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Classical Be stars in our Galaxy and the Magellanic Clouds

Annapurni Subramaniam[1*], Blesson Mathew[2], K. T. Paul[3], R. E. Mennickent[4] and B. Sabogal[5]

[1]*Indian Institute of Astrophysics, Bangalore 560034, India*
[2]*Astronomy & Astrophysics division, Physical Research Laboratory, Ahmedabad, India*
[3]*Dept. Physics, Christ University, Bangalore, India*
[4]*Dept.of Astronomy, University of Concepcion, Concepcion, Chile*
[5]*Departamento de Física, Universidad de los Andes, Cra. 1 No. 18A-10, Edificio Ip, Bogotá, Colombia*

Abstract. We summarise our studies of the Classical Be (CBe) stars in our Galaxy and in the Large and Small Magellanic Clouds. We studied their properties using optical and near-IR photometry and optical spectroscopy. The CBe stars in the open clusters of the Galaxy were found to belong to two types. B-type stars of spectral type earlier than B1 were found to evolve to CBe phase while the later type stars were found to be born as CBe stars. Thus, CBe phenomenon is unlikely only due to core contraction near the main sequence turn-off. Spectral details of 150 CBe stars were studied, where 48 stars are studied for the first time. This large data set covers CBe stars of various spectral types and ages found in different cluster environments of the northern open clusters. The spectra of 109 candidate CBe stars in the MCs, identified based on photometric variability were studied and the majority showed emission lines suggesting the presence of circumstellar material. We suggest that the photometric variability is a very effective and efficient tool to identify large number of candidate CBe stars and binaries in the Magellanic Clouds.

Keywords : classical Be stars, open clusters, Galaxy, Magellanic Clouds

*email: purni@iiap.res.in

1. Introduction

A Classical Be star (CBe) is a rapidly rotating B-type star with an equatorial circumstellar decretion disk, which is not related to the natal disk the star had during its accretion phases (Porter & Rivinius 2003). Struve (1931) suggested that rapidly rotating single stars of spectral class B are unstable, which eject matter at the equator, thus forming a nebuluous ring which revolves around the star and gives rise to emission lines. The present working definition of a CBe star is given as a non-supergiant B star whose spectrum has, or had at sometime, one or more Balmer lines in emission (Collins 1987). The term classical has been used to distinguish them from Herbig Be stars, which are intermediate mass (2−10 $M_\odot$) pre-main sequence candidates with circumstellar accretion disk. Present studies point out that CBe stars are not rotating at critical velocity and the circumstellar disk is formed by episodic mass loss from the central star, unlike the model proposed by Struve. CBe stars rotate at 70−80% of their critical velocity and hence the reason for the formation of disk may not be equatorial mass loss mechanism.

The properties of CBe stars can be summarised as:

1. CBe stars are one of the fastest rotators in the Galaxy (VSin$i$ > 100 km/s).
2. Emission lines are present in optical and infrared spectra indicating the presence of a circumstellar envelope (Struve 1931). The circumstellar regions are cooler (electron temperature ≤ 10^4 K) than photosphere and the electron densities are of the order of 10^{11} to 10^{12} electrons per cm^3. The mass loss rate derived from Infra-red (IR) measurements is about 10^{-8} $M_\odot$/year (Hartmann 1978, Waters 1986).
3. The study of resonance lines in the ultraviolet spectra of early CBe stars indicates high velocity (500−1000 km/s), rarified (10^9cm^{-3}) polar winds with a mass loss rate of 10^{-10} $M_\odot$/year (Snow & Marlborough 1976, Snow 81). The mass loss rates and density in polar region are about 100 times less than equatorial value. This suggests that the winds of CBe stars are asymmetric (Waters 1987).
4. CBe stars show photometric and spectroscopic long and short term variabilities.

The production of disk in CBe stars is still a mystery and majority of the studies point towards an optically thin equatorial disk formed by channeling of matter from the star through wind, rotation and magnetic field (Porter & Rivinius 2003). Rapid rotation, stellar wind, non-radial pulsation, magnetic field and binary interaction are the proposed mechanisms to explain Be phenomenon in CBe stars.

2. CBe stars in open clusters

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 these stars, they are assumed to be at the same distance and have the same chemical composition. Hence it is a perfect place to study CBe since we do not have a hold on these parameters in the field. Young open clusters are expected to house emission line stars (e-stars) since many are found to evolve over a time scale of 20−30 Myrs.

Mathew et al. (2008) performed a survey to search for e-stars in northern open clusters, belonging to different parts of the Galactic disk. Compared to field CBe stars, cluster candidates offer precise values of distance, reddening and chemical composition, which help to understand their evolutionary state better. A sample of 157 stars in 42 clusters were used to study the role of environment and mechanisms for the formation of CBe stars. They used slitless spectroscopy to find e-stars in clusters, which is an innovative concept for a survey of this magnitude. The medium resolution spectra of identified e-stars were taken and the spectral parameters like equivalent width and rotation velocity were used to understand the properties of disk and angular momentum evolution. Results based on individual clusters are presented below.

- Slitless spectroscopy survey identified 157 e-stars in 42 open clusters from a survey of 207 open clusters.
- We used UBV photometric data, most of which were taken from WEBDA, to construct optical CMD. These were fitted with ZAMS and evolutionary isochrones, using the age and distance values taken from data references. These values were used for the comparative analysis of their photometric parameters. A plot of the M_v vs $(B-V)_0$ of all detected CBe stars is shown in Fig.1. The location of e-stars in this diagram is used to understand their evolutionary phase.
- From the above cluster analysis, we propose the necessity for new photometric data for the clusters Berkeley 63, Berkeley 90, Bochum 2, Collinder 96, NGC 2414, NGC 6649, NGC 6910, NGC 7039, NGC 7261 and NGC 7510. This may help in re-estimating the CBe paramters from the modified cluster parameters.
- The near-IR JHK_s magnitudes taken from 2MASS for cluster members is used to construct near-IR Colour-Colour diagram (CCDm). The position of e-stars in near-IR CCDm, which is corrected for cluster reddening, is used to estimate near-IR excess. This in turn is used to quantify the nature of circumstellar matter, which is used as a probe to differentiate CBe stars from HAeBe candidates.
- The clusters Bochum 6, IC 1590, NGC 6823 and NGC 7380 which were found to have HAeBe stars.

Following the survey (Mathew et al. 2008), the spectra of the identified e-stars were obtained to study their spectral properties. The survey contains a large number of stars covering a wide spectral and age range, thus making the sample ideal for statistical analysis of various spectral characteristics. In order to compare these cluster e-stars with those in the field, spectra of field CBe as well as HAeBe stars were also obtained.

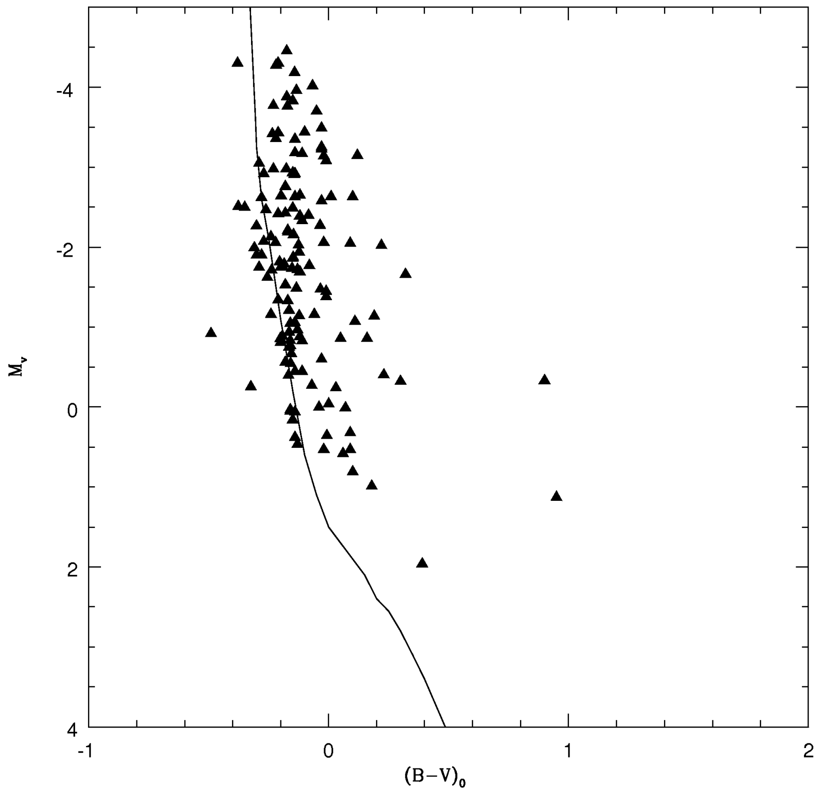

Figure 1. The M_v vs $(B-V)_0$ Colour Magnitude Diagram of all detected CBe stars.

Slit spectra for the emission stars were taken using Grism 7 (3800 Å – 6800 Å) and 167 μ slit combination in the blue region which gives an effective resolution of 4.41 Å(resolving power of 1330). The spectra in the red region is taken using Grism 8 (5800 Å – 8350 Å) /167 μ slit setup, which gives an effective resolution of 3.75 Å(resolving power of 2190). The spectra were found to have good signal to noise ratio greater than 100. Spectrophotometric standards such as Fiege 34, Wolf 1346, BD 284211 and Hiltner 600, observed on corresponding nights were used for flux calibration. All the observed spectra were wavelength calibrated and corrected for instrument sensitivity using IRAF tasks. The resulting flux calibrated spectra were normalised and continuum fitted using IRAF tasks. Spectra of three stars in IC 1590 are shown in figure 2. The top one is a CBe star, whereas the middle and the bottom spectra are candidate HerbigAe/Be stars. The spectra of e-stars in each cluster is compiled with optical CMD and near-IR CCDm. A comprehensive analysis of the stellar properties using measured spectral paramters is performed. The details of the spectroscopic survey can be found in Mathew & Subramaniam (2011).

The main results of this study can be summarised as:

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

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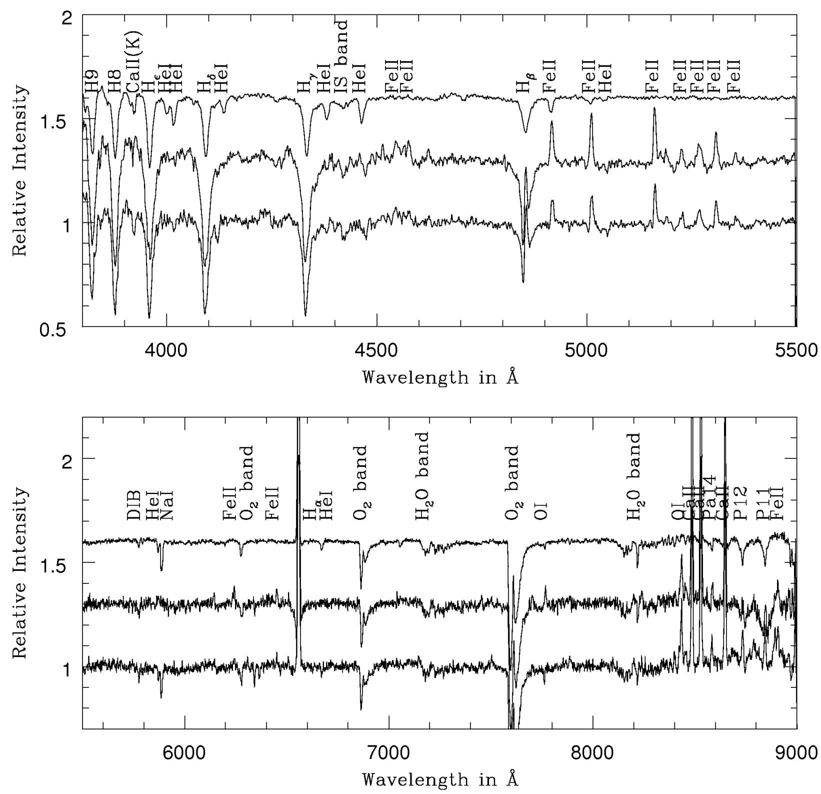

Figure 2. Spectra of a CBe star (top spectra) and two candidate Herbig Ae/Be stars in the cluster IC 1590.

- A total of 157 e-stars were identified in 42 clusters. We have found 54 new e-stars in 24 open clusters, out of which 19 clusters are found to house e-stars for the first time.
- The fraction of clusters housing e-stars is maximum in both the 0−10 and 20−30 Myr age bin (~ 40% each) and in the other age bins, this fraction ranges between 10% – 25%, upto 80 Myr.
- Most of the e-stars in our survey belong to CBe class (~ 92%) while a few are HBe stars (~ 6%) and HAe stars (~1%).
- 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.
- The Be 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.

- Apart from the Balmer lines in emission, spectra of most of the stars show FeII, Paschen and OI lines in emission while HeI is seen in absorption. About 86% of the surveyed emission stars show FeII lines in their spectra. We suggest Lyman β fluorescence as the mechanism for the production of 8446 Å line in 24% of the surveyed stars and 47% show line formation (OI 8446 Å & 7772 Å lines) due to collisional excitation. Of the total stars, 14 do not show correlation in FeII 7712 Å and OI 7772 Å line profiles. We found 60% of stars having CaII triplet in emission.

3. Candidate CBe stars in the magellanic clouds

Mennickent et al. (2002) presented a catalogue of 1056 CBe star candidates in the Small Magellanic Cloud (SMC) by studying light curve variations using OGLE II data base (Udalski et al. 1998, 2000) They classified these CBe star candidates of the SMC in four categories: type 1 stars showing outbursts (139 stars); type 2 stars showing sudden luminosity jumps (154 stars); type 3 stars showing periodic or near periodic variations (78 stars); type 4 stars showing light curves similar to Galactic CBe stars (658 stars). They also classified type 1 stars with luminosity jumps in their light curves as type1/type2 stars (18 stars). They suggested that type 4 could be CBe stars. They also proposed that some of the type 1 and type 2 stars might be CBe stars with accreting white dwarfs in a Be + WD binary, or they could be blue pre-main sequence stars showing accretion disc thermal instabilities. Spectroscopy is needed to confirm the suggestion that some of these stars are CBe stars. Also, more studies, especially in the near-infrared (NIR) are required to confirm the pre-main sequence hypothesis. On the other hand, they suggested that type 3 stars should not be linked to the Be star phenomenon at all.

Based on a similar inspection of OGLE II data, Sabogal et al. (2005) classified CBe candidates in the Large Magellanic Cloud (LMC) also as type 1 (581 stars), type 2 (150 stars), type 3 (149 stars), type 4 stars (1468 stars) and type 1/type 2 stars(98 stars). However many of the type 4 stars in the LMC are found to be reddened and located parallel to the main sequence, this feature was not found in the same diagrams of the SMC. The photometric properties of type 1 and type 3 stars on the LMC are very different from those of the SMC. Thus, the various types of stars identified based on variability seem to differ between the LMC and the SMC. The above studies identified a large number of candidate CBe stars which can be used to derive the parameters that are responsible for the Be-phenomenon as these types of stars in the MCs are metal poor when compared to the Galactic CBe stars. The above classification was based only on photometric variability. It is desirable to get some more properties like their NIR magnitudes and colours to understand these stars. In order to obtain their NIR properties, we used the NIR IRSF-MCPSC catalog (Kato et al. (2007); http://pasj.asj.or.jp/v59/n3/590315) which has JHK_s photometric data for about 15 million point sources spread over a 40 deg^2 area of the LMC and 2.7 million sources spread over a 11 deg^2 area of the SMC. The optically identified stars were cross-matched with NIR IRSF-MCPSC catalog to confirm their candidature in IRSF-MCPSC. Matches between both catalogs were found by comparing the RA and DEC co-ordinates in both the catalogs. Optical spectra were obtained for 119 candidate stars in the LMC and the SMC. Spectroscopic observations were conducted at the Cerro Tololo Inter-American Observatory (CTIO) and the Las Campanas Observatory (LCO) during 4 nights of October 2002 and 4 nights of November 2003, respectively. In addition, 48 spectra were obtained in LCO with the Modular Spectrograph and the SiTe2 detector.

The results of the above study are presented in Paul et al. (2012). We summarise the results of the spectroscopic study here.

- Spectra of 109 stars belonging to the types 1, 2 and 3 were analysed to study their spectral properties. Majority of the stars showed emission lines in the spectra suggesting the presence of circumstellar material. Types 1 and 2 were found to belong to early spectral type. Type 3 stars were found to belong to relatively late spectral types.
- We find that type 1, type 2 and type 3 stars have more or less similar spectral and NIR properties in the LMC and in the SMC. On the other hand, type 4 stars are found to have a subgroup in the LMC, with different optical and NIR properties. This subgroup is not found in the SMC or in our Galaxy. These stars do not have NIR ecxess, show large reddening, but are not located in regions with high reddening. The reddening corrected magnitudes make them the most brightest and massive stars in the sample. Detailed spectroscopic studies are needed to understand these enigmatic candidates. This new subclass is ~ 18% of the type 4 sample. The main type 4 sample is ~ 49% of the total sample, whereas the SMC has ~ 65% type 4 stars.
- Type 3 stars, which is the least populated type, are found to belong to B and A spectral types. These stars in the LMC have relatively less Hα *EW* when compared to those in the SMC. Some stars are found to have NIR excess and thea H_α *EW* correlates with the $(H-K)_0$ values, suggesting dust in the circumstellar material. These stars are possibly a mix of various types of stars like interacting binaries and double periodic variables.
- Type 2 stars show similar spectral properties in the LMC and the SMC.
- The type 1 stars are relatively more in the LMC (~ 24%) when compared to the SMC (~ 13%). The SMC type 1 stars are early type stars with large Hα *EW* and this class has properties similar to CBe stars. Some of the type 1 stars in the LMC do not show evidence of emission and their V_0 magnitudes suggest that they could belong to late B spectral types.
- The above results suggest that that the photometric variability is a very effective and efficient tool to identify large number of candidate CBe stars and binaries in the L&SMC.

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