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Studies of Young Stellar Objects

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Abstract. We present a detailed study of four young open star clusters and two OB associations using deep CCD *UBVRI* and 2MASS JHK_s measurements. Physical parameters of the clusters have been estimated using optical as well as near-IR data. Ages of objects under study range 10-100 Myr. Mass function slope of the sample of clusters are in agreement with the Salpeter (1955) value. From a comparison of mass function slope of clusters and OB associations in our Galaxy with those in external galaxies, we urgue that the star formation processes are such that they yield almost similar stellar mass distribution in vastly different star forming environments. Mass segregation suggests that the clusters under study are dynamically relaxed and hence mass segregation may be due to dynamical evolution or imprint of star formation or both. The extinction properties of a sample of 18 young star clusters have been investigated utilizing recent data available in literature. The study suggests that there is no uniformity in extinction properties amongst these clusters. A non-uniform extinction has been noticed for the first time in NGC 1502 and Tr 37 along with the existence of circumstellar shell around some early type stars in NGC 884, NGC 2264, Tr 14 and Tr 16.

Keywords : Star clusters - individual: Tr 1, Be 11, Basel 4 and NGC 7067; OB Associations: Bochum 1 and Bochum 6 - Star: Interstellar extinction, luminosity function, mass function, mass segregation - HR diagram.

1. Introduction

It has long been known that stars form in molecular clouds. It occurs only in the clumps which are most tightly gravitationally bound. A cloud core is unstable to collapse if the core mass is greater than the Jeans's mass and such core collapse gives birth of proto-stars. The proto-stars collapse at a later stage to eventually form young stars. These stars burn hydrogen in their central

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regions, and arrive at the main-sequence (MS). Prior to this phase, the young stars pass through the pre-main-sequence (PMS) evolutionary phase, wherein they are generally termed as Young Stellar Objects (YSOs). They are generally found in young open star clusters (age < 10^8 yrs) and OB associations.

Young open star clusters are the best places for studying YSOs. They seems to be ideal tools for a variety of present day astrophysical problems, but there are a number of problems to be solved before one can take full advantage of their diagnostic power. Like other (distant) objects, open clusters too suffer from the effects of absorption of light by interstellar matter, which has to be first estimated. The separation of cluster members from the background and foreground field stars is the second major problem to be solved. In the sky, cluster members and field stars are all projected on the same plane and there is no direct way to separate them. A number of observations related to their motions and brightness are needed to separate the cluster members from the field stars. A knowledge of these basic parameters is essential for utilizing the full diagnostic power of open star clusters.

An important aspect to understand star formation and stellar evolution is the question: how many stars of which masses formed or exist in an ensemble of stars? A function which describes the dependence of stellar numbers from their masses is called a stellar mass function. Detailed knowledge of the IMF in different environments is valuable for studies that attempt to describe the spectral, photometric and chemical evolution of integrated stellar systems because mass is one of the primary parameters which dictates the evolution of stars. The IMF also provides a valuable link between the easily observable population of luminous star in a stellar system and the fainter, but dynamically more important low mass stars.

Study of mass segregation in open clusters gives a clue about the spatial distribution of high and low mass stars within the clusters. At the time of formation, if the star cluster had a uniform spatial stellar mass distribution, then as the cluster evolves dynamically which leads to equipartition of kinetic energy in cluster members, the spatial stellar mass distribution changes and one usually finds that high mass stars are concentrated towards the center of the cluster, where as the distribution of the lower mass stars has a higher density in the outer parts.

2. Data used for the Thesis

2.1 Optical *UBVRI* CCD Observations and data reduction

The Johnson *UBV* and Cousins *RI* photometric observations were obtained for the four galactic open star clusters Tr 1, Be 11, Basel 4, and NGC 7067 and two OB associations Bochum 1 and Bochum 6 having ages < 10^8 years. The clusters selected for the study are either unstudied or poorly studied and they are located in the northern hemisphere. The observations of field regions were also taken for removing the field star contamination in the cluster regions. The observations of these clusters and field regions have been obtained using 2K×2K CCD system at the f/13 Cassegrain focus of the Sumpurnanand 104-cm telescope of the State observatory, Nainital. The

0.″.36/pixel plate scale resulted in a field of view of 12′.3×12′.3. The read-out noise and gain are 5.3 e^- and 10 e^-/ADU respectively. For the accurate photometric measurements of fainter stars, 2 to 3 deep exposures were taken in each passband. In addition to this, observations were taken in 2×2 pixel binning mode to improve the S/N ratio. Besides the cluster field, a number of standard star field were also observed for calibration purposes. For correcting the bias level to the image, a number of bias frames were taken during the observations while for the flat field correction, a number of flat frames were taken on the twilight sky in each filter.

Image processing of the observed data frames were done using the IRAF and MIDAS data reduction packages. Different cleaned frames of the same field in the same filter were co-added. Photometry of co-added frames was carried out using DAOPHOT software (Stetson 1987). PSF was obtained for each frame using several uncontaminated stars. In those cases where brighter stars are saturated on deep exposure frames, their magnitudes have been taken only from the short exposure frames. Wherever more than one measurement is available in a passband for a star, the final magnitude is an average of the individual measurements and its error is the ALLSTAR error of the average. When only one measurement is available, the error is taken to be the output of ALLSTAR.

2.2 Near-IR JHK_s data

The near-IR data are taken from the digital Two Micron All Sky Survey (2MASS) available at web site **http://www.ipac.caltech.edu/2MASS**. 2MASS is uniformly scanning the entire sky in three near-IR J, H and K_s bands. The value of uncertainty is ~ 0.155 mag for a star of K_s ~ 16.5 mag. The normal magnitude limits for the point source is 15.8 for J band, 15.1 for H band and 14.3 for K_s band. At high latitude, the 2MASS survey contains accurate detections 0.5-1.0 magnitudes fainter than the normal survey limits.

3. Results

3.1 Physical Parameters

Basic physical parameters like radius, reddening, distance and age have been determined for the four open clusters and two OB associations under study (see Table 1). The radial density profile of a open cluster has been used to estimate its angular radius. The values are 3′.0, 2′.4, 2′.5 and 3′.0 for the clusters Tr 1, Be 11, Basel 4 and NGC 7067 respectively. Our estimation of radius value is large for the clusters Tr 1 and NGC 7067 compared to the corresponding values available in the literature while for the clusters Be 11 and Basel 4 they are in agreement with published results. For deriving the cluster parameters, we used only photometric cluster members lying within a cluster radius from the center. Presence of variable interstellar extinction has been noticed in all young clusters under study. Mean reddening values derived using zero-age main-sequence (ZAMS) the slide fit method in $(U-B)$, $(B-V)$ two color diagrams of the clusters are 0.60±0.05, 0.95±0.05, 0.42±0.05 and 0.74±0.05 mag for Tr 1, Be 11, Basel 4 and NGC 7067 respectively. These values are in agreement with the corresponding published values. The derived $E(B-V)$ values for Bochum 1 and Bochum 6 using the members separated by kinematical method are 0.45±0.05 and 0.55±0.05 mag respectively. The distances to the clusters derived by fitting the ZAMS given by Schmidt-Kaler (1982) to the intrinsic CM diagrams are 2.6±0.10, 2.2±0.10, 3.3±0.15 and 3.7±0.15 Kpc for Tr 1, Be 11, Basel 4 and NGC 7067 respectively. The fitting of isochrones to the intrinsic CM diagrams indicate that the ages of Tr 1, Be 11, Basel 4 and NGC 7067 are 40±10, 100±10, 10±5 and 30±10 Myr respectively. For the three clusters namely Be 11, Basel 4 and NGC 7067, we have 2MASS JHK_s data. Age, distance and reddening determined using optical as well as JHK_s data for the clusters Be 11, Basel 4 and NGC 7067 confirm the values estimated earlier. The derived distance values for Bochum 1 and Bochum 6 using intrinsic CM diagrams and ZAMS are 2.8±0.4 and 2.5±0.4 Kpc respectively. For Bochum 1 the distance value is in agreement with Dias et al. (2002) while for Bochum 6 our value is lower. Fitting the post-MS theoretical isochrones in intrinsic CM diagram we estimated an age of about 10 Myr for both Bochum 1 and Bochum 6. All clusters except Be 11 investigated in the present study show no post-MS stellar evolutionary features. In Be 11, brighter members have just started evolving off the main-sequence. However, none of the cluster members are in the giant phase of the stellar evolution. Using the CM diagrams of Tr 1, Basel 4, and NGC 7067, we investigated the presence of PMS stars in them. This study indicates that there are pre-MS cluster members in the cluster Tr 1 (see Table 2). In order to determine the formation time of high-mass and low-mass stars in a star formation event, ages of both brighter post-MS and fainter pre-MS stars are estimated using corresponding theoretical stellar evolutionary tracks. A comparison of these two ages indicates that both high and low mass stars in the cluster Tr 1 have formed almost together within a time interval of less than 2 Myr or so. In the H-R diagrams of clusters Basel 4 and NGC 7067, low mass stars are not present at the location expected in the case of coeval star formation. They may be present below our observational limits and hence may have masses less than 1 $M_{\odot}$. In these clusters low mass stars therefore may have formed before the formation of massive stars.

Table 1. The derived fundamental physical parameters of the open star clusters and OB associations

Parameters	Open star clusters				Associations	
	Tr 1	Be 11	Basel 4	NGC 7067	Bochum 1	Bochum 6
$E(B-V)$ (mag)	0.60±0.05	0.95±0.05	0.42±0.05	0.74±0.05	0.45±0.05	0.55±0.05
Age (Myr)	40±10	100±10	10±5	30±10	10±5	10±5
Distance (Kpc)	2.6±0.10	2.2±0.10	3.3±0.15	3.7±0.15	2.5±0.2	2.8±0.2
Radius (arc min)	3.0	2.4	2.5	3.0	-	-

3.2 Mass function and Mass segregation

Mass function and mass segregation effects have been studied in four clusters namely Tr 1, Be 11, Basel 4 and NGC 7067 (see Table 3). The derived MF slope after taking into account the effects of field star contamination and photometric data incompleteness are 1.50±0.50, 1.22±0.24, 1.05±0.50 and 1.37±0.40 for Tr 1, Be 11, Basel 4 and NGC 7067 respectively. Our derived values of MF slopes are thus in agreement with that found for the Solar neighbourhood stars by Salpeter

Table 2. Frequency distribution in the V, $(B-V)$ of the clusters and field regions. N_c represent the number of stars in the cluster region corrected for data incompleteness factor determined while N_f denote the number of stars in the filed region in a particular magnitude and colour bin. N_1 represents the add of all N_c's while N_2 represents the add of all N_f's normalized for the area difference. N_m denote the total number of statistically expected cluster members in the magnitude bin.

Tr 1

V range	Number of stars in the $(B-V)$ range: 0.4-0.6		0.6-0.8		0.8 - 1.0		1.0 - 1.2		1.2 - 1.4		1.4 - 1.6		1.6 - 1.8		1.8 - 2.0		Total stars		
	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_1	N_2	N_m
14.0-15.0	18	1	4	1	2	2	2	1	0	1	0	0	0	0	0	0	26	6	20
15.0-16.0	4	2	13	4	5	6	7	4	1	1	2	2	1	2	0	0	33	21	12
16.0-17.0	0	0	10	6	18	16	13	10	3	3	3	2	3	1	0	0	50	38	12
17.0-18.0	0	0	2	4	13	20	36	22	11	6	10	3	3	1	0	0	75	56	19
18.0-19.0	0	0	0	0	6	21	40	47	44	13	10	4	3	1	0	0	103	86	17
19.0-20.0	0	0	1	2	6	11	38	36	65	24	28	6	14	1	4	0	156	80	76

Basel 4

V range	Number of stars in the $(B-V)$ range: 0.2-0.4		0.4 - 0.6		0.6 - 0.8		0.8 - 1.0		1.0 - 1.2		1.2 - 1.4		1.4 - 1.6		1.6 - 1.8		Total stars		
	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_1	N_2	N_m
14.0-15.0	4	1	3	2	0	1	0	0	2	0	1	0	0	0	0	0	10	4	6
15.0-16.0	1	0	12	2	2	4	4	1	0	0	0	1	1	0	0	0	20	8	12
16.0-17.0	0	0	1	0	17	5	8	6	1	2	2	2	0	0	0	1	29	16	13
17.0-18.0	0	0	0	0	2	1	27	14	9	6	1	3	2	1	1	0	42	25	17
18.0-19.0	0	0	0	0	0	0	11	7	26	21	8	4	3	2	0	0	48	34	14

NGC 7067

V range	Number of stars in the $(B-V)$ range: 0.5-0.7		0.7 - 0.9		0.9 - 1.1		1.1 - 1.3		1.3 - 1.5		1.5 - 1.7		1.7 - 1.9		1.9 - 2.1		Total stars		
	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_c	N_f	N_1	N_2	N_m
12.0-13.0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3
13.0-14.0	1	1	2	1	0	0	0	1	1	0	0	0	0	0	1	0	5	3	2
14.0-15.0	5	0	2	2	6	0	0	0	0	0	2	1	0	1	1	0	16	4	12
15.0-16.0	3	0	2	0	4	0	0	0	0	0	2	1	0	1	0	0	11	2	9
16.0-17.0	5	1	4	2	6	4	2	1	1	1	1	1	2	1	0	0	21	11	10
17.0-18.0	1	0	2	0	11	3	12	4	1	1	0	0	3	1	0	1	30	10	20
18.0-19.0	0	0	1	0	12	3	35	12	13	6	3	3	4	3	0	0	68	27	41
19.0-20.0	0	0	0	0	8	2	44	15	32	24	14	6	2	2	1	0	101	49	52

(1955). The derived values of MF slope 0.95±0.80 within mass range 3.0 - 17.0 $M_{\odot}$ for Bochum 1 and 0.81±0.22 within mass range 2.0 - 14.0 $M_{\odot}$ for Bochum 6 are also not too different from the Salpeter (1955) value. However, the error in slope determination is large. The MF slopes estimates of the clusters in the present work in combination with those of other clusters available in the literature indicate that there is no dependency of MF slope above 1 $M_{\odot}$ with galacto-centric distance, log(age) and longitude of the clusters of our Galaxy. A comparison of MF slope of the clusters in the Galaxy to those present in other galaxies indicates no noticeable differences in spite of different environmental conditions in which the star formation event took place. We therefore argue that the end product of star formation process is similar in vastly different star forming environments. This puts an important observational constraints on the theoretical models used to study the star formation processes.

Table 3. The slope of the mass function along with relaxation time T_e of the objects under study.

Objects	Mass range $M_{\odot}$	Mass Function slope (x)	log T_e
Clusters			
Tr 1	0.9 - 5.1	1.50±0.40	7.2
Be 11	1.0 - 4.5	1.22±0.24	7.1
Basel 4	0.9 - 3.7	1.05±0.50	7.0
NGC 7067	1.0 - 7.3	1.37±0.40	7.1
OB associations			
Bochum 1	3.0 - 17.0	0.95±0.80	
Bochum 6	2.0 - 14.0	0.81±0.22	

Mass segregation effects studied in the young open star clusters Tr 1, Be 11, Basel 4 and NGC 7067, indicates presence of mass segregation in them. The confidence level of mass segregation determined using K-S test are 99%, 80%, 50% and 70% for Tr 1, Be 11, Basel 4 and NGC 7067 respectively. A comparison of clusters age with its dynamical relaxation time (see Table 3) indicates that relaxation times are either smaller or roughly equal to the ages of the clusters. This suggest that the clusters under study are dynamically relaxed. Therefore, mass segregation may be due to dynamical evolution or imprint of star formation or both.

3.3 Nature and properties of interstellar extinction

The extinction properties towards young open star clusters investigated in detail by collecting data from literature as well as using our sample of clusters. The extinction law and the variation of color excess with position, luminosity as well as spectral class in young open star clusters NGC 663, NGC 869, NGC 884, NGC 1502, NGC 1893, NGC 2244, NGC 2264, NGC 6611, Tr 14, Tr 15, Tr 16, Coll 228, Tr 37, Be 86, Tr 1, Be 11, Basel 4 and NGC 7067 have been studied. The difference in the minimum and maximum values of $E(B-V)$ of cluster members has been considered as a measure of the presence of non-uniform gas and dust inside the clusters. Its value ranges from 0.22 to 1.03 mag in clusters under study, which indicates that non-uniform extinction is present in all the clusters as the values are significantly larger than 0.11, which can be accounted in terms of the factors other than this. The non-uniform extinction has been noticed for the first time in NGC 1502 and Tr 37. It is also found that the differential color excess in

Table 4. Near-IR flux excess/deficiency in members of clusters under study.

cluster	Webda Star No.	V (mag)	$E(V-J)$ (mag)	Δ(V−H) (mag)	Δ(V−K) (mag)	Sp Type
NGC 884	1781	9.26	1.57	−0.60	−0.58	B1IV
NGC 2264	90	12.71	1.17	0.91	1.98	B4V
	100	10.04	0.64	0.93	2.16	A2IV
	165	10.99	0.49	0.43	1.00	A2V
	46	9.18	0.70	0.09	0.72	A3V
Tr 14	15	11.85	1.88	0.53	1.27	B7V
Tr 16	68	12.14	1.50	0.63	1.71	O5V

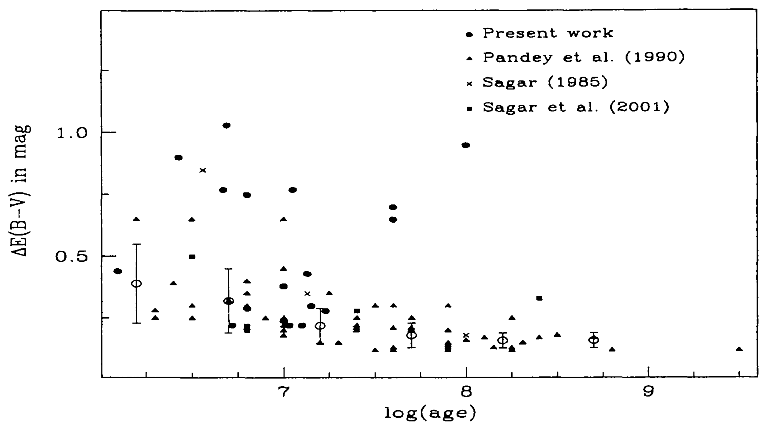

Figure 1. Variation of $\Delta E(B-V)$ ($\equiv E(B-V)_{max}$ - $E(B-V)_{min}$) cluster age. The values of $\Delta E(B-V)$ are taken from different sources as in the plot. The open circle and associated error bar denote the mean and standard deviation of the binned data.

open clusters, which may be due to the presence of gas and dust, decreases systematically with the age of clusters indicating that matter is used either in star formation or blown away by hot stars or both (see **Fig 1**). There is no uniformity in the variation of $E(B-V)$ with either position or spectral class or luminosity. Except in Tr 14, all clusters show a random spatial distribution of $E(B-V)$ indicating a random distribution of gas and dust inside the clusters. The $E(B-V)$ value correlates with both luminosity and spectral class only in the case of Coll 228, Tr 16 and Be 86. The members of these clusters at $\lambda \geq \lambda_R$ show larger values of color excess ratios than the normal ones. The value of $E(U-V)/E(B-V)$ for most of the cluster members is close to the normal interstellar value of 1.73. However, the color excess ratios with $E(B-V)$ at $\lambda \geq \lambda_J$ are smaller than the normal value for NGC 663, NGC 869, NGC 884 and NGC 1502 while they are larger for NGC 6611, Coll 228, Tr 16 and Tr 14. Thus there is no uniformity in the relationship of extinction properties amongst the clusters. Some early type stars in the cluster NGC 884, NGC 2264, Tr 14 and Tr 16 are found to have circumstellar shell around them for the first time (see Table 4).

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