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Spectroscopic study of a few Herbig Ae/Be stars in young open clusters

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Abstract. We present the spectroscopic study of 5 Herbig Ae/Be stars in young open clusters. These are identified from a survey of emission-line stars in young open clusters. The Herbig Ae/Be stars are found to show a linear correlation in H_α equivalent width versus reddening corrected $(H-K_s)$ colour plot, with a clear offset from the distribution of Classical Be stars. The candidates are found to show near infrared excess which was revealed through de-reddened $(J-H)$ versus $(H-K_s)$ colour-colour diagram and spectral energy distribution. From optical/near-IR photometry and spectroscopy, we suggest that Bochum 6-1, IC 1590-1 and NGC 6823-1 are Herbig Be while IC 1590-2 and NGC 7380-4 are Herbig Ae candidates. Bochum 6-1 is an interesting Herbig B[e] star with a high H_α equivalent width of -206 Å, which is the highest among the surveyed stars. We combined the optical and near-IR photometry to estimate the duration of star formation in the clusters, Bochum 6, IC 1590, NGC 6823 and NGC 7380. We found ongoing star formation in all these clusters, with an appreciable number of pre-main sequence stars. The age of these Herbig Ae/Be stars, estimated using pre-main sequence isochrones, were found to range between $0.25-3$ Myr. IC 1590 is found to be an interesting young cluster ($\sim$ 4 Myr) with 3 emission stars, each belonging to Herbig Ae, Herbig Be and Classical Be respectively. All the four clusters studied here were found to be forming stars for the last 10 Myr.

Keywords : stars: formation – stars: emission-line, Be – stars: pre-main sequence – : open clusters

1. Introduction

Stars which show emission lines in their spectra are found in young open clusters ($<$ 100 Myr). These stars can be classifed as Herbig Ae/Be (HAeBe) stars and Classical Be (CBe) stars. Both these class of stars are found to possess circumstellar disk, which produce emission lines over the photospheric spectrum. HAeBe stars are intermediate mass pre-main sequence (PMS) stars, found to possess a natal accretion disk which is a remnant of star formation (Hillenbrand et al. (1992), Waters & Waelkens (1998)). A CBe star is a rapidly rotating B-type star that produces an equatorial disk which is not related to the natal disk the star had during its accretion phases (Porter & Rivinius (2003)). The classification of emission-line stars (e-stars) as HAeBe stars and CBe stars has been a difficult task, especially in very young clusters ($\leq$ 10 Myr).

A survey to search for Be stars in young open clusters was conducted using slitless spectroscopy method (Mathew et al. 2008). In this survey, 207 open star clusters were studied and 157 e-stars were identified in 42 clusters. We found 54 new e-stars in 24 open clusters, of which 19 clusters were found to house e-stars for the first time. Even though the aim was to study 'Be phenomenon' in CBe stars, a few HAeBe candidates were also found among the surveyed stars. Most of the e-stars in the survey belonged to CBe class ($\sim$ 92%), while $\sim$ 6% are Herbig Be (HBe) stars and $\sim$ 2% belong to Herbig Ae (HAe) category. In Mathew et al. (2008), Berkeley 90-1, Bochum 6-1, IC 1590-1, NGC 146-S2, NGC 1893-1, NGC 6823-1, NGC 7380-1, NGC 7380-2, NGC 7510-1C were identified as possible HBe stars and IC 1590-2, NGC 7380-4, Roslund 4-1 as possible HAe stars from optical Colour-Magnitude Diagram (CMD), near infrared Colour-Colour Diagram (near-IR CCDm) and the presence of a nebulosity. In this paper we have compiled the spectroscopic information on these candidate stars, along with their photometric details, to identify the most likely HAeBe candidates.

Marco & Negueruela (2002) identified four PMS stars in the field of cluster NGC 1893 from low-resolution spectroscopy and photometry. The early-type PMS stars are found in the rim of the molecular cloud and in the vicinity of nebulae Sim 129 and Sim 130. They found possible cohabitation of HBe and CBe stars in the cluster, whose age is around 3 Myr. Testi et al.(1999) found clustering of low mass stars around early HBe stars while HAe stars are never associated in groups. They proposed that the formation of high-mass stars is influenced by dynamical interaction in a young cluster environment. Subramaniam et al.(2006) found 42% of the stars in the rich cluster NGC 7419 to have near-Infrared (near-IR) excess, which were confirmed to be PMS candidates. From a fit of PMS isochrones the turn-on age of the cluster is found to be $0.3-3$ Myr, which indicates a recent episode of star formation. Bhavya et al.(2007) studied recent star formation history in the Cygnus region using the clusters Berkeley 86, Berkeley 87, Biurakan 2, IC 4996 and NGC 6910. They proposed that Cygnus region has been actively forming stars for the last 7 Myrs. Hence young open clusters provide an ideal platform to study star formation since they harbour emission-line stars and PMS candidates. In similar lines, in this study, we have identified PMS stars in clusters with HAeBe stars and estimated the duration of star formation. The ages of the identified HAeBe stars were also estimated. The locations of PMS stars and HAeBe stars were compared to identify the presence of any clustered star formation around the HAeBe stars.

In the following sections we have described the techniques used to classify HAeBe candidates from the observed list of e-stars, using the correlation between H_α, OI equivalent width (EW) with near-IR excess. This is followed by the estimation of PMS stars, duration of star formation and discussion.

2. Observations

The spectroscopic observations of the 157 e-stars in clusters were obtained using HFOSC available with the 2.0m Himalayan Chandra Telescope, located at 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 K $\times$ 4 K CCD, where the central 500 $\times$ 3500 pixels were used for spectroscopy. The pixel size is 15 μ with an image scale of 0.297 arcsec/pixel. Slit spectra for the e-stars were taken using grism 7 and 167 μ slit combination in the blue region (3800Å−5500Å) which gives an effective resolution of 1330. The spectra in the red region (5500Å−9000Å) is taken using grism 8 and 167 μ slit setup, which gives an effective resolution 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, which were 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. The log of the observations of e-stars is given in table 1.

The near-IR 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) database. The 2MASS colours (J−H) and (H−K_s) are de-reddened using the relation from Bessel & Brett (1988) and near-IR CCDm is plotted for the identified stars in the cluster. The main sequence track and giant star location are taken from Bessel & Brett (1988) which is transformed to 2MASS photometric system using the relations from Carpenter (2001). The HAeBe star location is taken from Hernandez et al. (2005) while CBe star location is taken from Dougherty et al. (1994). The reddening bands are shown which limits the reddening due to normal interstellar dust. Stars which have near-IR excess are located to the right of reddening vector and are considered to be candidate PMS stars. The PMS stars show near-IR excess due to the presence of a dusty circumstellar material. The near-IR CCDm also helps to identify CBe and HAeBe stars separately, in which both of them occupy distinct regions (Lada & Adams 1992).

For determining the age of candidate PMS stars, optical CMDs are plotted after correcting for the cluster mean reddening value (E(B-V)). The zero-age main sequence

Table 1. The log of spectroscopic observations.

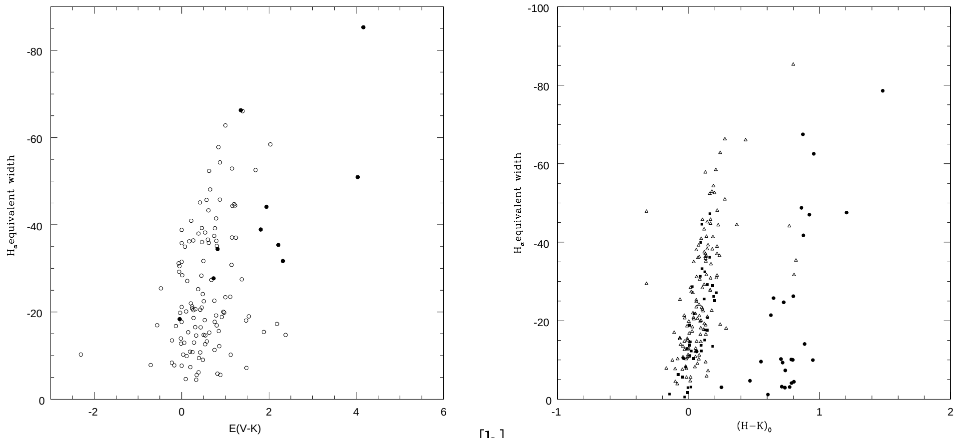
Date of observation	Emission star	Grism/ Slit	Exposure time in seconds
07-12-2005	Bochum 6-1	Grism 7/167l	600
		Grism 8/167l	600
28-09-2006	IC 1590-1	Grism 7/167l	720
		Grism 8/167l	600
28-09-2006	IC 1590-2	Grism 7/167l	720
		Grism 8/167l	600
28-09-2006	IC 1590-3	Grism 7/167l	720
		Grism 8/167l	600
25-10-2005	NGC 6823-1	Grism 7/167l	900
		Grism 8/167l	900
29-08-2006	NGC 7380-4	Grism 7/167l	1200
		Grism 8/167l	1200

(ZAMS) (Schmidt-Kaler 1982) is fitted and distance modulus (DM) is estimated. PMS isochrones of various ages from Seiss et al. (2000) are plotted and the position of candidate PMS stars is located. The error in the estimation of age is about 10%. The identified PMS stars and Be stars are shown separately among the cluster members. Their relative spatial distribution of PMS and Be stars is used to look for clustering, which gives an idea about active star formation.

For the construction of spectral energy distribution (SED), we have taken the photometric magnitudes from following database. U magnitudes from homogeneous means in the UBV System (Mermilliod 1994), B, V, R magnitudes from NOMAD Catalog (Zacharias et al. 2005), I from DENIS database (http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=B%2Fdenis) and J, H, K_s magnitudes from 2MASS database. The extinction corrected magnitudes have been converted to fluxes and the resulting plot between $\log(\lambda f_\lambda)$ and $\log(\lambda)$ is shown separately for e-stars in each clusters. The SED has been normalised at V magnitude to look for the excess in near-IR bands. The excess flux in K_s band due to dust emission have been used to separate HAeBe stars from CBe stars.

3. Results and discussion

In the following subsections, correlation between H_α, Paschen, CaII and OI lines with near-IR excess are presented. We used these correlations to identify HAeBe candidates among the surveyed stars.



[a] [b]

Figure 1. (a) Correlation between H_α EW and E(V−K_s) for all e-stars. The candidate CBe stars are shown as open circles while the suspected HAeBe stars are shown as filled circles. (b) Correlation between H_α EW and (H−K_s)$_0$ for all e-stars. Our candidate e-stars are shown as open triangles while the HBe stars from The et al. (1994) are shown as filled circles and CBe stars from Jaschek et al. (1982) as filled squares.

3.1 Correlation of H_α EW with near-IR Colour excess

Feinstein (1982) found a correlation between H_α EW and (K−L) colour suggesting that stars with high H_α EW show large IR excess. Neto & de Freitas-Pacheko (1982) found a linear correlation between H_α flux and the infrared flux at 3.8μm. These results suggest that the same region of Be star envelope produces IR excess and Balmer line emission.

Usually (V−K_s) is used to find excess from circumstellar region over the photospheric continuum since the emission from circumstellar medium starts dominating from V magnitude onwards. To quantify the contribution from circumstellar medium, we have deducted the colour excess of cluster from (V−K_s) using the E(B−V) value of the cluster. The photometric V magnitudes are taken from the references given in Mathew et al. (2008). We have estimated the colour excess E(V−K_s) using the relation E(V−K_s)=(V−K_s)$_0$-(V−K_s)$_S$ where (V−K_s)$_0$ is the corrected (for cluster excess) (V−K_s) colour and (V−K_s)$_S$ is the standard colour corresponding to the spectral type of candidate stars, taken from Koornneef (1983). Hence E(V−K_s) indicates the colour excess due to circumstellar material. A plot between the colour excess E(V−K_s) and H_α EW of e-stars is shown in Fig. 1a. The identified CBe stars among the surveyed candidates are shown as open circles while the suspected HAeBe stars (Mathew et al. (2008)) are shown as filled circles. We have not included Berkeley 90-1 and Bochum 6-1 in the plot since former do not have optical photometry while the latter has high H_α EW. As seen from Fig. 1a, the excess E(V−K_s) is found to be correlated with H_α EW.

Even though 6 stars are separated from the remaining candidates, this plot do not clearly distingish HAeBe stars from the surveyed CBe stars.

We propose the plot between H_α EW and $(H-K_s)_0$ colour as a tool to differentiate HAeBe stars from CBe stars. The near-IR colour $(H-K_s)$ has been corrected for cluster reddening using the relations by Rieke & Lebofsky (1985). We have plotted our surveyed stars with the catalogued field HAeBe stars (The et al. (1994)) and CBe stars (Jaschek & Egret (1982)) in Fig. 1b. The B and V band photometric magnitudes were taken from Tycho-2 Catalog (Hog 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 de-redden the (J−H) and (H−K) colours. A clear offset can be found between the distribution of field HAeBe and CBe stars. This is expected since HAeBe stars are found to have an extended circumstellar material with more dust content than CBe stars. The near-IR excess in CBe stars is due to free electrons while this adds up with dust excess in HAeBe stars. The stars Bochum 6-1, IC 1590-1, IC 1590-2, NGC 6823-1, NGC 7380-4 have been found along with catalogued HAeBe stars and hence it agrees with their previous identification as HAeBe stars (Mathew et al. 2008). We have not included Bochum 6-1 in this plot due to the high value of EW. The stars Bochum 6-1, IC 1590-1, NGC 6823-1 belong to HBe class while IC 1590-2 and NGC 7380-4 belong to HAe category. Berkeley 90-1 is not included in this analysis since E(B−V) is not available. The e-stars NGC 146-S2, NGC 1893-1, NGC 7380-1, NGC 7380-2, NGC 7510-1C and Roslund 4-1 were identified as HAeBe by Mathew et al. (2008), but are found to be along with catalogued CBe stars in this plot.

The stars which have missed detection in this plot (7 stars) might be the ones which have less circumstellar material and hence showing less H_α EW and near-IR excess. They might belong to Group III category, which is a classification of HAeBe stars done by Hillenbrand et al. (1992) based on SED. Hence from the photometric and spectroscopic estimates we conclude that out of 157 surveyed e-stars 3 are HBe candidates while 2 are HAe candidates. The H_α EW shows a striking correlation with $(H-K_s)_0$ colour, which implies that the presence of dusty regions favours the production of H_α by creating an environment to produce recombination radiation.

3.2 Correlation of OI, P14 and calcium triplet EW with $(H-K_s)_0$ colour

It has been pointed out by Briot (1977, 1981) that Be stars with calcium and Paschen lines are found to show high near-IR excess compared to other Be stars. We have searched for this trend in our surveyed 157 candidate e-stars. The presence of ionized calcium (CaII) in emission for some Be stars was found by Hiltner (1947). Andrillat et al. (1988) observed that if CaII lines are in emission, Paschen lines are also in emission with a similar dependence for absorption profiles also. Polidan & Peters (1976) connected the presence

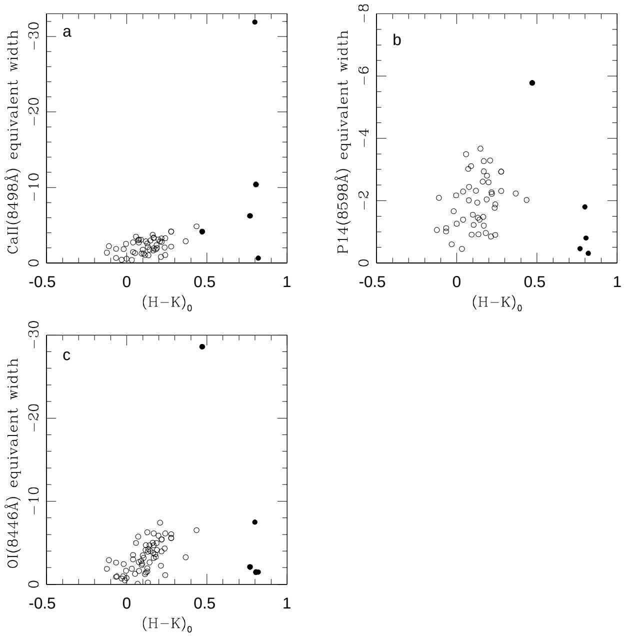


Figure 2. A plot of EW versus $(H-K)_0$ for e-stars is shown with CaII(8498 Å) in (a), Paschen 14(8598 Å) in (b) and OI(8446 Å)line in (c). The e-stars which were found to belong to HAeBe category are shown as solid circles while all the other e-stars are shown in open circles.

of CaII triplet (8498, 8542, 8662 Å) in emission to the binary nature of the star. They found no correlation between the line properties and the star-disk parameters.

Out of 157 candidate stars, 100 show Paschen 14 (P14, 8598 Å) line in emission and 92 show CaII triplet, while 146 show OI 8446 Å lines in emission. We have looked for the correlation of the EW of these line profiles with $(H-K_s)_0$, which is indicative of near-IR excess. The e-stars which were found to belong to HAeBe category are shown as solid circles while all the other e-stars are shown in open circles. We have used line profiles which have good signal for this correlation studies. The EW of CaII 8498 Å profile is found to be correlated with $(H-K_s)_0$ for the surveyed e-stars (figure 2(a)). The e-stars NGC 6823-1 and NGC 7380-4 seem to move away from the total candidate stars, with former showing a low EW of −0.64 Å while latter having a strong emission of −32 Å. We have not deblended the contribution of Paschen line from CaII line while measuring the EW. The EW of P14 line seems to show a sparse correlation with $(H-K_s)_0$ (Fig. 2b). Of the 5 classified HAeBe candidate stars, 4 stars are located away from the general trend. Bochum 6-1 is found to have P14 EW of −5.7 Å, which is the highest among the group of surveyed stars. Since the correlation of Paschen lines with $(H-K_s)_0$ is sparse, correlation observed here can be assumed to be mainly due to CaII line. The Be stars

Table 2. Photometric parameters of identified HAeBe stars.

HAeBe star	RA hh:mm:ss	Dec dd:mm:ss	V mag	J mag	H mag	K_s mag	Sp. type	Dist. kpc	Age Myr
Bochum 6-1	07:31:48.84	−19:27:37.2	13.30	11.33	10.83	10.22	B6	3.16	0.5
IC 1590-1	00:52:51.22	56:36:56.0	13.43	12.21	11.63	10.80	B8.5	2.94	2
IC 1590-2	00:52:45.67	56:37:53.8	13.95	12.49	11.62	10.75	A0	2.94	3
NGC 6823-1	19:43:04.38	23:18:48.8	13.73	11.55	10.53	9.54	B6.5	2.30	0.5−1
NGC 7380-4	22:47:22.39	58:01:21.5	14.72	10.79	9.76	8.84	A1	3.73	$\leq$0.25

Table 3. Spectral lines identified in HAeBe stars.

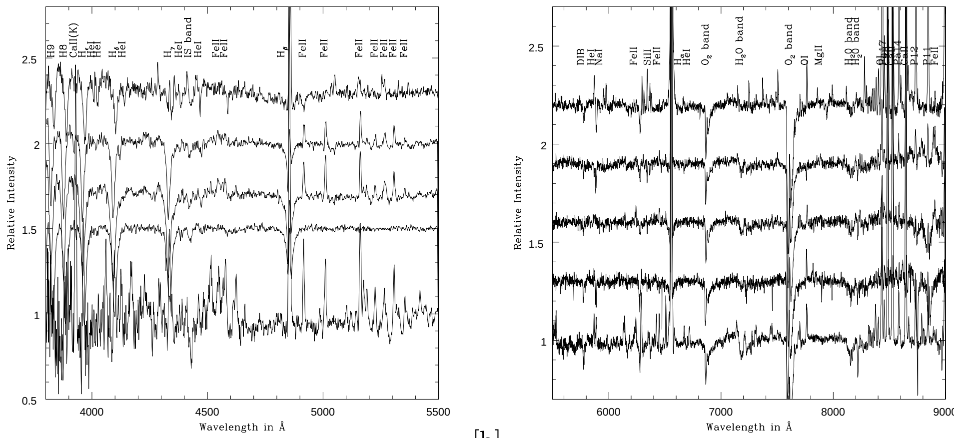
HAeBe star	H_α EW in Å	H_β EW in Å	OI 8446 EW	CaII 8498 EW	Special lines
Bochum 6-1	−206	−16.28	−28.6	-4.16	[FeII] (4287, 4358, 4413 and 5159 Å) in emission, SiII 6347 Å & 6371 Å in absorption
IC 1590-1	−44.12	−1.38	−2.09	−6.24	FeII lines (4549, 4584, 4924, 5018, 5169, 5235, 5276, 5316, 5363 Å) in emission
IC 1590-2	−31.70	−1.31	−1.46	−10.4	H_α & FeII(5018) P-Cygni profile
NGC 6823-1	−35.38	−2.66	−1.47	−0.64	HeI in emission
NGC 7380-4	−85.29	−14.10	−7.48	−32.0	NaI, KI, NII (5530, 5535 Å) in emission

which have Paschen emission lines do not have near-IR excess when compared to other Be stars, which does not support the results by Briot (1981). Our results seems to be statistically sound compared to 15 stars used in their analysis.

All the 5 classified HAeBe stars are found to be well separated from the group of surveyed e-stars in the plot between OI 8446 Å and near-IR colour $(H-K_s)_0$ (Fig. 2c). The star Bochum 6-1 is found to have the highest value of OI EW (−28.6 Å) among the surveyed stars. This plot correlates well with H_α EW versus $(H-K_s)_0$ colour distribution of e-stars. Hence this plot can also be used as a criterion to differentiate CBe stars from HAeBe stars.

4. HAeBe stars as members of parent clusters

In this section we put up all the evidences (optical CMD with PMS isochrones fitted, near-IR CCDm and optical spectra) along with SED to test the above classification. Previous studies about the cluster have been included to understand the cluster environment and the cluster parameters used for deducing the stellar parameters. Hence in the following subsections we also describe the star formation scenario in the parent clusters with which



[a] [b]

Figure 3. (a) The spectra of the e-stars Bochum 6-1, IC 1590-1, IC 1590-2, NGC 6823-1 and NGC 7380-4 in the wavelength range 3800 – 5500 Å is shown from top to bottom in the figure. (b) The spectra in the wavelength range 5500 – 9000 Å is shown in the figure.

these e-stars are associated. If we find stars younger than 1 Myr, we suggest that the cluster has ongoing star formation.

For the clusters Bochum 6, IC 1590, NGC 6823 & NGC 7380 optical and near-IR data are combined to detect the PMS candidates. This also helps to check whether the star formation process in the cluster is continuous or due to a single burst. The procedure used to identify PMS candidates is explained in Subramaniam et al. (2006) and Bhavya et al. (2007). The coordinates, photometric magnitudes (V, J, H, K_s), distance and age estimated for the e-stars treating them as members of corresponding clusters is given in Table 2. Of the 4 clusters described here as hosting e-stars, Bochum 6, NGC 6823 and NGC 7380 are found to have single e-stars. The open cluster IC 1590 is found to have a CBe, HAe and HBe candidate each. For a relative comparison we have included the CBe candidate in SED plot, eventhough rest of the analysis is focussed only on HAeBe candidates. Spectra of the above mentioned HAeBe stars in the wavelength range 3800–9000 Å are given in Fig. 3. A detailed list of the spectral lines is tabulated in Table 3. The combined SED of all the e-stars is shown in Fig. 4.

4.1 Bochum 6

The open cluster Bochum 6 ($RA = 07^h32^m00^s$, $Dec = -19^o25'$, $l = 234.745^o, b = -0.218^o$) was observed by Moffat et al. (1975) for the first time and concluded that this contains 5 OB stars. They estimated a reddening value of 0.70 and distance of 4 kpc from photoelectric observations. They suggested that the cluster appears to coincide with the HII region S309, whose photometric and kinematic distances are 6.30 kpc and 2.24 $\pm$ 0.36

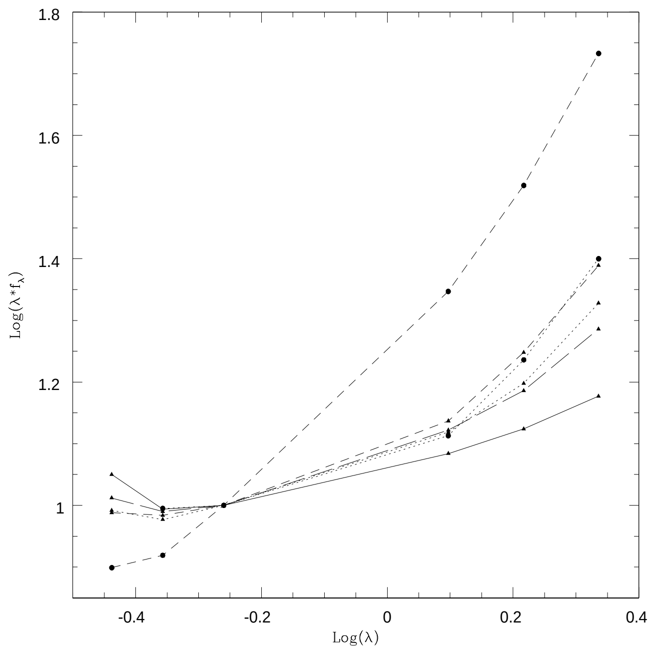


Figure 4. The Spectral Energy Distribution for e-stars IC 1590-3 (bold-line + triangle), IC 1590-1 (dot-line + triangle), IC 1590-2 (short-dash + triangle), Bochum 6-1 (long-dash + triangle), NGC 6823-1 (dot-line + circle) and NGC 7380-4 (short-dash + circle) are shown. The CBe star IC 1590-3 is shown as reference.

kpc respectively. From deep UBVRI CCD photometry, Yadav et al. (2003) determined an E(B−V) of 0.71 ± 0.13 and a distance of 2.5 ± 0.4 kpc. They estimated an age of 10 ± 5 Myr by fitting Schaller et al. (1992) isochrones of Solar metallicity. We have identified a peculiar e-star, Bochum 6-1, in this cluster from the survey of e-stars in young open clusters (Mathew et al. 2008). The e-star corresponds to the star 2143 in Yadav et al. (2003) and is found to be of B6 spectral type.

We have taken UBV CCD photometric data of 1459 stars from Yadav et al. (2003) which was cross correlated with 2MASS photometric data. 146 stars were found to have UBV CCD and JHK$_s$ magnitudes. After de-reddening the (J−H) and (H−K$_s$) colors using E(B−V) = 0.71 (Yadav et al. 2003), near-IR CCDm is plotted as shown in Fig. 5a. There are 20 stars (including e-star) located below the reddening vector, of which 2 stars occupy same location in near-IR CCDm. The e-star is highly reddened in near-IR CCDm and found to be located inside the HAeBe location. There is also nebulosity associated with Bochum 6-1. The SED (Fig. 4) shows a sharp rise is J, H, K$_s$ magnitudes due to near-IR excess. This is due to the circumstellar dust around this candidate HBe star.

For the cross-correlated stars, optical CMD is plotted (Fig. 5b) after reddening

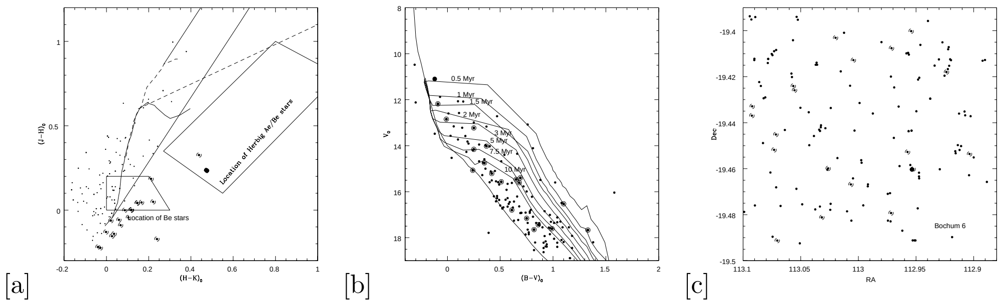


Figure 5. (a) Near-IR CCDm of Bochum 6. The normal stars in cluster are shown as small circles. Encircled ones are candidate PMS stars and filled circle represents e-star. (b) Optical CMD of Bochum 6. PMS isochrones of ages 0.5−10 Myr are plotted. Bochum 6-1 is found to occupy 0.5 Myr isochrone. (c) Location of PMS stars and e-stars are shown in the field of Bochum 6.

correction. ZAMS is fitted for a DM of 12.5 (corresponding to a distance of 3.16 Kpc). Yadav et al. (2003) estimated the distance as 2.5±0.5 Kpc. The PMS stars are found to be located in all the 1 to 10 Myr isochrones giving the cluster an age range of at least 10 Myr. The e-star is located near the main sequence. Yadav et al. (2003) found out an age of 10 ± 5 Myr for Bochum 6, in which case both high mass and low mass stars have formed together. Their study did not consider stars fainter than V = 14.5 as cluster members. They assumed that the probability of forming the low mass stars are negligible in OB associations. In our study we include stars upto a limit of 19 magnitue and low mass stars are also taken into account. The candidate PMS stars are located along the boundary of the cluster (Fig. 5c). The PMS stars are located in a ring like structure and none are located near the cluster center. The HBe star is also located in the ring-like structure. We do not find any evidence of any significant clustering around this star.

Bochum 6-1 is peculiar due to the presence of intense Balmer lines with H_α EW of −206 Å (Fig. 3b) and H_β EW of −16.28 Å (Fig. 3a) along with OI 8446 Å line having a linewidth of −28.6 Å. The unusually high value of H_α EW (which is quite high compared to the mean H_α EW of −40 Å for surveyed stars) might be having some contribution from the HII region S309. The spectra of Bochum 6-1 show 5 FeII lines in emission, while SiII lines 6347 Å and 6371 Å are seen in absorption. It also shows 4 forbidden FeII ([FeII]) lines (4287, 4358, 4413 and 5159 Å) in emission, which corresponds to B[e] star. Hence from photometric and spectroscopic analysis it is deduced that Bochum 6-1 could be a HBe star in B[e] phase.

4.2 IC 1590

The young cluster IC 1590 ($l = 123.1^o, b = -6.2^o$) contains a group of stars clustered around the O-type trapezium system HD 5005 (Sharpless (1954), Abt (1986)). The

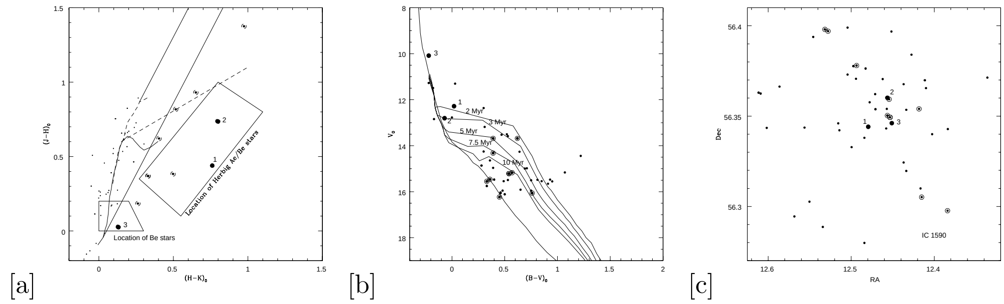


Figure 6. (a) The near-IR CCDm of the cluster IC 1590 is shown with PMS candidates as encircled symbols and e-stars as filled circles. (b) Optical CMD of IC 1590. PMS isochrones of ages 2−10 Myr are plotted. IC 1590-1 and IC 1590-2 occupy 2 Myr and 3 Myr PMS isochrones respectively. (c) Location of PMS stars and e-stars are shown in the field of IC 1590.

cluster is embedded in the HII region NGC 281, or Sh-2 184, of diameter 20 arc minutes. The HII region is surrounded by an extensive HI cloud which contains several cometary globules. The HII region seems to be associated with two CO molecular clouds NGC 281A and NGC 281B which were mapped in CO^{12} and CO^{13} by Elmegreen & Lada (1978). Guetter & Turner (1997) used photoelectric and CCD photometry for 279 stars in the cluster region and estimated a distance of 2.94 ± 0.15 kpc. They estimated an age of 3.5 Myr using 63 identified probable members of the cluster without much evidence for age spread. The cluster appears to have a high R_v value of 3.44, which is larger than the galactic value. A value of −1.00 ± 0.21 is estimated for the initial mass function from the luminosity function of the cluster members. The e-stars are numbered as 215, 151 and 214 in Guetter & Turner (1997), while in this paper it is given in the order IC 1590-1, IC 1590-2, IC 1590-3. IC 1590-3 is of B2 spectral type while IC 1590-1 and IC 1590-2 are found to be B8.5 and A0 respectively. We found nebulosity associated with IC 1590-1 and IC 1590-2.

The UBV values and position coordinates (B1950 coordinates) of 246 stars were taken from Guetter & Turner (1997). These were matched with 2MASS database and for 56 stars both JHK_s and UBV magnitudes were found. After de-reddening the (J−H) and (H−K_s) colours using mean cluster reddening value, E(B−V)= 0.37 (Guetter & Turner 1997), near-IR CCDm is plotted. In the near-IR CCDm, 12 stars were found to be located below the reddening vector of which 2 occupy the same position. They are considered to be candidate PMS stars, as shown in Fig. 6a. Out of 3 e-stars, IC 1590-1 and IC 1590-2 are located inside the HAeBe location and IC 1590-3 is located inside the CBe star location.

In the optical CMD (Fig. 6b), ZAMS is fitted for a DM of 12.34. PMS isochrones of ages 2−10 Myr are plotted. It can be seen that all the candidate PMS stars are located in the 2−10 Myr isochrones, suggesting that star formation is a continuous process in the cluster. There are low mass stars in the cluster which are older than the estimated age of 3.5± 0.2 Myr by Guetter & Turner (1997). The e-stars IC 1590-1 and IC 1590-2 are located along 2 and 3 Myr isochrones respectively, while e-star IC 1590-3 is located along the main sequence track. By looking into the position of these e-stars, we can assume that IC 1590-1 and IC 1590-2 are of HAeBe nature and IC 1590-3 is a CBe star. In the cluster field all the e-stars are found be located close to the center, as shown in Fig. 6c. No significant clustering is found near the HAeBe stars. The cluster seems to have formed stars for a duration of at least 8 Myr.

All the Balmer lines except H_α and H_β are found in absorption/filled-in for the e-stars IC 1590-1, IC 1590-2 and IC 1590-3. The emission profile of H_α shows P-Cygni nature for IC 1590-2 and double-peak for IC 1590-3 while it is normal single peak profile for IC 1590-1. The P-Cygni profile indicates that the H_α line might be formed in wind/outflow, which is a characteristic of HAeBe stars. The double-peak H_α profile is usually indicative of the CBe star. H_β is found to have an asymmetric emission in absorption profile for IC 1590-1 and IC 1590-2 while it is in absorption for IC 1590-3.

As seen in Fig. 3a, quite a number of FeII lines (4549, 4584, 4924, 5018, 5169, 5235, 5276, 5316, 5363 Å) are found in emission for IC 1590-1 and IC 1590-2 while no such nature is seen for IC 1590-3. The 5018 Å FeII profile is found to show P-Cygni feature for IC 1590-1 and IC 1590-2, which is a signature of wind/outflow associated with the star. In the red region of the spectrum (Fig. 3b), CaII triplet is found in emission along with the Paschen lines (8467 (P17), 8598 (P14), 8750 (P12), 8862 (P11)) for IC 1590-1 and IC 1590-2 while they are found to be in absorption for IC 1590-3. The helium lines (4026, 4471, 5876, 6678, 7065 Å) are found to be visibly present in IC 1590-3 which matches with early spectral type estimated for the star from photometry. OI 8446 Å line shows intense emission for IC 1590-1 and IC 1590-2 while it is absent in IC 1590-3. Hence the spectral line features confirms our prediction from optical and near-IR photometry that IC 1590-1 and IC 1590-2 are PMS HAeBe stars. To support our argument we have shown the SED for the e-stars in Fig.4. It can be seen that the distribution shows rising trend in H and K_s bands for IC 1590-1 and IC 1590-2, when compared to IC 1590-3.

4.3 NGC 6823

The cluster NGC 6823 (Trumpler class IV3p, $RA = 19^h43^m09^s$, $Dec = +23^o18'$, $l = 59.402^o, b = -0.144^o$,) is surrounded by the HII region NGC 6820. This cluster is associated with VulOB1 association and this complex is similar to the star formation complex in Orion. The cluster contains O and early B-type stars and is situated in an HII region with several cometary globules. Stone (1988) divided the cluster into a central trapezium system, a nucleus of radius in between 0.6 to 3.5$'$ and a corona of radius greater than 3.5$'$ using Kholopov's criteria (Kholopov 1969). From UBV photometric study, Stone (1988) found that the luminosity function for the stars in the inner region is similar to initial luminosity function while the outer ones appears to have an excess of bright cluster stars. Many of the stars in the outer region are found to be PMS objects.

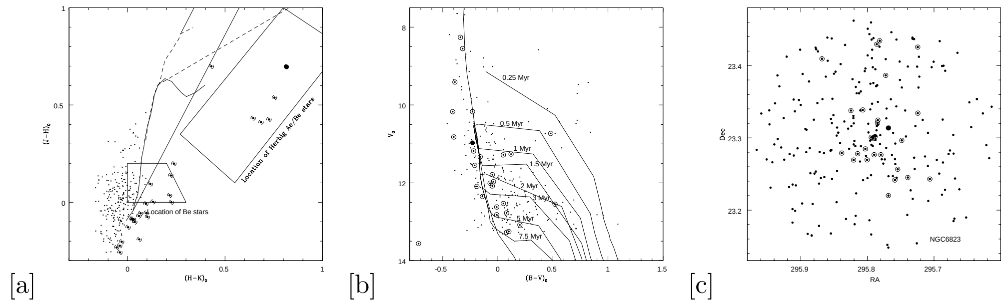


Figure 7. (a) The near-IR CCDm of the cluster NGC 6823 is shown in figure with e-stars shown as filled triangles. (b) Optical CMD of NGC 6823. PMS isochrones of ages 0.25−7.5 Myr are plotted. The e-star if found to lie between 0.5 and 1 Myr isochrone. (c) Location of PMS stars and e-stars are shown in the field of NGC 6823.

Guetter (1992) used CCD UBV photometry to study the nuclear region and photoelectric photometry to study the coronal region of the cluster. He estimated a distance of 2.1 $\pm$ 0.1 kpc and age in the range 2−11 Myr. The trapezium stars are found to be the youngest when compared to the coronal stars with nuclear objects falling in between.

UBV CCD photometric data of 440 stars were taken from Massey et al. (1995). After cross correlation with 2MASS values, only 253 stars were identified to have UBV and JHK_s magnitudes. (J−H) and (H−K_s) colours were de-reddened using mean cluster reddening value E(B-V) = 0.89 (Massey et al. 1995) and the resulting near-IR CCDm is plotted (Fig. 7a). 27 stars are taken as candidate PMS stars since they are located below the reddening vector. The e-star NGC 6823-1 is considerably reddened (around 1 magnitude) as shown in the near-IR CCDm and hence can be considered as a candidate HBe star.

In the CMD (shown in Fig. 7b), ZAMS is fitted for a DM of 11.81 (Massey et al. 1995). Most of the candidate PMS stars are located in the isochrones of ages 0.25 to 7.5 Myr. Massey et al. (1995) sugggested that there is an age spread of 5 Myr in this cluster. The number of PMS stars are more at the center of the cluster, suggesting an ongoing star formation (Fig. 7c). The UBV CCD photometric data for e-star, NGC 6823-1, is taken from Guetter (1992) and it is found to be of B6.5 spectral type. The cluster sequence is not clearly defined even though we have used the best available CCD data. Since the CMD is found to show a considerable scatter, a sequence through the outer envelope puts the star in PMS phase. From PMS isochrone fitting the age of the star is found to be in between 0.5 and 1 Myr. Even though we do not find any nebulosity to be associated with NGC 6823-1, the e-star is found to be in midst of a group of PMS stars, implying it to be young. The e-star is located close to the cluster center, as can be seen from Fig. 7c. The duration of star formation in this cluster is at least 7.5 Myr.

The spectra of NGC 6823-1 is interesting due to the presence of neutral helium (HeI) lines in emission. The HeI lines 4026 Å, 4388 Åand 4471 Å shows emission in absorption profiles while 5876 Å shows emission above the continuum, which is indicative of HBe stars. The higher order Balmer lines are seen in absorption, H_β has emission in absorption profile (Fig. 3a) while H_α shows emission (Fig. 3b). Both the OI lines 7772 Å and 8446 Å are in emission along with CaII triplet lines. All the major Pachen lines like P11, P12, P14, P17, P19 are in emission (Fig. 3b). The SED (Fig. 4) shows a rising trend in J, H, K_s magnitudes which is an indicative of circumstellar dust in HBe stars. Hence the e-star is likely to belong to HBe category.

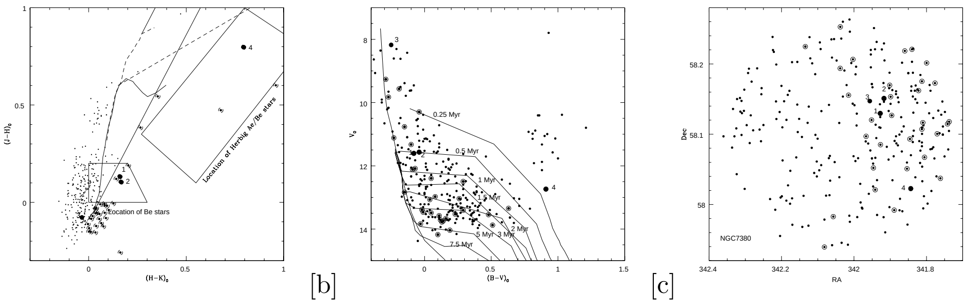
4.4 NGC 7380

Moffat (1971) studied the cluster NGC 7380 ($RA = 22^h 47^m 21^s, Dec = 58^o 07' 54''$, $l = 107.141^o$, $b = -0.884^o$) using photographic UBV photometry down to V $\sim$ 16 mag, and found a distance of 3.6 ± 0.7 kpc and an age of 2 Myr. He found a deficit of faint stars in the central region (r≤3’) and two dust shells at central radius r = 6.5’ and r = 10.4’. Massey et al. (1995) estimated a distance of 3732 pc and an average E(B−V) of 0.64 ± 0.03 from spectroscopy.

From our survey we found the stars numbered 1130, 55, 4 and 2249, as given in Massey et al. (1995) are found to show emission. The spectral types of the 4 e-stars has been estimated to be B9, B9, B0.5V and A1 respectively. The UBV CCD values of 893 stars, taken from Massey et al. (1995), were cross correlated with 2MASS values and 277 stars were identified as having both UBV and JHK_s magnitudes. The near-IR colours are de-reddened using the mean cluster reddening value E(B-V) = 0.64 (Massey et al. (1995)) and near-IR CCDm is plotted, as shown in Fig. 8a. We identified 34 stars in PMS category from its location in near-IR CCDm. The e-stars NGC 7380-1 and NGC 7380-2 are located inside the CBe location while NGC 7380-3 is below it and NGC 7380-4 is in HAeBe location (reddened by about 1 mag). All the e-stars except NGC 7380-2 are found to be associated with nebulosity.

In the optical CMD, ZAMS is fitted for a DM of 12.86 (Massey et al. 1995). Massey et al. (1995) determined the age of the cluster as 2 Myr taking massive stars (above 25 $M_\odot$) only. Our study shows that there are low mass stars having the age range 0.25 to 10 Myr (Fig. 8b). The e-stars NGC 7380-1 and NGC 7380-2 are located on the 0.5 Myr isochrone and NGC 7380-3 is located at the top of MS. The star NGC 7380-4 is fitted with 0.25 Myr PMS isochrone and it is found to be located away from other e-stars (Fig. 8b). In the cluster field, the e-stars NGC 7380-1, NGC 7380-2 and NGC 7380-3 are located close to the center (Fig. 8c).

Most of the PMS candidates are found to be crowded around the e-stars suggesting it to be an active star forming region. The PMS stars are located in a crescent like struture on the western side of the cluster. Also, the PMS stars are beyond a radius of about 6 arcmin, which coincides with the location of the inner dust shell. Thus, recent star



[a] [b] [c]

Figure 8. (a) The near-IR CCDm of the cluster NGC 7380 is shown with e-stars as filled circles and PMS as encircled symbols. (b) Optical CMD of NGC 7380. PMS isochrones of ages 0.25−7.5 Myr are plotted. The star NGC 7380(4) seems to be young than 0.25 Myr since it is found to lie beyond 0.25 Myr isochrone.

formation has taken place in the western region, which coincides with the location of the dust shells. The duration of star formation estimated for this cluster is around 7.5 Myr.

The spectra of NGC 7380-4 (Fig. 3) is special among the list of surveyed stars due to the presence of NaI (5890, 5896 Å), KI (7699 Å) and NII (5530, 5535 Å) lines in emission. The OI lines 7772 Å and 8446 Å are seen in emission along with CaII triplet and Paschen lines P11, P12, P14, P17 and P19. The CaII triplet lines are strongest among the surveyed e-stars with 8498 Å line showing an EW of −32 Å. About 21 FeII lines are seen in emission. From SED (Fig. 4) we can see that the flux of the e-star NGC 7380-4 is rising toward the longer wavelengths in the near-IR region which seems to confirm that it belongs to HAe category.

5. Conclusion

1. From the photometric and spectroscopic estimates we conclude that out of 157 surveyed e-stars 3 are probably HBe candidates while 2 are HAe candidates. The correlation between H_α EW and $(H-K_s)_0$ colour was used to classify HAeBe stars from CBe stars. The e-stars are found to show a linear correlation in H_α EW and $(H-K_s)_0$ colour with a clear offset between both classes. This striking correlation emphasizes the role of circumstellar material in the production of H_α radiation by recombination process. The correlation between OI 8446 Å line and near-IR colour $(H-K_s)_0$ is also found to distinguish CBe from HAeBe stars. Even though the colour excess $E(V-K_s)$ is found to correlate well with H_α EW, it cannot be effectively used as a criterion to classify CBe stars from HAeBe stars.

2. Bochum 6-1 is quite unusual star among our surveyed stars, due to the presence of intense emission lines. The presence of HII region S309 might have contributed to the high value of H_α EW, which is around −206 Å. The e-star is found to be in HBe location

in near-IR CCDm, which along with SED proves the presence of dusty circumstellar material. Bochum 6-1 is found to be HBe star in a shell phase, which is inferred from the presence of forbidden FeII lines. Eventhough the turn-off age of the cluster is found to be 10 Myr, we found 20 PMS stars in age range 1 to 10 Myr in the cluster. The candidate PMS stars are located along the boundary of the cluster.

3. We found that IC 1590-1 and IC 1590-2 belong to HBe and HAe respectively from optical & near-IR photometry, spectroscopy and SED. This is one of the rare young clusters ($\sim$ 4 Myr) in which HAeBe stars coexist with CBe candidate. The age of IC 1590-1 is found to be 2 Myr while that of IC 1590-2 is 3 Myr from PMS isochrone fitting. We identified 12 PMS candidates in the cluster, which are found to have ages in the range 2−10 Myr. The e-stars are located close to the cluster center with few PMS candidates, suggesting active star formation. The active star formation is reflected by the presence of HII region, molecular clouds and the presence of trapezium system like Orion.

4. NGC 6823-1 is found to be 0.5 − 1 Myr HBe star, reddened by 1 magnitude in near-IR CCDm and the spectra having helium lines either in emission or as shell feature. We have found 27 PMS stars in the age range 0.25 − 7.5 Myr, of which most are close to the cluster center, suggesting an ongoing star formation.

5. NGC 7380-4 is a stand-alone candidate among the surveyed stars with NaI (5890, 5896 Å), KI (7699 Å) and NII (5530, 5535 Å) lines in emission apart from OI, CaII triplet, Balmer and Paschen lines in emission. The star is found to be a HAe candidate with a near-IR excess of around 1 magnitude and excess flux in K_s band in SED. The star is associated with nebulosity and the location of the star in optical CMD indicates a very young age ($\leq$ 0.25 Myr). We have identified 34 PMS stars in the age range 0.25 − 10 Myr, which are distributed around 3 e-stars. This is indicative of the star formation occuring in the cluster, in a crescent like region located to the west of the cluster center.

6. The duration of star formation was found to be about 10 Myr in all the 4 clusters, which host the identified HAeBe stars.

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