Be phenomenon in open clusters: results from a survey of emission-line stars in young open clusters

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ABSTRACT

Emission-line stars in young open clusters are identified to study their properties, as a function of age, spectral type and evolutionary state. 207 open star clusters were observed using the slitless spectroscopy method and 157 emission stars were identified in 42 clusters. We have found 54 new emission-line stars in 24 open clusters, out of which 19 clusters are found to house emission stars for the first time. About 20 per cent clusters harbour emission stars. The fraction of clusters housing emission stars is maximum in both the 0-10 and 20-30 Myr age bin (\sim 40 per cent each). Most of the emission stars in our survey belong to Classical Be class (\sim 92 per cent) while a few are Herbig Be stars (\sim 6 per cent) and Herbig Ae stars (~2 per cent). The youngest clusters to have Classical Be stars are IC 1590, NGC 637 and 1624 (all 4 Myr old) while NGC 6756 (125–150 Myr) is the oldest cluster to have Classical Be stars. The Classical Be stars are located all along the main sequence (MS) in the optical colourmagnitude diagrams (CMDs) of clusters of all ages, which indicates that the Be phenomenon is unlikely due to core contraction near the turn-off. The distribution of Classical Be stars as a function of spectral type shows peaks at B1-B2 and B6-B7 spectral types. The Be star fraction [N(Be)/N(B+Be)] is found to be less than 10 per cent for most of the clusters and NGC 2345 is found to have the largest fraction (~ 26 per cent). Our results indicate there could be two mechanisms responsible for the Classical Be phenomenon. Some are born Classical Be stars (fast rotators), as indicated by their presence in clusters younger than 10 Myr. Some stars evolve to Classical Be stars, within the MS lifetime, as indicated by the enhancement in the fraction of clusters with Classical Be stars in the 20-30 Myr age bin.

Key words: stars: emission-line, Be - stars: formation - stars: pre-main-sequence.

to possess a natal accretion disc which is a remnant of star formation

(Hillenbrand et al. 1992). CBe stars and HBe stars are emission-line

stars in different evolutionary phases. Both these stars are found to

possess a circumstellar disc from which we can see emission lines

over the photospheric spectrum. The emission is found to come from

this equatorial disc as recombination radiation, mainly in Balmer

lines like H α and H β . The circumstellar equatorial disc in HAeBe

stars is a remnant of the star formation activity, which has been

formed by accretion mechanism. The production of disc in CBe

stars is still a mystery and majority of the studies point towards

an optically thin equatorial disc formed by channelling of matter

from the star through wind, rotation and magnetic field (Porter &

Slettebak (1985) stated that Be stars may be found above the

Rivinius 2003 and references therein).

1 INTRODUCTION

Open clusters are dynamically associated system of stars which are found to be formed from giant molecular clouds through bursts of star formation. Apart from the coeval nature of the stars, they are assumed to be at the same distance and have the same chemical composition. Hence, it is a perfect place to study emission stars since we do not have a hold on these parameters in the field. Young open clusters are found to contain emission stars since the emission stars are found to undergo evolution over a time-scale of less than 100 Myr.

Early-type emission stars are broadly classified as Classical Be (CBe) stars and Herbig Be (HBe) stars. CBe stars are fast rotators whose circumstellar disc is formed through decretion mechanism (wind/outflow) (Porter & Rivinius 2003). Herbig Ae/Be (HAeBe) stars are intermediate-mass pre-main-sequence (PMS) stars, found

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exhibit a relatively constant frequency, roughly equal to that of Be field stars. Lloyd Evans (1980) identified and studied Be stars in NGC 3766 and IC 2581. Mermilliod (1982) studied 94 Be stars in 34 open clusters. He found that the distribution of Be stars peaked at spectral type B1–B2 and B7–B8, confirming earlier results. He also found that the Be stars occupy the whole main-sequence (MS) band and are not confined to the region of termination of the MS. Recently, McSwain & Gies (2005) conducted a photometric survey of 55 southern open clusters and identified 52 definite Be stars and 129 probable candidates. They also reported that the spin-up effect at the end of the MS phase cannot explain the observed distribution of Be stars.

Fabregat & Torrejon (2000) suggested the Be phenomenon will start to develop only in the second half of a B star's MS lifetime, because of structural changes in the star. They noted that Be star-disc systems should start to appear in clusters 10 Myr old, corresponding to the mid-point MS lifetime of B0 stars, and their frequency should peak in clusters 13–25 Myr, corresponding to the mid-point MS lifetime of B1-B2 stars (Zorec & Briot 1997). The theoretical models of Meynet & Maeder (2000) and Maeder & Meynet (2001) indicate that the ratio of angular velocity to critical angular velocity steadily increases throughout the MS lifetime of early-type B stars. This might explain why the Be phenomenon is prevalent in the later part of a B star's MS lifetime. Keller, Bessell & Dacosta (2000) and Keller et al. (2001) found most of the Be stars close to the turn-off of the clusters they observed.

Wisniewski & Bjorkman (2006) identified numerous candidate Be stars of spectral types B0–B5 in clusters of age 5–8 Myr, challenging the suggestion of Fabregat & Torrejon (2000) that CBe stars should only be found in clusters of at least 10 Myr old. These results suggest that a significant number of B-type stars must emerge on to the ZAMS as rapid rotators. They detected an enhancement in the fractional content of early-type candidate Be stars in clusters of age 10–25 Myr, suggesting that the Be phenomenon does become more prevalent with evolutionary age. Wisniewski et al. (2007) did detailed imaging polarization observations of six Small Magellanic Cloud and six Large Magellanic Cloud clusters, known to have large populations of B-type stars. Their results support the suggestion of Wisniewski et al. (2006) that CBe stars are present in clusters of age 5–8 Myr.

The structure of this paper is as follows. The details of observations and data analysis are presented in Section 2 and the analysis of Be stars in clusters is presented in Section 3. We present the results and discussion in Section 4 and conclusions in Section 5.

2 OBSERVATION AND DATA ANALYSIS

The spectroscopic and the *R*-band imaging observations of the clusters have been obtained using the Hanle Faint Object Spectrograph Camera (HFOSC) instrument, available with the 2.0-m *Himalayan Chandra Telescope (HCT)*, located in Hanle and operated by the Indian Institute of Astrophysics. Details of the telescope and the instrument are available at the institute's homepage (http://www.iiap.res.in/). The CCD used for imaging is a 2 × 4 K CCD, where the central 2 × 2 K pixels were used for imaging. The pixel size is 15 µm with an image scale of 0.297 arcsec pixel⁻¹. The total area observed is approximately 10 × 10 arcmin². The cluster region was observed in the slitless spectral mode with grism as the dispersing element using the HFOSC in order to identify stars which show H α in emission. This mode of observation using the HFOSC yields an image where the stars are replaced by their spectra. This is similar to objective prism spectra. The cluster region was



Figure 1. The slitless spectral image of NGC 7419.

initially observed in *R* band to obtain the positions of stars. Then, the grism was introduced to obtain the spectra. These two frames are blinked/combined in order to identify stars that show emission in slitless (dispersed) image. The broad-band *R* filter (7100 Å, BW = 2200 Å) and Grism 5 (5200–10300 Å, low resolution) of HFOSC CCD system were used in combination without any slit. This combination provides spectra in the H α region.

A sample spectral image of the cluster NGC 7419 is shown in Fig. 1. The integration time used to obtain this image was 10 min. The bead-like enhancements over the continuum correspond to emission in H α . The clusters were observed more than once to confirm detections and to detect variable emission stars. We have used graded exposures for regions where bright stars are present. The central region for crowded clusters was rotated to account for the overlap of dispersed image. Certain clusters were imaged with H α filters to check for nebulosity. The log of the observations is given in external data base. This table lists all the clusters observed as well as the number of emission stars detected.

In this study, we have performed a systematic survey of young, open clusters in the northern sky, in order to increase the sample of emission stars in clusters and to study their properties. We performed this survey during the period 2003–2006, using the method of slitless spectroscopy. Due to the location of this telescope, the survey mainly concentrated on clusters in the northern declinations and those north of the declination of -20° . Hence, the objects in the RA range of 8^h to 18^h were not observed. Emission stars are found to show an IR excess, which is a combination of free-electron excess and dust excess. Hence, we have combined the optical *UBV* information with the near-infrared (NIR) data from Two Micron All Sky Survey (2MASS) to study the amount of IR excess.

In order to study the identified emission stars as well as the hosting cluster in detail, we have taken the photometric data from the references listed in WEBDA (http://www.univie.ac.at/webda/navigation.html) as shown in Table 1. For a few clusters such as King 21, NGC 146, 6756, 6834 and 7419, we have obtained the

Table 1. Details of emission-line stars in surveyed clusters.	(Asterisks denote the absence of emission stars in those clusters.
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Berkeley 62 Berkeley 63 Berkeley 86	1 1 2 4	10	1 CBe		
Berkeley 63 Berkeley 86	1 2 4			Phelps & Janes (1994)	*
Berkeley 86	2 4		1 CBe		*
	4	10	2 CBe	Forbes et al. (1992)	3
Berkeley 87		8	4 CBe	Turner & Forbes (1982)	5
Berkeley 90	1		1 HBe		*
Bochum 2	1	4.6	1 CBe		*
Bochum 6	1	10	1 HBe	Yadav & Sagar (2003)	*
Collinder 96	2	63	2 CBe	Moffat & Vogt (1975)	*
IC 1590	3	4	1 CBe, 1 HAe, 1 HBe	Guetter & Turner (1997)	4
IC 4996	1	8	1 CBe	Delgado et al. (1998)	2
King 10	4	50	4 CBe	Phelps & Janes (1994)	6
King 21	3	30	3 CBe		*
NGC 146	2	10-16	1 CBe, 1 HBe	Subramaniam et al. (2005)	*
NGC 436	5	40	5 CBe	Phelps & Janes (1994)	*
NGC 457	2	20	2 CBe	Phelps & Janes (1994)	7
NGC 581	4	12.5	4 CBe	Phelps & Janes (1994)	4
NGC 637	1	4	1 CBe	Phelps & Janes (1994)	*
NGC 654	1	10	1 CBe	Pandev et al. (2005)	6
NGC 659	3	20	3 CBe	Phelps & Janes (1994)	5
NGC 663	22	25	22 CBe	Pandev et al. (2005)	34
NGC 869		12.5	6 CBe	Slesnick, Hillenbrand & Massey (2002)	28
NGC 884	6	12.5	6 CBe	Slesnick et al. (2002)	25
NGC 957	2	10	2 CBe	Hoag et al. (1961)	
NGC 1220	- 1	60	1 CBe	Ortolani Carraro & Covino (2002)	*
NGC 1624	1	4	1 CBe	Sujatha & Babu (2006)	*
NGC 1893	1	4	1 HBe	Massey Johnson & Degioia-Eastwood (1995)	4
NGC 2345	12	60-100	12 CBe	Moffat (1974)	*
NGC 2414	2	10	2 CBe		*
NGC 2414	2	80	4 CBe	Vaday & Sagar (2004)	
100 2421	7	00	4 CDC	Moffat et al. (1075) Babu (1083)	*
NGC 6640	7	25	7 CBe	Walker & Laney (1087), Talbert (1075)	
NGC 0049	1	25	/ CDe	Madore (1975) The & Poslund (1963)	*
NGC 6756	2	125 150	2 CB	Wadole (1975), The & Rostund (1965)	*
NGC 6823	2	63	2 CBc	Guetter(1002)	5
NGC 6824	1	40	1 HDc	Guetter (1992)	2
NGC 6010	4	40 6 3	4 CBe	Hence at al. (1061)	S *
NGC 0910	2	1000	1 CBe	Hossen (1972)	*
NGC 7039	1	1000	1 CBc	Ralag et al. (2001)	2
NGC 7126	5	10	J CBe	Dalog et al. (2001) Digulati Jargutianiag & Kapadi (1007)	2
NGC 7255	1	12.5	1 CBe	Piguiski, Jeizykiewicz & Kopacki (1997)	1
NGC 7290	3	40		Massay at al. (1005)	2
NGC 7410	4	10-12	1 CDC, 2 NDC, 1 HAC	Subarmaniam at al. (2006)	د در
NGC 7510	25	25	25 CBe	Subramaniam et al. (2006)	37
NGC /510 Declum 1.4	3	10	2 CBe, I HBe/CBe	Barbon & Hassan (1996) $D_{1} = 1 = 4 = 1$ (2004)	2
Kosiuna 4	2	16	т Све, т НАе	Deigado et al. (2004)	3

photometry using *HCT*. After cross-correlating the emission stars from our *R*-band image with the location given in the reference, the photometric parameters were taken. We have also taken the E(B - V) and distance values listed in the reference to estimate the absolute magnitude M_V and $(B - V)_0$. The spectral type is determined from the M_V and $(B - V)_0$ using Schmidt-Kaler (1982).

The optical data have to be combined with NIR photometry to look for NIR excess in emission stars. The NIR photometric magnitudes in J, H, K_s bands for all the candidate stars are taken from 2MASS (http://vizier.u-strasbg.fr/cgi-bin/VizieR?-source=II/246) data base. The (J - H) and (H - K) colours obtained were transformed to Koornneef (1983) system using the transformation relations by Carpenter (2001). The colours are dereddened using the relation from Rieke & Lebofsky (1985), since the slope of the reddening vector matches with this extinction relation. For this purpose, we have made use of the optical colour excess

E(B - V), which corresponds to the reddening of the cluster to which the emission star is associated. To classify emission stars based on NIR excess, we have used the 2MASS colours of the known catalogued HBe stars (The, de Winter & Perez 1994) and CBe stars (Jaschek & Egret 1982) along with our candidate stars. The *B*- and *V*-band photometric magnitudes were taken from Tycho-2 Catalogue (Høg et al. 2000; Cat. I/259), which along with the known spectral types were used to determine colour excess E(B - V). This was used to estimate E(J - H) and E(H - K) using the relations by Rieke & Lebofsky (1985), which in turn was used to deredden the (J - H) and (H - K) colours.

Among the surveyed clusters which contain emission stars, we have studied NGC 7419 (Subramaniam et al. 2006), NGC 146 (Subramaniam et al. 2005) and four clusters (Berkeley 86, Berkeley 87, IC 4996 and NGC 6910) in the Cygnus region (Bhavya, Mathew & Subramaniam 2007) in detail. The turn-on age of these

clusters estimated by fitting PMS isochrones was found to be different from the turn-off age, suggesting continued or multiple episodes of star formation in the above open clusters. In this survey, we identified 157 emission-line stars and estimated their distance, age and spectral type from the optical colour-magnitude diagram (CMD) of open clusters to which they are associated. We also identified their evolutionary phase by finding their location in the cluster MS. We looked for nebulosity around the emission stars in addition to the location in optical CMD and NIR colour-colour diagram, to separate possible HBe stars from CBe stars. In an attempt to separate these emission stars, we have plotted the NIR colour-colour diagram for catalogued field CBe and HBe stars, along with the cluster emission stars. The distribution of clusters which have Be stars was studied in Galactic coordinates with respect to the clusters which do not contain emission stars to look for any preferential location for clusters with emission stars.

The slitless spectroscopy technique identifies only stars with emission in H α above the continuum. Stars with emission just enough to fill the H α line, or those with partial filling, cannot be identified. Thus, this survey identifies stars with definite emission. Thus, the identifications, numbers and statistics presented in this paper can be taken as a lower limit.

3 CLUSTER ANALYSIS

From the slitless spectra of 207 clusters, we identified 42 clusters to have emission stars. On the whole, we identified 157 emission stars. The list of clusters which contain emission stars along with the number identified in each cluster is given in Table 1. The conclusion we have drawn about the candidature of e-stars, i.e. whether they belong to CBe/HAeBe category, is also tabulated. We have also cross-correlated our finding with the number of e-stars listed in WEBDA for each cluster. A detailed list of emission stars along with the coordinates, V magnitude, (B - V) colour and the spectral type is available online. We have identified emission-line stars in 19 clusters, which were not in the Be star list of WEBDA. These 19 clusters are found to have 49 emission stars. Together with the new identifications from already known clusters with emission stars (five clusters), we have found 54 new emission-line stars in 24 open clusters. Among the newly identified clusters with emission stars, NGC 2345 (12 stars), NGC 6649 (seven stars) and NGC 436 (five stars) are noteworthy.

37 clusters are found to have optical photometric data. We have constructed the M_v versus $(B - V)_0$ CMDs for them and they are given in an external data base. A representative CMD for the cluster IC 1590 is shown in Fig. 2. The UBV CCD photometric data were taken from Guetter & Turner (1997) and the emission stars are identified as 215, 151 and 214 in their catalogue while it is given in the order of 1, 2, 3 in this paper. They have estimated the age of the cluster to be 4 Myr, and we have plotted the post-MS isochrone corresponding to that age. The cluster members are shown as points while the Ae/Be stars are shown as special symbols in the CMD. The emission stars shown in squares are found to be HAeBe candidates, while that in filled circle is a CBe star. We used Padova isochrones (Bertelli et al. 1994) of solar metalicity. The data points are fitted with ZAMS (Schmidt-Kaler 1982) which is shown in solid line while post-MS isochrones of 4 Myr are shown in dashed line. The position of the Be stars in the CMD is checked to look for the evolutionary effect, which has been quoted as one of the reasons for Be phenomenon in CBe stars. If the emission stars are preferentially located near the evolved region or turn-off of the cluster MS, it is



Figure 2. The M_v versus $(B - V)_0$ plot of the cluster IC 1590 is shown with the HBe star as open square, HAe star as filled square and CBe star as filled circle. The data points are fitted with ZAMS which is shown in solid line while the post-MS isochrone of 4 Myr is shown as dashed line.

an indication of evolutionary effect. In the CMD shown, the CBe candidate is located below the MS turn-off.

The NIR $(J - H)_0$ versus $(H - K)_0$ colour-colour diagram (NIR CCDm) were plotted for the clusters to classify emission stars based on their infrared excess. The location of the MS and reddening vectors is taken from Koornneef (1983) and the IR sources in the 10 \times 10 arcmin² cluster field are shown as dots while the emission stars are shown in special symbols. This diagram is not dereddened for emission stars whose colour excess E(B - V) is not known. A detailed analysis of the individual clusters which contain emission stars along with the optical CMDs and NIR CCDm is provided in an external data base. We have shown the NIR CCDm of the cluster IC 1590 in Fig. 3 as a representative of the surveyed clusters. The emission stars shown in filled and open squares are found to show considerable NIR excess (~1 mag). From H α imaging, it has been found that they are found to be associated with nebulosity. By combining optical and NIR information, we can infer that these two stars (1, 2) belong to HBe and HAe category, respectively, while the star shown in filled circle (star 3) belongs to CBe category.

4 RESULTS AND DISCUSSION

In this survey, we have identified 157 emission-line stars in 42 clusters, from the total number of 207 clusters surveyed. Among the 207 clusters, 28 clusters do not have age estimates. They are Barkhatova 1, 4, 6, 7, 11, Berkeley 6, 43, 45, 63, 84, 90, Czernik 20, Kharchenko 1, Mayer 2, NGC 2364, 3231, 6525, 6822, 6882, 7024, Roslund 18, 32, 36, Turner 3, 4, 8, vdB-Hagen 80 and 92. We have detected two emission stars in two clusters (Berkeley 63 and 90), for which age information is not available. The clusters without age information were picked up based on their young appearance with the presence of bright stars. Therefore, the number of clusters with age estimation is 179. Thus, 40 out of 179 clusters (22 per cent) are found to have emission stars in them. 39 clusters are found to be older than 100 Myr and two among them have CBe stars. Hence,



Figure 3. The NIR CCDm of the cluster IC 1590 is shown with the HBe star as open square, HAe star as filled square and CBe star as filled circle. The MS is shown in bold curve while the reddening vectors are shown as dashed lines.

out of the 207 clusters surveyed, 140 were found to have age less than 100 Myr, with 38 clusters housing emission stars (27 per cent). In general, most of the identified emission stars are CBe candidates (145 stars, 92.3 per cent), whereas some are HBe candidates (nine stars, 5.7 per cent). A few (three, 1.9 per cent) HAe candidates are also present.

The clusters with e-stars are mostly younger than 50 Myr, whereas there are a few clusters which are quite old to have these stars. The oldest clusters to have these stars are NGC 6756 and 7039, where the age of the second cluster is debatable. NGC 6756, with an age of 125-150 Myr, is thus the oldest cluster to house two CBe stars. NGC 6834, an 80 Myr cluster, is found to house four CBe stars, but with our CCD photometry the age was re-estimated to be about 40 Myr. Another interesting cluster is the 60-100 Myr old NGC 2345, where we have detected 12 e-stars. No emission stars were known in this cluster. NGC 436 (40 Myr) is another not-so-young cluster, where we have detected five CBe stars for the first time. NGC 6649 is a young 30 Myr cluster in which we have identified seven CBe candidates for the first time. On the other extreme, there are some very young clusters (~4 Myr), where we have identified CBe candidates (NGC 1624, 637 and IC 1590). In some clusters, CBe and HBe/Ae stars are found to co-exist (NGC 146, IC 1590, NGC 7380 and Roslund 4). The largest number of CBe stars are found in NGC 7419 (25 stars), closely followed by NGC 663 (22 stars). As mentioned earlier, the technique used here only identifies definite emission stars and thus the statistics presented here are lower limits. Since this survey has covered a large number of clusters, we have done statistical analysis of the fundamental parameters of the emission stars and the clusters which house them. The following sections discuss these.

4.1 Colour-magnitude diagram of the emission stars

The M_v versus $(B - V)_0$ CMD of the emission stars in all the clusters is shown in Fig. 4. From the distribution of stars in the



Figure 4. The CMD of the emission stars is shown in the figure with *y*-axis being the absolute magnitude and *x*-axis being the extinction-corrected colour.

diagram, we can see that a few could belong to HBe stars. Stars brighter than $M_v \sim -3.0$ are located to the right of the ZAMS. There are about 20 stars in this group and this might be due to reddening or due to evolution away from the MS. From the analysis of the CMDs of 37 clusters, we identified only about 12 stars to be located close to the MS turn-off and probably evolving away from the MS. Thus, the deviation from the MS is likely to be due to both evolution and reddening. In the range, $M_v = -3-0.0$, most of the CBe stars are located very close to the ZAMS with some located to the right, probably due to reddening. This figure and also the summary given below show that most of the CBe stars are still in the MS evolutionary phase. Thus, the emission mechanism is not connected with the core-contraction at the MS turn-off.

To summarize the results from the CMD analysis of individual clusters, the clusters Bochum 2, NGC 2414, 7261 do not have the data corresponding to the emission stars. We have found nine clusters to be less than 10 Myr. These clusters contain 15 emission stars out of which 10 belong to CBe category while five belong to HBe class. We have found the cohabitance of both classes of estars in the clusters IC 1590 and NGC 6910. The clusters IC 1590, NGC 637 and 1624 were found to have young CBe stars whose age is about 4 Myr. We have observed 16 clusters to be in the age range 10-19 Myr which contain a total of 42 emission stars out of which 35 belong to CBe category, five HBe stars and two HAe stars. We have found seven clusters to be in 20-40 Myr age bin which contain a total of 65 emission stars, all of which are CBe stars. This age bin contains rich clusters like NGC 663, 6649 and 7419 which contribute 22, seven and 25 Be stars to the total sample. Since the remaining clusters in this group have at least three Be stars, we can infer that this age range favours a rich environment for the formation of Be stars. From a spectral-type evolution point of view, B-type stars earlier than B5 are found to be in and around MS phase during this period.

The clusters King 10, NGC 6834 and 7261 are found in 40– 50 Myr age range which contain 11 CBe stars. We have four clusters in the age bin 60–100 Myr which have a total of 19 CBe stars, out of which 12 are from the cluster NGC 2345. We have a couple of clusters with age greater than 100 Myr: NGC 6756 and 7039. NGC 6756 is found to have an age range of 125–150 Myr, which is found to have two CBe stars with spectral types B3.5 and B2.5, respectively. Even though we have fitted an age of 1000 Myr to the cluster NGC 7039, the presence of emission star makes the age estimation suspicious. Hence, deeper and new *UBV* CCD observations are needed to have any say about this cluster.

From the analysis of the individual cluster CMDs with emission stars, 12 are found to be near the turn-off in the CMD. They are IC 4996 (1, B2), King 10 (B, B1), King 10 (E, B2), King 21 (C, B0.5), NGC 659 (2, B0), NGC 663 (7, B0), NGC 663 (16, B0), NGC 663 (P6, B0.5), NGC 663 (12V, B0.5), NGC 2421 (1, B3.5), NGC 6649 (1, B1.5) and Roslund 4 (2, B0). Our catalogue number and spectral type are given in brackets. Hence, majority of the emission stars are not on the evolved part of the MS. This result does not favour core contraction scenario for the CBe phenomenon.

4.2 M_v versus age of the emission stars

A plot of M_v with respect to age of the emission stars is shown in Fig. 5. Stars in the age range 0–10 Myr are distributed between $M_v = 0.5$ and 3. 0. That is, these clusters lack CBe stars of spectral type earlier than B1. On the other hand, these very early spectral types as well as the later spectral types are seen in the age range 10– 30 Myr. A trend is seen for the emission stars to shift to late B spectral type with age, especially for the stars in 40–80 Myr. This trend is deviated by the two stars in the cluster NGC 6756, which is older than 100 Myr.

The trend which is noteworthy is the absence of very early CBe spectral types in clusters younger than 10 Myr. This suggests that the spectral types earlier than B1 show CBe phenomenon after 10 Myr. If this is true, this suggests that the Be phenomenon in spectral types earlier than B1 is due to evolutionary effect. The existence of this younger age limit is only indicative here. Search



Figure 5. A plot of M_{ν} versus the age in Myr of the emission stars is shown. The emission star belonging to cluster NGC 7039 is not plotted due to uncertainty in age estimation.



Figure 6. Distribution of clusters with emission stars (filled triangles) and clusters without emission stars (open triangles) is shown in the figure.

and identification of CBe stars in more clusters in this age range are required to confirm this result.

4.3 Position of emission stars in Galactic coordinates

We have plotted the surveyed clusters in the Galactic plane (Galactic longitude–latitude, l–b plane) as shown in Fig. 6. The total surveyed clusters are shown as open triangles while the clusters which harbour emission stars are shown as filled triangles. It can be seen that most of the emission stars lie within a longitude range of $120^{\circ}-130^{\circ}$ which correspond to Perseus arm of the Galaxy. Most of the rich clusters like NGC 7419 (109° in l), NGC 663 (129° in l) and h & χ Persei (NGC 869 and NGC 884; 135° in l) are found to lie in this region, which points to a vigorous star formation activities. The rich cluster NGC 2345 (226° in l) is found in Monoceros region of the Galaxy along with the clusters like Bochum 2, Bochum 6, Collinder 96 and NGC 2421.

We were not able to survey clusters in the Carina, Crux and Norma spiral arm of the Galaxy since they are southern objects which are not accessible using our observation facility. Most of the surveyed clusters lie along the Galactic plane, as expected, while some like IC 348 (-17?8 in b), NGC 1758 (-10?5 in b), NGC 2355 (11?8 in b), NGC 2539 (11?1 in b) lie away from the plane. The location of clusters in the Galactic plane is shown in Fig. 7. This also suggests a preferential occurrence of clusters with CBe stars in the second Galactic quadrant. Only a few clusters are found to have Be stars in the third quadrant. These plots indicate that regions with vigorous star formation are coincident with clusters containing CBe stars.

4.4 Distribution of emission stars versus cluster age

We have surveyed 207 open clusters, out of which 140 were younger than 100 Myr, 39 clusters were older than 100 Myr, while the age of 28 clusters is unknown. Out of the total number of clusters surveyed, 20.28 per cent have been found to have emission stars. The fraction of clusters which have emission stars with respect to



Figure 7. The figure shows the distribution of clusters with emission stars (filled triangles) and without emission stars (open triangles).



Figure 8. Fraction of clusters which have emission-line stars with respect to the total number of clusters surveyed is shown in the figure.

total surveyed clusters as a function of age is shown as histograms in Fig. 8. The statistics of the clusters are given in Table 2. We find that the maximum fraction of clusters which house CBe stars fall in the age bin 0–10 and 20–30 Myr (~40 per cent). There seems to be a dip in the fraction of CBe clusters in the 10–20 Myr age bin. For older clusters, the estimated fraction ranges between 10 and 25 per cent. The reduction in the fraction from 0 to 10 Myr age bin to 10 to 20 Myr age bin could be due to evolutionary effects and also due to the MS evolution of the probable HBe stars. Also, the fraction in the 10–20 Myr age bin is similar to the value found for older clusters. There seems to be an enhancement in the cluster fraction with Be stars in the 20–30 Myr age bin.

In Table 2, we have also shown the McSwain & Gies (2005) results in parenthesis. They have good number of clusters younger

Table 2. The list of clusters with and without emission stars in various age bins. For comparison, values obtained by McSwain & Gies (2005) are given in parenthesis.

Age bin in Myr	Non-emission star clusters	Emission star clusters	Total clusters surveyed	Fraction of emission star clusters
0-10	30(6)	18(11)	48(17)	0.375(0.647)
10-20	21(4)	8(10)	29(14)	0.275(0.714)
20-30	6(4)	4(4)	10(8)	0.4(0.5)
30-40	9(3)	2(1)	11(4)	0.181(0.25)
40-50	5	2	7	0.285
50-60	8	1	9	0.111
60-70	3	1	4	0.25
70-80	6	2	8	0.25
80-90	5	0	5	0
90-100	9	0	9	0
>100	37	2	39	0.051

than 40 Myr and there are only a few older clusters. The CBe cluster fraction from their data indicates that the largest fraction (0.71) is in the 10–20 Myr, with lesser fractions in the 0–10 and 20–30 age bins. Thus, McSwain & Gies (2005) data set indicates that the fraction of clusters with Be stars increases after 10 Myr, whereas our data set shows the rise after 20 Myr. The striking result is that both the sets indicate a rise in the age bin, 10–30 Myr, from the initial fraction. It should be noted that these two data sets have sampled different part of the Galactic disc. This result is similar to that reported by Wisniewski et al. (2006).

When we estimate the fraction of CBe stars observed in various age bins, the statistics are dominated by the CBe-rich clusters. Out of the 155 emission-line stars (age of two stars is not known), distributed in 40 clusters, 19.3 per cent (30 of 155) of the stars are found to belong to 1–10 Myr group, with the 10 Myr clusters belonging to this group. About 61.9 per cent (96) are in the 10–40 Myr age group including the candidates of 40 Myr old clusters. We have found seven emission stars (4.5 per cent) in the 40–50 Myr age group. The surprising aspect is the presence of 19 stars in 50–100 Myr group (12.2 per cent), which are the stars from the clusters Collinder 96, NGC 1220, 2345 and 2421. For the sake of completion, we have to include the clusters older than 100 Myr like NGC 6756 and 7039 (2 per cent contribution to the total list of e-stars) to this list of old clusters.

We find that CBe phenomenon is pretty much prevalent in clusters younger than 10 Myr, \sim 40 per cent of clusters house CBe stars and about 20 per cent CBe stars are younger or as old as 10 Myr. McSwain & Gies (2005) also find a good fraction of clusters to have CBe stars. Thus, using a much larger sample, we confirm similar results obtained by Wisniewski et al. (2006, 2007) and McSwain & Gies (2005). Thus, these CBe stars are born as CBe stars, rather than evolved to become CBe stars. Since we do not find any CBe stars earlier than B1 in clusters of this age range, our results mildly suggest that this happens mainly for spectral types later than B1.

We also find that the fraction of clusters with CBe stars significantly increases in the age range 20–30 Myr, similar to the result found by Wisniewski et al. (2006) (10–25 Myr) and McSwain & Gies (2005) (10–20 Myr). All these results put together indicate that there is an enhancement in the 10–30 Myr age range. These suggest that stars in these clusters evolve to become CBe stars. Thus, there could be two mechanisms responsible for the Be phenomenon. Rapid rotation is generally considered as the reason for the CBe phenomenon. First mechanism is where the stars start off

as CBe stars early in their lifetime, as indicated by CBe stars in very young clusters. These are probably born fast-rotators. These types of stars are found in all age groups of clusters. These types of stars are likely to be later than B1, as indicated by the paucity of very early type CBe stars in young clusters. The second mechanism is responsible for the enhanced appearance of Be stars in the 10–30 Myr age group clusters. This is likely to be an evolutionary effect. As seen in Fig. 5, the 10–30 Myr age range has a large number of CBe stars in the spectral type earlier than B1. This component is probably due to the structural or rotational changes in the early B-type stars, in their second half of the MS life time (Fabregat & Torrejon 2000).

4.5 Distribution of emission stars as a function of spectral type

Out of the total 157 emission stars, spectral types of 140 have been estimated based on available photometric data. The photometric *UBV* magnitudes available from the literature have been corrected for reddening and distance to determine the spectral type using Schmidt-Kaler (1982). Mermilliod (1982) studied the distribution of Be stars as a function of spectral types, which is found to show maxima at types B1–B2 and B7–B8. The positions of these maxima are identical to those of gaps already noted in the (U - B) versus (B - V) plane at exactly B1–B2 and B7–B8. Our analysis shows bimodal peaking in the distribution in B1–B2 and B5–B7 spectral bins (Fig. 9).

Fabregat (2003) has studied the Be star frequency as a function of the spectral subtype for Galactic and Magellanic cloud clusters in the 14–30 Myr age interval. He found that Be stars of the earlier subtypes are significantly more frequent than in the Galactic field, and that late Be stars are scarce or non-existent. Our results indicate that about 32 per cent of the emission stars belong to spectral type later than B5. We have found 26 stars in B0–B1 spectral bin, 23 in B1–B2 bin, 20 in B2–B3 bin, six in B3–B4 and five in B4– B5 spectral bin (Fig. 9). In this analysis also, the statistics are dominated by the clusters rich in CBe stars. It can be seen that most of the CBe stars in rich clusters belong to early B type. Thus, the enhanced peak seen in the B0–B1 bin is due to the rich clusters.



Figure 9. The distribution of the surveyed emission stars with respect to the spectral type is given. The solid squares show the total candidates while the open circles show the number of candidates after removing the contribution from five rich clusters.

The distribution obtained after removing the contribution from rich clusters like NGC 7419, 2345, 663 and h & χ Persei is also shown in Fig. 9. It can be seen that the B0–B1 enhancement is substantially reduced. The distribution is more or less even with peaks in B1–B2 and B6–B7 spectral bins.

4.6 Be star fraction

Jaschek & Jaschek (1983) estimated the mean frequency of Be stars to be around 11 per cent from Bright Star Catalogue considering all spectral type and luminosity classes. The Be phenomenon has always been connected with the question that whether all B-type stars pass through the Be phase or not. In order to address that question, we have found the ratio of Be stars to total B-type stars [N(Be)/N(Be+B)] in the surveyed clusters. We have estimated this fraction in 37 clusters for which reliable photometry was available. The ratio is found to be less than 0.1 (10 per cent) for most (29 clusters) of the clusters. The rich clusters NGC 7419, 663 and 2345, which are having more than 10 e-stars, are found to be well separated from the rest (Fig. 10).

The Be star fraction of NGC 2345 is highest among the surveyed clusters (26 per cent) while the rich clusters like NGC 7419 (11 per cent) and NGC 663 (4.5 per cent) show a lesser value. The clusters which stand out from the rest are labelled in Fig. 10. These include clusters having multiple emission stars like NGC 6649 (Be star fraction of 17.9 per cent), Berkeley 87 (18.2 per cent), NGC 2421 (11.7 per cent), Collinder 96 (18.2 per cent) and NGC 1220 (16.6 per cent). McSwain & Gies (2005) also found the Be star fraction to be ≤ 10 per cent for most of the clusters. Fabregat & Gutierrez-Soto (2005) have estimated Be star fraction in NGC 663 and h & χ Persei to be around 9.5 and 6.8 per cent, respectively. They have found 188 B-type stars in NGC 663 out of which 18 are Be stars while we have found a total of 486 B-type stars including 22 Be candidates. For h & χ Persei, they have estimated a total of 218 stars among which 15 showed emission while we have found



Figure 10. The figure shows the ratio of Be stars with respect to total B-type stars in the surveyed clusters.



Figure 11. Extinction-corrected NIR CCDm of emission stars (open triangles) in open clusters with MS (bold curve) and reddening vectors (dashed lines). The known CBe stars (filled squares) and HBe stars (filled circles) from the catalogue are also shown in the figure.

1065 B stars out of which 12 showed emission, which results in a Be fraction of 1.1 per cent.

4.7 Distribution of emission stars in NIR colour-colour diagram

The NIR CCDm of the cluster emission stars along with the catalogued CBe stars and HAeBe stars is shown in Fig. 11. The diagram also shows the MS and the reddening line (Koornneef 1983). The cluster emission stars, which are displaced from the CBe location, where all the catalogued CBe stars lie, are discussed below. The emission stars NGC 7380-4 (1.005, 0.855), IC 1590-1 (0.953, 0.500), IC 1590-2 (0.999, 0.790) and NGC 6823-1 (1.045, 0.767) are located in the HAeBe location. Some stars like Bochum 6 (0.596, 0.295), NGC 884-2 (0.545, 0.226), NGC 7419-1 (0.515, 0.219), NGC 146-S1 (0.356, 0.320) and Roslund 4-1 (0.296, 0.359) are located in the region between the HAeBe and CBe distribution. The stars NGC 436-3 (0.165, 0.705) and NGC 7128-1 (0.254, 0.741) are found to be beyond the reddening vector. In the former case, it might be due to the variation of colour excess around the star while in the latter case the quality of the data is poor with a flag of DEE. Thus, this comparison confirms that most of the cluster emission stars are CBe type of stars, and only a few stars are HBe candidates.

Some of the catalogued Herbig stars (The et al. 1994), like HBC334 (0.286, 0.268), V374Cep (0.351, 0.189), HD 35929 (0.296, 0.190), HD 130437 (0.273, 0.142), V361Cep (0.170, 0.085), HD 37490 (0.100, 0.099), HBC324 (0.059, 0.016), CPD-613587 (0.029, -0.016), HD 76534 (-0.040, -0.121), HD 53367 (-0.050, -0.092), HD 141569 (0.004, 0.020), V599Car (0.035, 0.083), HD 141569 (-0.004, 0.020), are found to be in the CBe location while LkH α 208 (0.589, 0.249) and TYCrA (0.241, 0.379) are found to be in the transition region in between the two zones. Out of the catalogued CBe stars (Jaschek & Egret 1982), only BD+56573 (0.573, 0.274) is found to be in the transition zone between HAeBe and CBe stars. The presence of HAeBe stars in CBe location may be due to

the evolutionary scenario in which an HAeBe star can lose disc and deredden to a CBe location. This type of HAeBe stars may be spun up candidates since CBe stars are high rotators. We have found a few cluster candidates in this transition phase. The rotation velocity of these stars could progressively increase as we come down along the reddening vector, from HAeBe location to CBe location. We are doing extensive analysis of the rotation velocity information from spectral-line analysis of our candidate stars as well as field stars.

5 CONCLUSION

1. We have searched for emission-line stars in 207 clusters out of which 42 have been found to have at least one. This can be a lower limit, considering the variability of emission stars and detection limit of the instrument.

2. A total of 157 emission stars were identified in 42 clusters. We have found 54 new emission-line stars in 24 open clusters, out of which 19 clusters are found to house emission stars for the first time.

3. The fraction of clusters housing emission stars is maximum in both the 0–10 and 20–30 Myr age bin (\sim 40 per cent each) and in the other age bins; this fraction ranges between 10 and 25 per cent, up to 80 Myr.

4. Most of the emission stars in our survey belong to CBe class (\sim 92 per cent) while a few are HBe stars (\sim 6 per cent) and HAe stars (\sim 2 per cent).

5. The youngest clusters to have CBe stars are IC 1590, NGC 637 and 1624 (all 4 Myr old) while NGC 6756 (125–150 Myr) is the oldest cluster to have CBe stars.

6. The CBe stars are located all along the MS in the optical CMDs of clusters of all ages, which indicates that the Be phenomenon is unlikely due to core contraction near the turn-off.

7. The distribution of CBe stars as a function of spectral type shows peaks at B1–B2 and B6–B7. Rich clusters like NGC 7419, 2345, 663 and h & χ Persei are found to favour the formation of early-type Be stars.

8. Among 37 surveyed clusters, 29 are found to have Be star fraction [N(Be)/N(B+Be)] to be less than 10 per cent while rich clusters such as NGC 2345 (26 per cent) and NGC 6649 (17.9 per cent) have more than 15 per cent.

9. The CBe phenomenon is very common in clusters younger than 10 Myr, but there is an indication that these clusters lack CBe stars of spectral type earlier than B1. The fraction of clusters with CBe stars shows an enhancement in the 20–30 Myr age bin, which indicates that this could be due to evolution of some B stars to CBe stars. The above two findings suggest that there could be two mechanisms responsible for CBe phenomenon. The first mechanism is where some stars are born CBe stars. Our results mildly suggest that this happens mainly for spectral types later than B1. The second mechanism is where the B stars evolve to CBe stars, likely due to evolution, enhancement of rotation or structural changes. This is likely to happen in early B spectral types.

10. We have made an effort to classify emission stars on the basis of IR excess using NIR CCDm. Using the catalogued field CBe and HBe stars, we have found that CBe stars are strictly confined to the location prescribed to them in terms of IR excess, while HBe stars are seen to migrate from HBe location to CBe location. Some of the cluster stars are also found to belong to this category. Detailed spectral analysis is planned to understand these stars.

11. Most of the clusters that contain emission stars are found in Cygnus, Perseus & Monoceros region of the Galaxy, which are locations of active star formation.

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