained for synthetic clusters provides a check to basic assumptions made to derive synthetic parameters, the same is done below.

3.1. Colour-magnitude diagram

In Fig. 2, we plot $I(M_V)$ against $I(B-V)_0$. The values of $I(M_V)$ range from −9.0 to −1.0 mag while $I(B-V)_0$ varies from −0.4 to 1.2 mag. The variations in the parameters are thus significantly larger than the corresponding errors in them. The $I(M_V)$ is related linearly with the

Table 1. continued.

Name of cluster 1	$(m-M)$ (mag) 2	$E(B-V)$ (mag) 3	$\log t$ (t in years) 4	Integrated Absolute Values $I(M_V)$ (mag) 5	$I(U-V)_0$ (mag) 6	$I(B-V)_0$ (mag) 7	$I(V-R)_0$ (mag) 8	$I(V-I)_0$ (mag) 9
NGC 2421	13.23	0.50	7.25	−4.75	−0.89	−0.21	–	–
NGC 2439	14.39	0.39	7.13	−8.00	0.38	0.52	–	–
NGC 2453	13.53	0.47	7.00	−5.15	–	−0.25	–	−0.12
NGC 2477	12.00	0.33	8.95	−5.70	0.66	0.49	–	0.67
NGC 2489	13.25	0.45	8.18	−3.91	1.06	0.35	–	–
NGC 2506	12.89	0.13	9.07	−4.31	0.76	0.54	0.37	0.78
NGC 2567	11.47	0.09	8.43	−3.68	–	0.56	–	–
NGC 2627	14.62	0.63	8.20	−4.84	–	0.24	–	0.00
NGC 2658	14.18	0.40	8.30	−3.87	−0.03	0.03	–	–
NGC 2660	13.52	0.38	9.22	−4.08	0.95	0.61	–	1.31
NGC 2670	11.63	0.45	7.73	−4.24	–	0.62	–	0.74
NGC 2682	9.75	0.07	9.72	−3.16	1.06	0.78	0.56	–
NGC 2818	13.11	0.18	8.97	−3.54	0.61	0.48	0.17	0.37
NGC 2910	11.16	0.07	8.50	−3.14	–	0.12	–	–
NGC 3114	9.95	0.06	7.93	−5.33	–	0.22	–	–
NGC 3766	11.98	0.20	7.42	−7.09	−0.53	0.11	–	−0.14
NGC 4103	12.16	0.29	7.46	−4.70	−0.82	−0.18	−0.04	−0.03
NGC 4755	12.90	0.40	7.26	−8.65	−0.85	−0.11	−0.05	−0.03
NGC 4815	14.64	0.78	8.48	−6.02	0.32	0.29	–	–
NGC 5168	13.34	0.66	8.18	−3.72	0.52	0.33	–	–
NGC 5460	9.23	0.12	8.06	−3.84	–	0.04	–	–
NGC 5606	12.98	0.49	6.87	−5.02	−1.14	−0.24	−0.10	−0.22
NGC 5617	12.57	0.51	7.57	−4.25	−0.87	−0.17	–	–
NGC 5999	13.00	0.45	8.60	−3.85	–	0.18	–	0.29
NGC 6005	13.59	0.45	9.08	−3.66	–	0.45	–	0.80
NGC 6031	12.75	0.50	8.40	−3.87	–	−0.03	–	0.00
NGC 6067	12.34	0.37	7.97	−6.18	–	0.31	–	0.61
NGC 6087	10.26	0.18	7.91	−5.09	−0.03	0.18	–	–
NGC 6192	12.94	0.66	7.96	−4.57	−0.46	−0.10	–	–
NGC 6204	11.63	0.43	7.92	−3.75	−0.58	−0.07	–	–
NGC 6231	12.30	0.41	6.75	−8.34	−1.15	−0.23	–	−0.18
NGC 6253	11.53	0.20	9.70	−2.68	1.15	0.81	0.58	0.97
NGC 6451	13.55	0.67	8.05	−4.45	−0.23	0.11	–	0.52
NGC 6475	7.08	0.06	8.11	−3.89	–	0.12	–	0.50
NGC 6520	13.34	0.44	8.14	−5.03	−0.54	−0.04	–	–

total mass of the cluster and according to Lyngå (1982), $I(M_V) \sim -8$ mag correspond to 4×10^3 $M_\odot$. Part of the variation in integrated parameters of the clusters can be understood in terms of the difference in the total mass of the clusters. A comparison of the observed data points with the Battinelli & Capuzzo-Dolcetta (1989) theoretical evolutionary model for solar composition indicates that range in total mass of the present sample of clusters is from ∼25 to 4×10^4 $M_\odot$. The scatter in $I(B-V)_0$ at a given $I(M_V)$ increases with decreasing integrated brightness of the cluster. This can be understood if one considers the fraction f of red giants/supergiants present in the cluster. The fraction is calculated for the three brightest bins of V magnitude assuming that the brightest bins are not affected by the incompleteness of the data. For a given $I(M_V)$ (or total mass) of the cluster, the value of f will depend upon the age, the mass function (MF) and dynamical state of the cluster and consequently the $I(B-V)_0$ value increases with the cluster age. On the other hand, for star clusters of the same age and $I(M_V)$, but differing MF and the dynamical evolution, the integrated colours of those open clusters will be relatively redder in which relatively heavier stars are present since, due to evolution, the stars will become red giants/supergiants and will therefore affect the $I(B-V)_0$. Figure 2, in fact, provides an observational support for this, as the clusters with a large fraction of red giants/supergiants have relatively redder $I(B-V)_0$ values. The spread in the values of $I(M_V)$ and $I(B-V)_0$ present in Fig. 2 can thus be understood in terms of above mentioned factors.

Table 1. continued.

Name of cluster	$(m-M)$ (mag)	$E(B-V)$ (mag)	$\log t$ (t in years)	Integrated Absolute Values $I(M_V)$ (mag)	$I(U-V)_0$ (mag)	$I(B-V)_0$ (mag)	$I(V-R)_0$ (mag)	$I(V-I)_0$ (mag)
1	2	3	4	5	6	7	8	9
NGC 6603	15.31	0.79	8.30	−6.40	–	0.22	–	0.26
NGC 6611	14.03	0.76	6.10	−7.15	−1.36	−0.28	–	–
NGC 6649	16.01	1.37	7.69	−6.92	−0.34	0.08	–	–
NGC 6705	12.61	0.42	8.05	−6.00	−0.43	0.18	–	–
NGC 6709	10.90	0.32	8.01	−3.43	–	0.11	–	0.51
NGC 6716	9.51	0.13	7.97	−2.84	−0.32	0.00	–	–
NGC 6755	13.69	0.85	7.78	−4.21	−0.70	-0.14	–	–
NGC 6791	13.93	0.20	9.86	−4.14	1.84	1.02	–	1.45
NGC 6823	14.40	0.85	6.56	−7.22	−1.12	-0.24	−0.16	−0.27
NGC 6871	12.41	0.47	6.95	−7.28	−1.13	−0.24	–	–
NGC 6913	13.47	0.78	7.19	−6.96	−0.81	−0.10	–	–
NGC 7044	14.63	0.70	9.20	−3.93	1.06	0.58	–	0.82
NGC 7380	14.20	0.60	6.96	−7.50	−0.69	−0.18	–	–
NGC 7419	17.28	1.71	7.15	−6.51	−0.90	0.04	−0.05	−0.11
NGC 7510	16.03	1.02	7.00	−7.69	–	−0.16	–	–
NGC 7654	12.95	0.65	7.72	−7.08	–	0.14	–	-0.09
NGC 7762	11.74	0.76	9.23	−1.45	–	0.55	–	–
NGC 7790	14.10	0.53	7.74	−4.75	−0.30	−0.03	–	–
Trum 1	14.02	0.63	7.43	−5.65	−0.92	−0.04	–	–
Trum 5	14.24	0.58	9.50	−5.06	–	0.84	–	1.01
Trum 14	14.21	0.52	6.50	−8.03	−1.31	−0.27	−0.12	−0.22
Trum 16	14.08	0.52	6.43	−8.98	−1.42	−0.36	–	–
Be 2	16.16	0.80	8.90	−4.18	0.60	0.46	–	–
Be 7	14.61	0.80	6.60	−4.54	−0.94	−0.15	–	–
Be 14	15.37	0.52	9.20	−4.07	0.60	0.67	–	0.51
Be 18	14.50	0.46	9.63	−4.90	2.14	0.93	–	–
Be 21	15.93	0.76	9.34	−3.41	1.56	0.37	–	–
Be 22	16.01	0.64	9.68	−3.27	–	0.88	–	–
Be 29	16.40	0.21	9.60	−4.64	–	0.70	–	–
Be 30	15.00	0.50	8.48	−5.11	0.21	0.29	–	–
Be 31	14.25	0.13	9.90	−2.57	0.95	0.73	–	–
Be 32	13.20	0.16	9.53	−2.97	1.06	0.78	–	–
Be 33	15.57	0.70	8.85	−4.61	–	0.43	–	0.62
Be 39	13.78	0.12	9.90	−4.28	–	0.93	–	–

The integrated colour-magnitude diagram seems to confirm the reliability of cluster-integrated photometry as only just a few lie to the left of the ZAMS. The anomalously blue ($I(B-V)_0 < -0.33$) colours are within the uncertainties in the integrated $I(B-V)_0$ colour. As already mentioned by Sagar et al. (1983), contrary to the suggestions made by Gray (1965), the observed as well as theoretical relations between $I(M_V)$ and $I(B-V)_0$ do not seem to be linear.

3.2. Evolutionary effects

In addition to the data of 302 clusters discussed above, we include the data of 50 additional clusters from Battinelli et al. (1994) for further discussion. They could not be used in Fig. 2 due to lack of knowledge of the fraction of red giants/supergiants in individual clusters. The observed as well as theoretical dependences of the integrated magnitude and colours are plotted against log(age) in Fig. 3. This indicates that as a cluster becomes older, its integrated brightness decreases while the integrated colours become redder, as expected due to stellar evolutionary effects. However, at a given cluster age, there is a scatter in integrated parameters. In $I(M_V)$, the standard deviation (σ) in various log (age) bins ranges from 0.9 to 1.7 mag while in integrated colours it ranges from 0.04 to 0.3 mag. The scatter in the integrated magnitudes is thus larger than that in the integrated colours and can not be accounted for in terms of errors in $I(M_V)$. This can be explained in terms of difference in the initial mass of the parent cloud from which a cluster is formed. It can vary from 10^4 to 10^6 $M_{\odot}$, as the star formation efficiency is

Table 1. continued.

Name of cluster	$(m-M)$ (mag)	$E(B-V)$ (mag)	$\log t$ (t in years)	Integrated Absolute Values: $I(M_V)$ (mag)	$I(U-V)_0$ (mag)	$I(B-V)_0$ (mag)	$I(V-R)_0$ (mag)	$I(V-I)_0$ (mag)
1	2	3	4	5	6	7	8	9
Be 42	12.45	0.74	9.03	−0.72	0.71	0.64	0.33	–
Be 54	14.27	0.77	9.60	−3.21	–	0.85	–	–
Be 58	14.61	0.55	8.42	−5.04	0.37	0.32	–	–
Be 62	14.05	0.86	7.00	−4.04	−0.58	−0.08	–	–
Be 64	16.30	1.05	9.00	−4.01	–	0.60	0.48	0.59
Be 69	14.60	0.65	8.95	−3.16	0.59	0.38	0.15	0.42
Be 81	15.59	1.00	9.00	−4.70	–	0.60	–	–
Be 86	12.93	0.88	7.05	−5.98	−1.20	−0.28	−0.09	−0.12
Be 99	14.41	0.30	9.50	−3.66	–	1.00	–	–
IC 1311	13.93	0.28	9.20	−3.90	1.17	0.85	–	–
IC 1590	13.37	0.32	6.54	−6.52	−1.19	−0.20	–	–
IC 1805	14.27	0.80	6.67	−8.07	−1.13	−0.23	–	–
IC 2602	6.23	0.05	7.36	−4.28	–	−0.19	–	–
IC 4665	8.29	0.19	7.58	−3.40	–	−0.10	–	–
IC 4651	9.90	0.13	9.52	−2.89	–	1.03	–	0.81
IC 4996	13.44	0.66	7.00	−7.17	−1.25	−0.27	−0.17	−0.37
Pism 19	16.39	1.45	9.04	−4.59	–	0.45	–	–
Pism 20	16.41	1.20	6.38	−8.69	−1.26	−0.23	–	–
Coll 74	13.21	0.38	9.11	−2.88	0.80	0.76	–	1.15
Coll 228	12.76	0.30	6.69	−7.70	−1.26	−0.24	–	–
Coll 261	12.57	0.27	9.95	−2.87	–	1.07	–	1.05
Coll 272	13.25	0.45	7.11	−5.31	−0.75	−0.16	−0.01	0.01
Haff 6	13.94	0.43	9.00	−3.81	–	0.47	–	–
King 7	15.71	1.25	8.80	−4.96	–	0.25	–	–
King 10	16.24	1.16	7.70	−5.34	−0.77	−0.19	−0.11	0.68
Stock 24	13.85	0.50	8.08	−5.04	–	0.26	–	–
Rup 32	15.24	0.50	7.08	−5.20	–	−0.26	–	–
Rup 79	14.40	0.76	7.66	−4.46	−0.68	−0.13	–	–
Rup 115	13.75	0.65	8.78	−3.50	–	0.29	–	0.55
Rup 120	13.75	0.70	8.18	−3.76	–	0.14	–	0.27
Terzan 7	17.48	0.12	9.89	−5.20	–	0.80	–	–
Melo 71	12.25	0.01	8.65	−3.83	0.85	0.64	–	0.77
Melo 105	13.08	0.48	8.29	−4.27	−0.04	0.07	–	–
Dolid 25	16.19	0.81	7.11	−8.11	−0.32	0.02	–	–
Bochum 2	15.65	0.86	6.56	−6.05	−1.43	−0.30	–	–

generally only a few percent and the observed total stellar mass of the cluster varies from ∼25 to $4 \times 10^4\ M_\odot$ (see Sect. 3.1). Since the clusters formed from the massive molecular clouds will contain a larger number of brighter stars in comparison to those clusters which are formed from the less massive molecular clouds, there will be a range in integrated parameters of star clusters of a given age.

The age dependence of the integrated parameters has been discussed by many investigator (see Gray 1965; Sagar et al. 1983; Balázs 1986; Pandey et al. 1989; Battinelli et al. 1994). The least-square linear regressions used in the present sample of 352 yield the following relations between the various parameters:

$$I(M_V) = (1.20 \pm 0.08)(\log\ t) + (-14.12 \pm 0.66) \quad (6)$$

with $\chi^2 = 2.017$

$$I(U-V)_0 = (0.74 \pm 0.03)(\log\ t) + (-6.07 \pm 0.23) \quad (7)$$

with $\chi^2 = 0.171$

$$I(B-V)_0 = (0.31 \pm 0.01)(\log\ t) + (-2.36 \pm 0.09) \quad (8)$$

with $\chi^2 = 0.037$

$$I(V-R)_0 = (0.22 \pm 0.02)(\log\ t) + (-1.65 \pm 0.17) \quad (9)$$

with $\chi^2 = 0.011$

$$I(V-I)_0 = (0.44 \pm 0.03)(\log\ t) + (-3.25 \pm 0.25) \quad (10)$$

with $\chi^2 = 0.048$

where t is the age (in years) of the cluster. The above relations indicate that the age of a cluster can be estimated

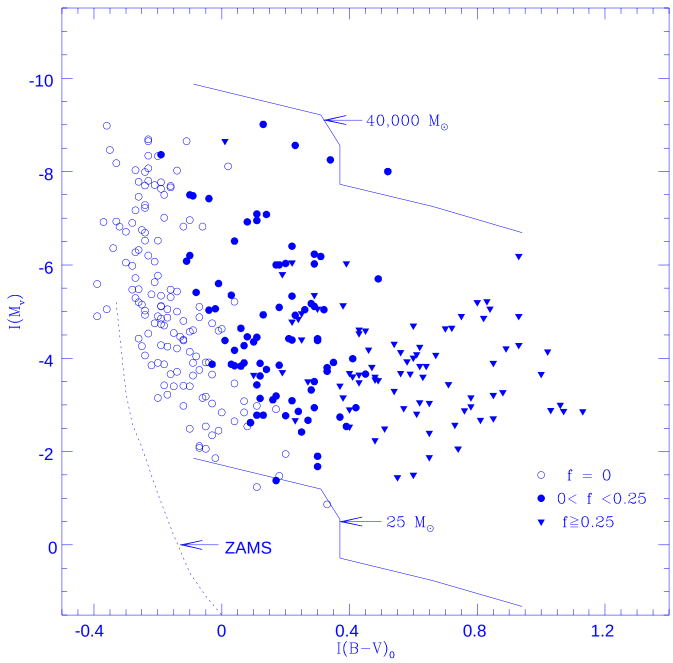

Fig. 2. The $I(M_V)$, $I(B-V)_0$ diagram. f is the fraction of red giants/supergiants in the open clusters. The curves with solid lines are theoretical evolutionary tracks given by Battinelli & Capuzzo-Dolcetta (1989). The dotted curve is the location of the zero-age main sequence (ZAMS) given by Schmidt-Kaler (1982).

from the observed integrated parameters of star clusters of solar metallicity in external galaxies and it can be determined accurately with integrated colours in comparison to integrated magnitudes. Amongst colours, the $I(U-V)_0$ colour provides the best age estimate.

A comparison of the coefficients of the relations 6 to 8 with the corresponding values given by Gray (1965) and Balázs (1986) indicates that the present coefficients are better determined due to use of larger sample. In order to see whether higher orders fit the data points better, the least-square fitting of a polynomial of second order has been carried out. They yield the following relation:

$$I(B-V)_0 = (0.07 \pm 0.01)(\log\ t)^2 + (-0.79 \pm 0.16)(\log\ t) + (1.99 \pm 0.64) \quad (11)$$

with $\chi^2 = 0.033$ indicating a marginal improvement over the χ^2 value earlier obtained with the linear relation. Similar improvements are also observed in other relations, e.g., in

$$I(M_V) = (-0.36 \pm 0.08)(\log\ t)^2 + (6.90 \pm 1.24)(\log\ t) + (-36.53 \pm 4.88), \quad \chi^2 = 1.904. \quad (12)$$

The average value of observed parameters is compared with the the synthetic parameters in Fig. 3. This indicates that:

(i) The theoretical dependences of $I(B-V)_0$ –log (age) and $I(U-B)_0$ –log (age), given by Pandey et al. (1989); Maraston (1998) and Brocato et al. (1999) agree fairly well with the observed ones. However, the theoretical dependences of $I(V-R)_0$ and $I(V-I)_0$ on log (age), given by Maraston (1998) and Brocato et al. (1999) differ from the observed one for clusters younger than ∼100 Myrs.

(ii) The observed dependence of integrated luminosity on the age is compared with models in Fig. 3. The theoretical dependences were obtained for a fixed value of MF barring the work of Pandey et al. (1989) who assumed a time-dependent initial mass function (IMF). The comparison indicates that a steeper MF is needed to match the integrated luminosities of oldest clusters (age $\geq 10^9$ years). Elson & Fall (1985) reported that, unlike the relation between colour and age, the relation between luminosity and age depends strongly on the IMF.

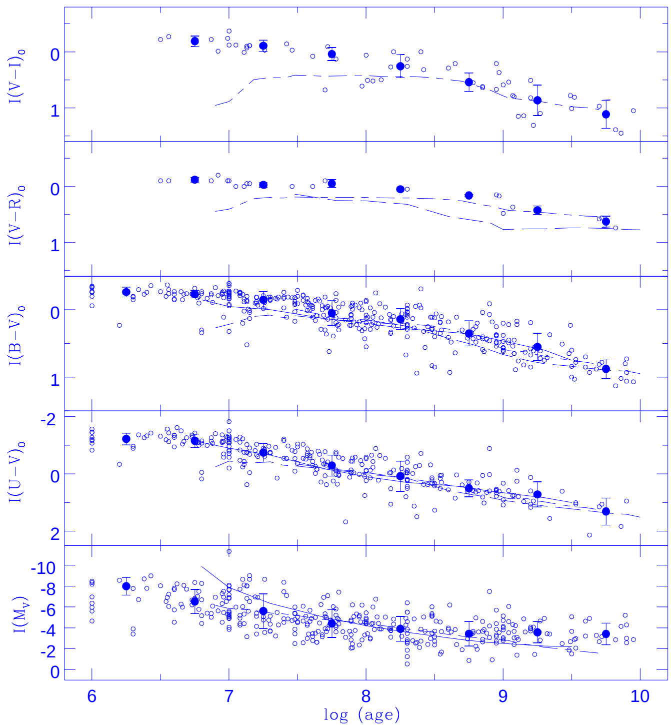

Fig. 3. The $I(M_V)$ and integrated colours are shown as a function of log (age). The curves represent the theoretical dependences predicted by models. Solid line is by Pandey et al. (1989) for whole cluster, long dash line is by Maraston (1998) and short long dash line is by Brocato et al. (1999). The filled circles and error bars are the average and σ respectively of the data points binned in log(age).

4. Luminosity distribution of open clusters

Figure 4 shows the integrated absolute magnitude distribution of 352 clusters according to their ages which indicates a maximum at $I(M_V) = -3.5$ mag and a sharp cut off at $I(M_V) = -2.0$ mag which agree with the results earlier obtained by van den Bergh & Lafontaine (1984) and Bhatt et al. (1991). Van den Bergh & Lafontaine (1984) concluded that the sharp cut-off at $I(M_V) = -2.0$ mag is

Table 2. Completeness radius and surface density for the different magnitude intervals.

$I(M_V)$ interval (mag)	Total number of clusters	Clusters within 3.0 kpc	Completeness radius, r (kpc)	Number of clusters within r	Surface density, σ (cluster/kpc^2)
2 to 1	1	1	–	–	–
1 to 0	0	0	–	–	–
0 to −1	4	4	–	–	–
−1 to −2	10	9	–	–	–
−2 to −3	47	48	2.00	40	3.18
−3 to −4	81	68	2.51	63	3.18
−4 to −5	78	62	3.16	65	2.07
−5 to −6	56	45	3.98	50	1.01
−6 to −7	33	20	5.01	28	0.36
−7 to −8	21	15	6.61	21	0.15
−8 to −9	19	13	6.92	18	0.12
−9 to −10	1	0	–	–	–
−10 to −11	0	0	–	–	–
−11 to −12	1	0	–	–	–

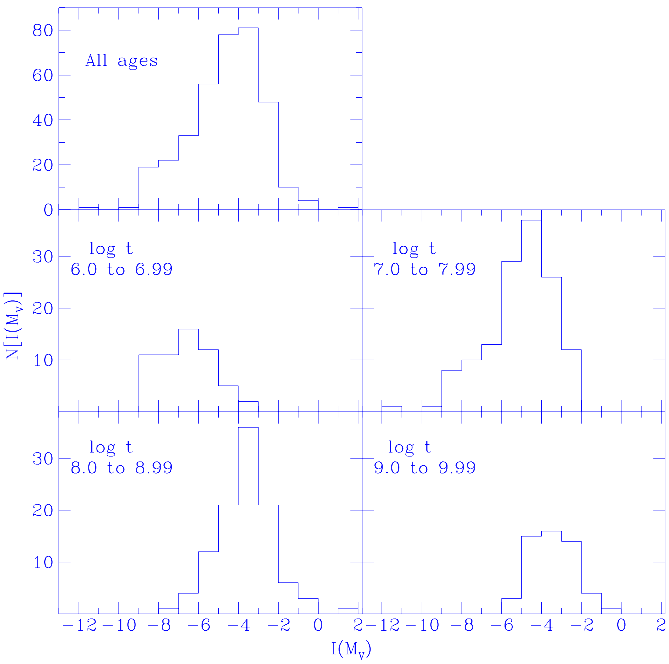

Fig. 4. The histograms are the frequency distribution of the luminosity of 352 clusters according to their ages.

probably due to selection effects while Bhatt et al. (1991) concluded that the observed distribution of open clusters fainter than $I(M_V) = -2.0$ mag may not be entirely due to selection effects. There may be some physical causes of the cut-off at $I(M_V) = -2.0$ mag. It is important to consider the limiting number of stars to form a cluster because if a multiple-star system with five components is also defined as a cluster then one can expect that the number of clusters fainter than $I(M_V) = -2.0$ mag could be large. Although the star formation efficiency is maximum in the low-mass ($\sim$100 $M_\odot$) molecular clouds (Pandey et al. 1990), it is also true that low-mass clouds generate poor clusters only. The lifetime of star clusters depends on the richness of the clusters (Pandey & Mahra 1986; Janes & Adler 1982). Poor clusters have a shorter lifetime compared to the rich ones and very poor clusters (say 5 to 10 stars only) will be disrupted on a very small time scale and consequently, it seems that these will not contribute in any way to the statistics at fainter limits.

From the luminosity distribution for different age groups shown in Fig. 4, one can see that young clusters and the majority of older clusters have integrated magnitudes brighter than $I(M_V) = -2.0$ mag, while a few old clusters have magnitudes fainter than that. The reason is that with age, dynamical evolution produces mass segregation in a cluster while stellar evolution depletes massive stars (Nilakshi et al. 2002 and references therein). The old clusters which have magnitudes brighter than $I(M_V) = -2.0$ mag most probably contain a number of red giants/supergiants.

5. Surface density and data completeness

The surface density of open clusters in the galactic plane, σ, has been obtained using the relation

$$\sigma = N/\pi r^2 \quad (13)$$

where, N is the number of open clusters observed within the completeness radius r, for each magnitude interval. The cluster population N and the surface density have also been tabulated in Table 2 for different magnitude intervals. A plot of log N against log d (where d is the distance of the cluster) for different integrated brightness is shown in Fig. 5.

Data completeness has been estimated assuming that log $N \propto$ log d as suggested by Bhatt et al. (1991). Table 2 and Fig. 5 show that present sample can be considered complete up to $\sim$3.0 kpc whereas the data used by van den Bergh & Lafontaine (1984) and Bhatt et al. (1991), were complete only up to $\sim$400 pc and $\sim$2.0 kpc respectively.

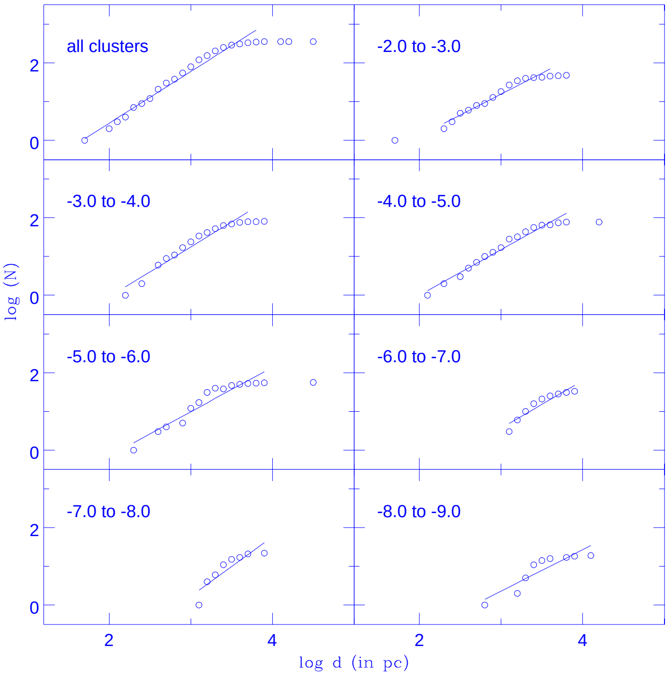

Fig. 5. The log N versus log d plots for different integrated magnitude intervals.

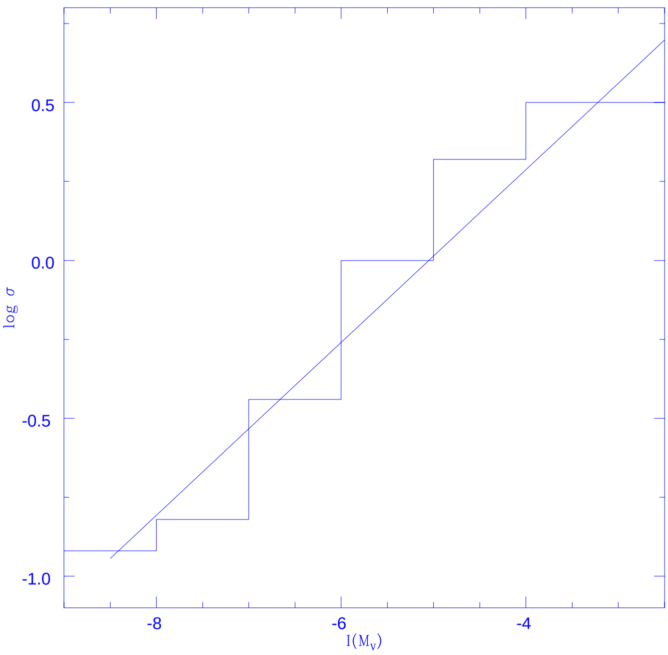

Fig. 6. The integrated luminosity function of the open clusters.

The integrated luminosity function of open clusters brighter than -2.0 mag is shown in Fig. 6 and can be represented by the relation

$$\log \sigma(I(M_V)) = (0.27 \pm 0.03) I(M_V) + (1.38 \pm 0.17) \quad (14)$$

which is in good agreement with the relation obtained by Bhatt et al. (1991). Extrapolation of this equation to higher luminosities, and assuming that the galactic disc has an area of 500 kpc^2, yields approximately 10 clusters with $I(M_V) = -11.0$ mag. The luminosity function by

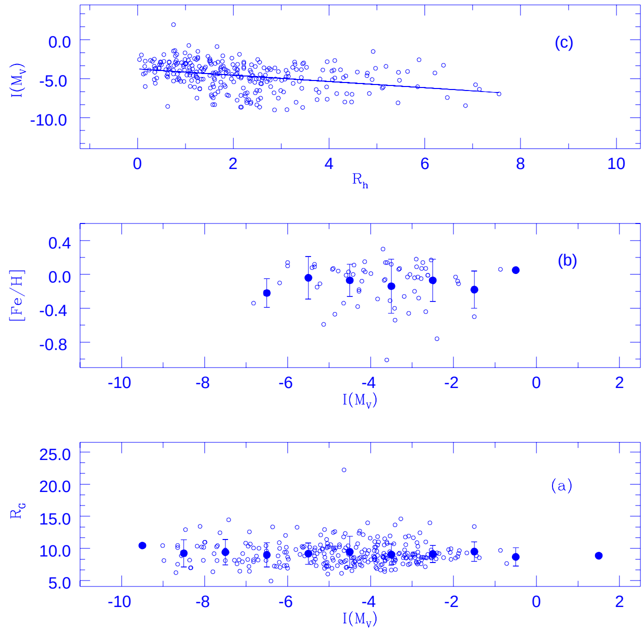

Fig. 7. The galactocentric distance $R_{\rm G}$, $I(M_V)$; the metallicity [Fe/H], $I(M_V)$ and the heliocentric distance $R_{\rm h}$, $I(M_V)$ plots are shown in **a)**, **b)** and **c)** panels respectively. The filled circles and error bars in **a)** and **b)** are the average and σ respectively of the data points binned in $I(M_V)$.

van den Bergh & Lafontaine (1984) yields 10^2 clusters with $I(M_V) = -11.0$ mag in the same area. This means that according to the slope of luminosity function obtained in the present analysis only about 1% of the clusters in the galactic disc have a magnitude of -11.0 mag while this is about 10% according to the luminosity function obtained by van den Bergh & Lafontaine (1984). The disagreement in the slope of the luminosity function obtained in the two studies may be due to large sample, towards the fainter end of the luminosity distribution, used in the present analysis. The present results should therefore be considered more realistic.

6. Relationship with galactocentric distance, metallicity and heliocentric distance

Figures 7a and b show the variation of $I(M_V)$ with galactocentric distance, $R_{\rm G}$ (in kpc) and metallicity, [Fe/H], respectively. They indicate that the $I(M_V)$ does neither depend on $R_{\rm G}$ nor on [Fe/H].

Figures 7c shows the variation of $I(M_V)$ with heliocentric distance $R_{\rm h}$ of the clusters. Like Barkhatova & Pylskaya (1983) and Balázs (1986) the relation between $R_{\rm h}$ and $I(M_V)$ can be represented by the following equation

$$I(M_V) = (-0.40 \pm 0.08) R_{\rm h} + (-3.76 \pm 0.23) \quad (15)$$

where $R_{\rm h}$ is in kpc. Balázs (1986) found similar effects but he suggests that this correlation is simply caused by selection effects.

7. Conclusions

The integrated magnitudes and colours of 140 open clusters have been derived. Along with results published earlier they have been used to study the characteristics of integrated parameters of galactic star clusters. The main conclusions are:

1. The comparison of observed dependence of integrated luminosity on the age indicates that a steeper MF is needed to match the integrated luminosities of oldest clusters.
2. The integrated luminosity function can be represented by the relation

$$\log \sigma(I(M_V)) = (0.27 \pm 0.03) I(M_V) + (1.38 \pm 0.17).$$

This indicates that about 1% of the open clusters in the galactic disc is brighter than $I(M_V) = -11$ mag.

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