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Pre-main sequence stars, emission stars and recent star formation in the Cygnus region

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Abstract. The recent star formation history in the Cygnus region is studied using 5 clusters (IC 4996, NGC 6910, Berkeley 87, Biurakan 2 and Berkeley 86). The optical data from the literature are combined with the 2MASS data to identify the pre-main sequence (pre-MS) stars as stars with near IR excess. We identified 93 pre-MS stars and 9 stars with H_α emission spectra. The identified pre-MS stars are used to estimate the turn-on age of the clusters. The duration of star formation was estimated as the difference between the turn-on and the turn-off age. We find that, NGC 6910 and IC 4996 have been forming stars continuously for the last 6 – 7 Myr, Berkeley 86 and Biurakan 2 for 5 Myr and Berkeley 87 for the last 2 Myr. This indicates that the Cygnus region has been actively forming stars for the last 7 Myr, depending on the location.

Nine emission line stars were identified in 4 clusters, using slit-less spectra (Be 87 - 4 stars; Be 86 - 2 stars, NGC 6910 - 2 stars and IC 4996 - 1 star). The individual spectra were obtained and analysed to estimate stellar as well as disk properties. All the emission stars are in the MS, well below the turn-off, in the core hydrogen burning phase. These stars are likely to be Classical Be (CBe) stars. Thus CBe phenomenon can be found in very young MS stars which are just a few (2–7) Myr old. This is an indication that CBe phenomenon need not be an evolutionary effect.

Keywords : stars : emission-line, Be; pre-main sequence – stars : formation – (stars) : circumstellar matter – (Galaxy) : open clusters and association

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1. Introduction

Cygnus region, located between $70^\circ < l < 80^\circ$ is a region of recent star formation activity in the Milky Way and is rich in massive early type stars concentrated in OB associations. The presence of nebulosity and massive stars indicate that the stars have been forming till very recently and the young clusters found here are the result of the recent star formation event. Though the above fact is known, what is not known is that when this star formation process started and how it proceeded in the region. Thus the aim of the paper is to understand the star formation timescale in this complex, using the recently formed young open clusters.

Though one assumes that all the stars in a cluster have the same age, this assumption is not valid when the candidate cluster is very young. In the case of young clusters (≤ 10 Myr), there is a chance for a spread in the age of the stars, depending on the duration of star formation. An estimation of this formation time-scale in the clusters formed in a star forming complex, will indicate the duration of star formation and its direction of propagation within the complex. In principle, duration of star formation is defined as the difference between the ages of the oldest and the youngest star formed in the cluster. In practice, the age of the oldest star is assumed as the age of that star which is about to turn-off from the main-sequence (MS) (turn-off age) and the age of the youngest star is the age of the youngest pre-MS star (turn-on age). The turn-off age of many clusters are known, but the turn-on age is not known for most of the clusters. The estimation of turn-on age requires the identification of pre-MS stars in the cluster. Hence the duration of star formation in young star clusters is not clearly understood. This quantity cannot be estimated for older clusters where all the stars have reached the MS. The star clusters studied here are Berkeley 86, NGC 6910, IC 4996, Berkeley 87 and Biurakan 2. We aim to combine the ages and the star formation duration in these clusters to understand how the star formation proceeded in the Cygnus region.

A number of stars are known to show H_α emission in this region. The photometric analysis of the clusters suggested the possible presence of a few emission line stars. As a follow up, we searched, identified and studied these stars. Since the estimation of cluster parameters will help in identifying the ages and spectral types of these stars, their emission properties can be linked to their evolutionary status. Early type emission stars are broadly classified as Classical Be (CBe) stars and Herbig Ae/Be (HAeBe) stars, which belong to intermediate mass pre-MS category. CBe stars are fast rotators whose circumstellar disk is formed through decretion mechanism (wind/outflow) (Porter & Rivinius 2003). HAeBe stars are found to possess a natal accretion disk which is a remnant of star formation (Hillenbrand et al. 1992). The emission is found to come from this equatorial disk as recombination radiation, mainly in Balmer lines like H_α and H_β. We have used slitless spectroscopy to search for these emission stars. Emission stars are found to show an IR excess, which is a combination of free-electron excess and dust excess. We combine the parent cluster parameters and the spectral properties of emission stars, and try to classify them. Fabregat & Torrejon (2000) suggested that emission stars found in clusters younger than 10 Myr belong to the HBe type and CBe stars are found only in clusters older than 10 Myr. On the other hand, the HAeBe phenomenon is known to last only for a few Myr (Hillenbrand et al. 1992). Thus it will be interesting to identify and classify emission stars in clusters younger than 10 Myr.

In the following section, we present the data used and discuss the analysis of the photometric data. Section 3 deals with the results obtained for the 5 clusters. In section 4, we present the spectra and discuss the emission line stars. A discussion of the star formation in Cygnus region is presented in section 5. The conclusions drawn from this study are listed in section 6.

2. Observations and analysis

The photometric data of clusters in the UBV optical pass bands are taken from WEBDA (http://obswww.unige.ch/webda), a website devoted for star clusters. The photometric data in the near-infrared (NIR) in J, H, K pass bands are taken from 2MASS data (http://www.ipac.caltech.edu/2mass/overview/access.html). The reddening and extinction towards the clusters are already available in WEBDA. The ZAMS data for distance determination were taken from Schmidt-Kaler (1982). The pre-MS isochrones for estimating the pre-MS age of the cluster are taken from Siess et al. (2000)

2.1 Identification of pre-MS stars

In the optical colour-magnitude diagram (CMD), both pre-MS stars and field stars occupy the same region (right side of the MS) and we cannot distinguish between the two in the CMD. Spectroscopic identification of pre-MS stars could be done at the brighter end, but is inefficient for fainter stars. In the case of pre-MS stars, the dust grains in the circumstellar disk absorb a fraction of visible or ultraviolet photons emitted by the central star, heating it to a higher temperature. The disk re-radiates the absorbed energy in infra-red wavelengths. Thus the presence of NIR excess is used to distinguish between the pre-MS stars and field stars in the optical CMD. Thus, pre-MS stars can be identified using near-infrared (NIR) photometry. By cross-correlating optical and infrared images of the cluster field, the J, H, K magnitudes of optically identified stars were found. We used the (J−H) vs (H−K) NIR colour-colour diagram to identify stars with NIR excess and to determine their nature (Subramaniam et al. 2005). The intrinsic location of un-reddened giants and MS stars, and the normal reddening vector, which limits the reddening due to normal interstellar dust are used to distinguish various types of stars with NIR excess. By relating their position in the NIR colour-colour diagram with the general location of HAeBe and CBe stars, we identify candidate stars belonging to the above classes.

2.2 Estimation of turn-on age

The stellar magnitudes were corrected for reddening and extinction. Though the distance to the clusters have already been estimated, we re-estimated the distance, which in most cases turned out to be similar to the already estimated value. The dereddened and extinction corrected CMD is fitted with ZAMS to estimate the distance modulus (DM). The turn-off age of the clusters have already been estimated and we adopt these values.

In the NIR colour-colour diagram, stars which have NIR excess were identified. These stars were plotted on the optical CMD, as candidate pre-MS stars (indicated by a different symbol). Pre-MS isochrones of different ages from Siess et al. (2000) were fitted to these stars on the CMD. The presence of pre-MS stars in more than one isochrone shows that the pre-MS stars have a range in age, which in turn would indicate that the stars were formed over a time-scale. The age of the youngest pre-MS star would be the turn-on age of the cluster.

3. Results

3.1 IC 4996

IC 4996 is located ($RA = 20^h14^m24^s$, $Dec = +37°29'$, $l = 75.36°, b = 1.31°$) in the direction of the Cygnus and is part of a star forming region. An IRAS map of the region (Lozinskaya & Repin 1990) shows the presence of a dusty shell around the cluster. Zwintz and Weiss (2006) have performed time series CCD photometry in Johnson B and V filters to find 40 stars to lie in the classical instability strip of the 113 stars analysed in the cluster. They have discovered two delta Scuti-like pre-MS stars in the cluster. The parameters obtained by Delgado et al. (1998) for the cluster are $E(B-V)$=0.71 ± 0.08 mag, DM = 11.9 mag and age of 7.5 ± 3Myr. They suggested a number of pre-MS stars in the cluster, which are located at 0.5 and 1 magnitude above the MS in the V vs (B−V) CMD, around the location of spectral types A-F. Delgado et al. (1999) estimated the spectral types and heliocentric radial velocities for 16 stars in the cluster and the mean radial velocity was found to be -12 ± 5 kms^{-1}. Vansevicius et al. (1996) estimated the distance and age of the cluster to be 1620 pc and 9 Myr respectively, using BVRI CCD photometry. Pietrzynski (1996) performed variability studies on the cluster and found an RR Lyrae type variable and another eclipsing system. According to WEBDA, cluster contains two B type emission stars.

We used the optical data of Delgado et al. (1998), available from WEBDA. From the field of the cluster, 84 optically identified stars were found to have counterparts in the 2MASS data. We combined the V, (B−V), (U−B) (taken from WEBDA) and J, H, K (taken from 2MASS) magnitudes for 84 stars. From the NIR colour-colour diagram (Fig. 1), 22 members are found to be located below the reddening vector. Among them, 15 could be considered to be candidate pre-MS stars and these are shown as dots with

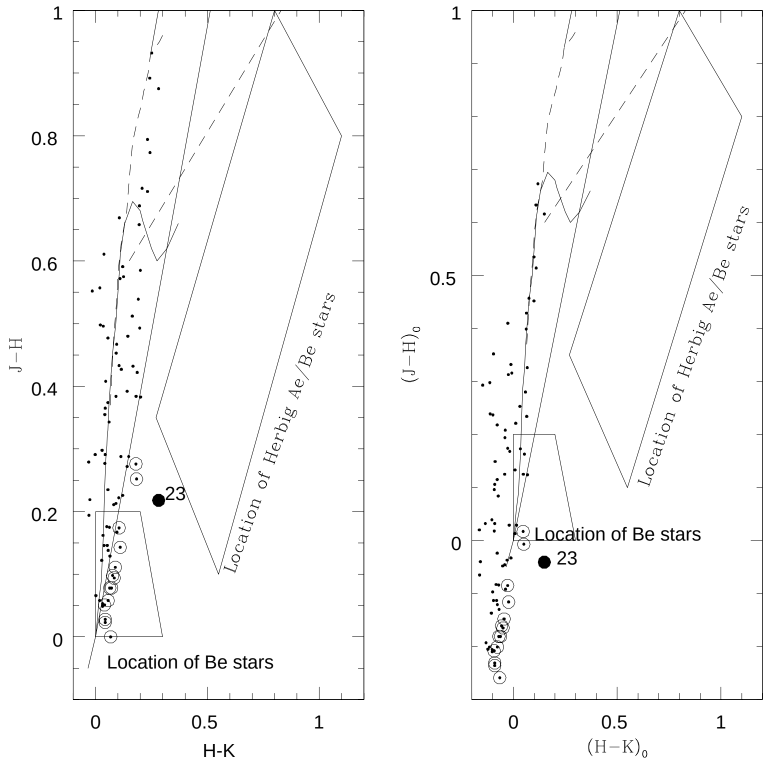

Figure 1. NIR colour-colour diagram for the cluster IC 4996. Dots indicate normal stars. Encircled dots indicate pre-MS stars. Stars with H_α emission are shown as labeled and filled circle. The left panel shows colours uncorrected for reddening, whereas the right panel shows colours corrected for reddening. The reddening value as estimated from the ZAMS fitting is used for NIR dereddening, using the relation in Bessell & Brett (1988).

open circles around them. Star numbered 23 is found to have H_α emission and shown as labeled filled circle. The MS and the giant star locations in the CMD are shown (Bessell & Brett 1988). The location of T-Tauri stars is shown as the dashed straight line (Meyer et al. 1997). The location of Be stars is taken from Dougherty et al. (1994) and the location HAeBe stars is taken from Hernandez et al. (2005). The diagram on the left is not corrected for the reddening towards the cluster, whereas the figure on the right is corrected for the reddening. The reddening value as estimated from the ZAMS fitting is used for dereddening. The relation from Bessell & Brett (1988) is used for converting reddening in the optical to NIR. Star 23 is likely to be a CBe candidate.

The identified stars are reddening and extinction corrected by taking E(B−V) as 0.7 mag and R_v as 3.1. The DM is estimated as 11.8 ± 0.2. and the distance as 2291 ± 225 pc, which is similar to that estimated by Delgado et al. (1998). The turn-off age of

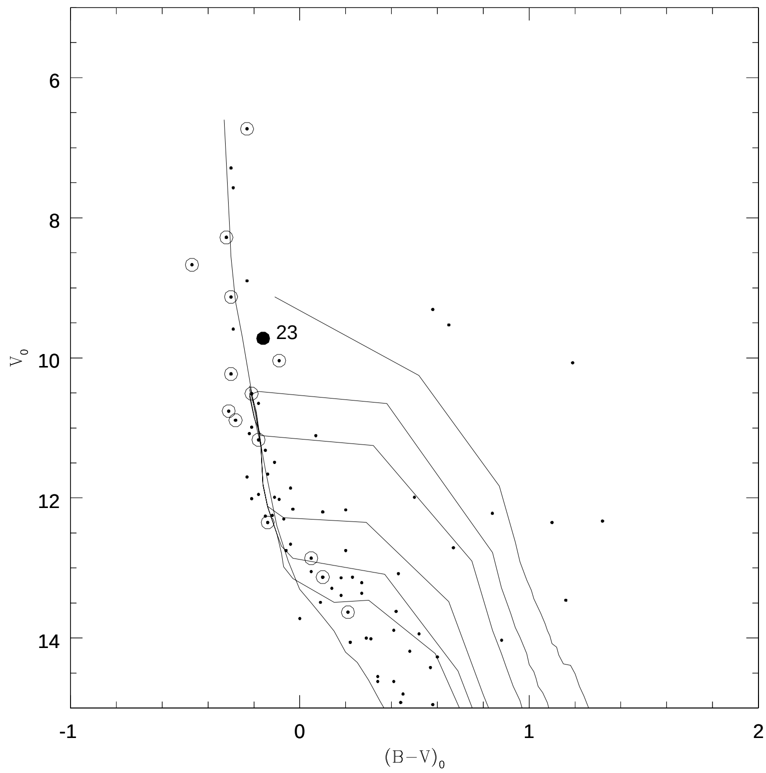

Figure 2. Pre-MS isochrone fittings for the cluster IC 4996. The isochrones for the ages 0.25, 0.5, 1, 3, 5 and 7 Myr are shown.

the cluster is 7.5 ± 3 Myr (Delgado et al. 1998). Pre-MS isochrones for ages 0.25, 0.5, 1, 3, 5 and 7 Myrs are plotted as shown in Fig. 2. The presence of pre-MS stars on or near all the pre-MS isochrones shows that the stars have been forming continuously for the last 7 Myr. Also, the presence of pre-MS stars near the tip of the MS indicates that some of the high mass stars could be very young and the star formation stopped very recently. Thus, the duration of star formation is similar to the age of the cluster, i.e., ~ 7 Myr. The H_α emission star is located slightly to the right of the MS and there are a few candidate pre-MS stars located nearby. Therefore, this star could either be a MS CBe star or a pre-MS HBe star. If it is a pre-MS star, then the isochrones indicate its age to be between 0.5 – 0.25 Myr. If it is a CBe star, then its age is ≤ 7 Myr.

To study the distribution of pre-MS stars within the cluster, we compared the location of pre-MS stars and normal stars, as shown in Fig. 3. Pre-MS stars are shown as filled circles and normal stars as open circles. The emission line star (23) is also labeled. The pre-MS stars are found to be located relatively closer to the center of the cluster when compared to the normal stars.

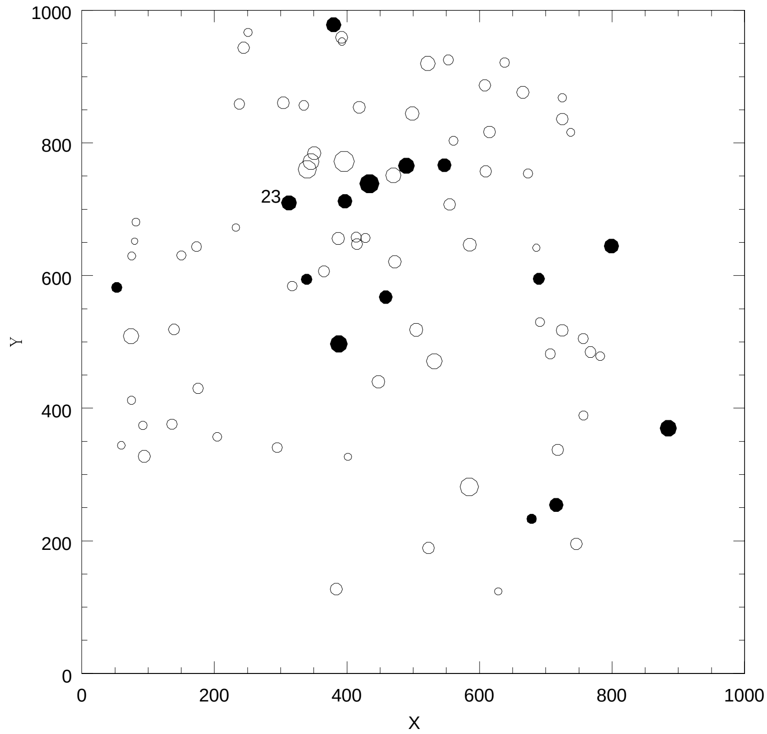

Figure 3. Cluster field of IC 4996 showing pre-MS stars and normal stars separately. Normal stars are shown as open circles, pre-MS stars are shown as filled circles and the emission stars are shown as labeled filled circles.

3.2 NGC 6910

NGC 6910 ($RA = 20^h21^m18^s$, $Dec = 40°37'$, $l = 78°.66, b = 2°.03$) is a young open cluster located in the Cygnus region and is a part of the Cygnus OB9 association. This cluster is located in the core of the star forming region, 2 Cygni. It is surrounded by a series of gaseous emission nebulae which resemble Barnard's loop in the Orion. From UBV CCD observations down to V=18 mag for 206 stars in the cluster, Delgado et al. (2000) found eleven pre-MS stars of spectral type A to G. They estimated the cluster parameters to be $E(B-V) = 1.02 \pm 0.13$, DM = 11.2 ±0.2 and age = 6.5 ± 3 Myrs. Kolaczkowski et al. (2004) found four beta Cep-type stars along with three H_α emission stars, while searching for variable stars in the cluster. They suggest a possibility of finding a large number of beta Cep stars in the cluster due to higher metallicity of the cluster. Using VI_c and H_α photometry they have determined an age of 6 ± 2 Myr, DM of 11.0 ± 0.3 mag and an $E(B-V)$ value varying from 1.0 to 1.4 magnitude. Shevchenko et al. (1991) studied the cluster using UBVR photoelectric photometry. From the photometry of 132 stars, they found the HAeBe stars BD +40 41 24 and BD +41 37 31 to be associated

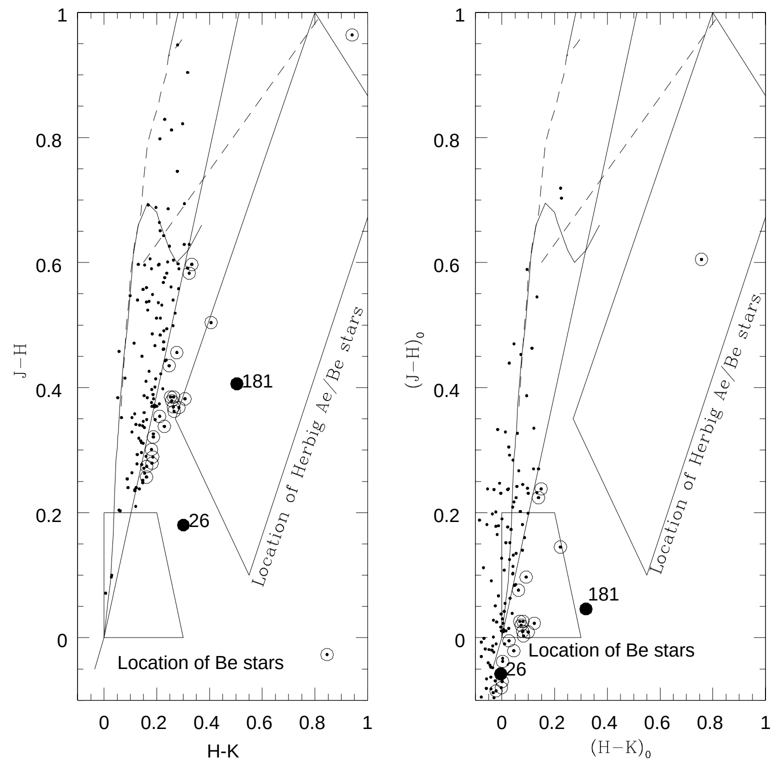

Figure 4. NIR colour-colour diagram for the cluster NGC 6910. Symbols and panels have the same meaning as in Fig. 1.

with it. The extinction is high in the region with a value of $E(B-V)$ = 1.2 mag and the value of R = 3.42 ± 0.09. Using intermediate-band photoelectric photometry for 16 cluster members, Crawford et al. (1977) obtained a reddening value of $E(b-y)$=0.75 mag and a DM of 10.5 mag. They found that a type Ia super giant star of M_v = -6.9 to be associated with the cluster. According to WEBDA there is no emission star in the cluster.

The U, B−V, U−B values of 148 stars are taken from WEBDA (Delgado et al. 2000). The J, H, K values of these stars are taken from 2MASS by cross-correlating optical and IR images. NIR colour-colour diagram is plotted as shown in Fig. 4. 47 stars were found to be located below the reddening vector. Out of them, 23 members were found to have relatively large IR excess and were considered as candidate pre-MS stars. Stars, 26 and 181 do not have CCD photometry, we have used the UBV photographic photometry of Hoag et al. (1961). These stars show H_α emission and are shown as dark filled circles. After dereddening, star 181 can be found very close to the CBe location, indicating its CBe nature.

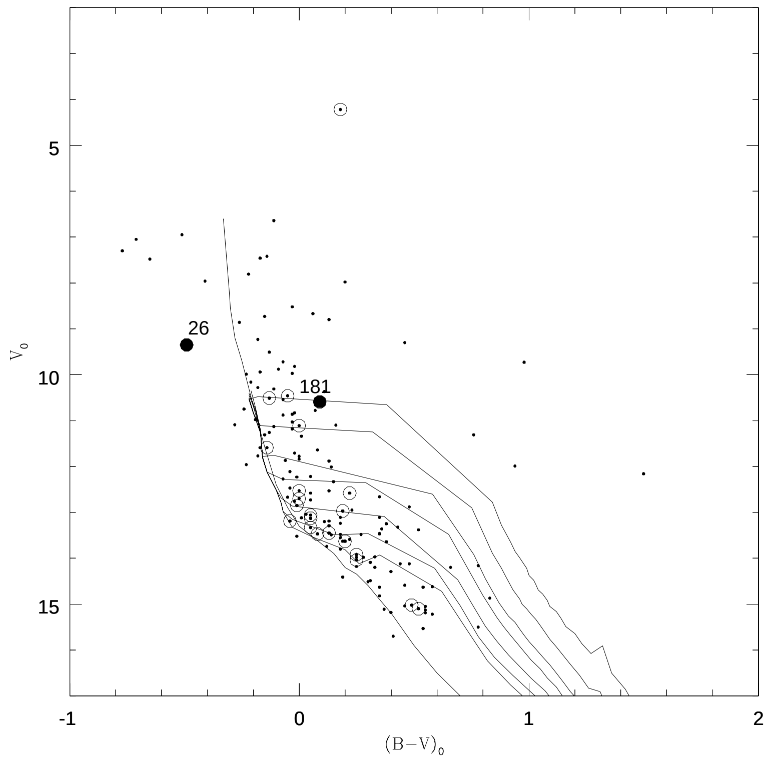

Figure 5. Pre-MS isochrone fittings for the cluster NGC 6910. The isochrones for the ages 0.5, 1, 2, 3, 5, 7.5 and 10 Myr are shown.

The reddening and extinction corrections are done by assuming E(B−V) as 0.97 mag and R_v as 3.1. ZAMS fitting is done as shown in Fig. 5, the DM is estimated as 11.8±0.2 mag and the distance as 2291±225 pc. The turn-off age of the cluster is 6.5±3 Myr (Delgado et al. 2000). The pre-MS isochrones for 0.5, 1, 2, 3, 5, 7.5 and 10 Myrs are overlaid on the CMD. The presence of pre-MS stars with these ages shows that star formation processes are occurring in the cluster continuously. More number of stars are formed in the early stages and continuing up to 3 Myr. After that the star formation seems to have continued but in a slower rate, till 0.5 Myr. We find that a few pre-MS stars are as old as 10 Myr. Also for this cluster, we get the duration of star formation as the cluster age itself $\sim$ 7 Myr, though there is an indication that the star formation started 10 Myr ago. The H_α emission star 181 is found to be located near the 0.5 Myr isochrone, indicating that this could also be a candidate HBe star. The star 26 is located to the left of the MS, hence we do not discuss the nature of this star based on the photometry. The peculiar location may be due to two reasons - we used the photographic data for these two stars and there may be some error in the data of this star, or, the reddening is very

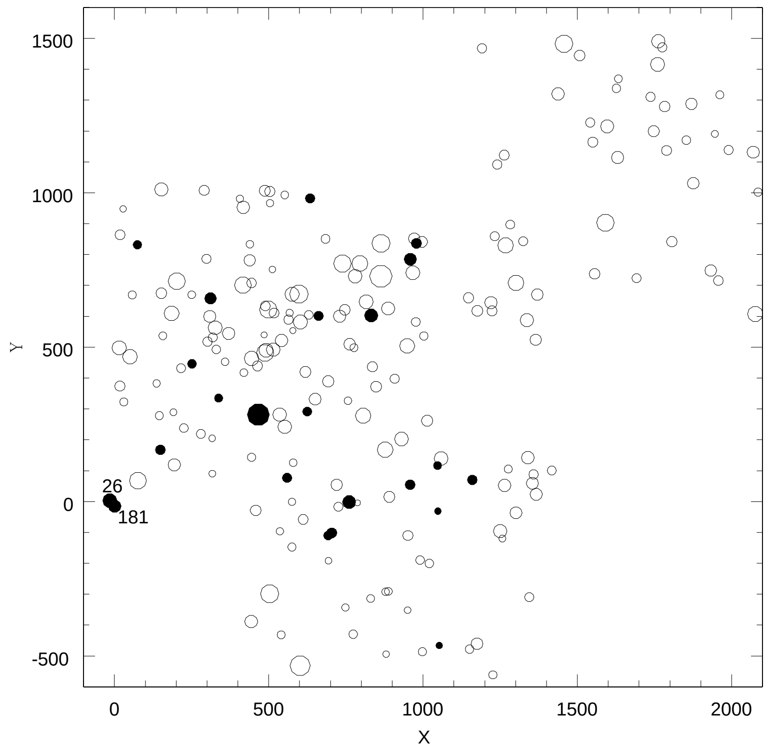

Figure 6. Cluster field of NGC 6910 showing pre-MS stars and normal stars separately. The symbols have the same meaning as in Fig. 3.

different for this star. If these two stars belong to the CBe class, then these stars are $\leq$ 7 Myr old.

The pre-MS stars are shown separately as dark circles and normal stars are shown as open circles, as in Fig. 6. We find that the pre-MS stars are scattered throughout the face of the cluster. The emission stars 26 and 181 are located very close to each other.

3.3 Berkeley 87

The open cluster, Berkeley 87 (Dolidze 7,$RA = 20^h21^m42^s, Dec = 37°.22$), located at $l = 75°.71, b = +0°.31$ is a sparse grouping of early-type stars lying in a heavily obscured region in the Cygnus. Turner & Forbes (1982) derived a distance of 946 $\pm$ 26 pc and an age of 1-2 Myr for the cluster from UBV photometry of 105 stars. The age as reported in WEBDA is 14 Myr. The distance was estimated to be 0.9 kpc from the interstellar line depth of the cluster members (Polcaro et al. 1989). It is part of the star formation region ON 2, which harbours many compact HII regions, strong OH masers and CO and ammonia molecular clouds. Diffuse emission in CIV 5802-12 A doublet and X-ray emission in 2-6 keV range has been detected in the cluster, which is interpreted as due to the interaction of the strong wind from a Wolf Rayet star (ST 3) of velocity 5200 kms^{-1} with the cluster members. A high energy Gamma ray source 2CG 075+00 ($\leq$100 Mev) has been found to be associated with this cluster. Be 87 contains a peculiar emission-line B super giant HDE 229059 (Hiltner 1956), two faint objects (VES 203 and VES 204) which show H$_\alpha$ in emission (Coyne et al. 1975), the red super giant BD +37 39 03 and the faint variable star V439 Cygni. According to WEBDA the cluster contains 5 B type emission stars.

The optical data of 94 stars (Turner & Forbes 1982) were combined with the 2MASS data. 19 stars were identified to have possible NIR excess from the NIR colour-colour diagram (Fig. 7). Out of them, 13 members having relatively higher (H$-$K) magnitudes were grouped as candidate pre-MS stars. Stars 9, 15, 38 and 68 (Turner & Forbes 1982) are stars with H$_\alpha$ emission, shown as filled circles. Star 38 and 15 occupy the HAeBe location, after the reddening correction. Stars 9 and 68 are likely to be CBe stars. There is significant differential reddening in this cluster, as discussed below. Therefore, the above classification should be taken with some caution.

In the NIR colour-colour diagram, many stars are found outside the reddening vector. Some stars are more reddened than others i.e., there is a variation of reddening in different parts of cluster field. All cluster members do not have the same $E(B-V)$ value. Color correction and extinction correction are done by choosing $E(B-V)$ as 0.45 for stars having (H$-$K) value less than 0.1 and as 1.35 for stars having (H$-$K) value higher than 0.1 along with R_v=3.1. The variation in $E(B-V)$ gives an indication of the non-uniform distribution of interstellar material within the cluster. The resulting CMD is shown in figure 8. The wide MS in the CMD is an indication of significant differential reddening across the cluster. The dereddening in the NIR is done using the lower value of the two reddening values.

ZAMS fitting estimated the DM to be 10.8 $\pm$ 0.2 mag. The distance estimated is 1445 $\pm$ 145 pc, higher than the value estimated by Turner & Forbes (1982). The pre-MS isochrones for the ages 0.15, 0.2, 0.25, 0.5, 1, 1.5 and 2 Myrs are plotted on the CMD (shown in Fig. 8). Most of the pre-MS stars are located in isochrones of ages ranging from 0.15 to 2 Myr. Therefore, the turn-on age of the cluster is less than 1 Myr, which is consistent with the recent star formation activity in the cluster vicinity. This recent star formation activity is likely to have started 2 Myr back, as indicated by the age of the pre-MS stars. The cluster has a turn-off age of 14 Myr, as indicated in WEBDA. On the other hand, the age of 2 Myr as estimated by Turner & Forbes (1982), is in good agreement with our estimation of the starting time of the star formation. Therefore, this may be a very young cluster with a turn off age of 2 Myr. Therefore, we consider the turn-off age of Be 87 as 2 Myr. The emission line stars in this cluster are very young. If they are HAeBe stars, then they are as young as 0.15 Myr. If they are CBe stars, then

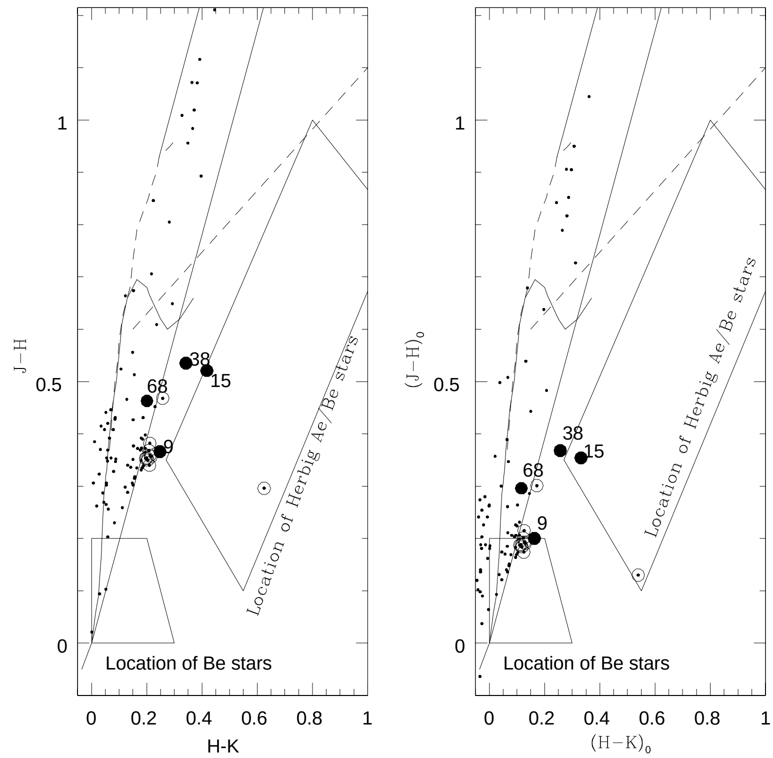

Figure 7. NIR colour-colour diagram of the cluster, Be 87. Symbols and panels have the same meaning as in Fig. 1.

they are $\leq$ 2 Myr old. Thus, if these stars are CBe stars, these might be one of the very young CBe stars known.

The location of pre-MS stars in the field of the cluster is shown in Fig. 9. It can be seen that there is a clustering of pre-MS stars as well as the emission stars towards the central region of the cluster.

3.4 Biurakan 2

The galactic cluster, Biurakan 2, is $(RA = 20^h09^m12^s, Dec = 35°.29,\ l = 72°.751, b = 1°.345)$ also located in the vicinity of the association, Cygnus OB-1. The cluster was studied by Dupuy and Zukauskas (1976) using photoelectric and photographic photometry. They estimated an average value of E(B−V)=1.39±.09 towards the cluster, DM as 10.8±0.2 mag, which corresponds to a distance of 1445±133 pc and age $\leq$10 Myr. According to WEBDA there is no Be star in the cluster.

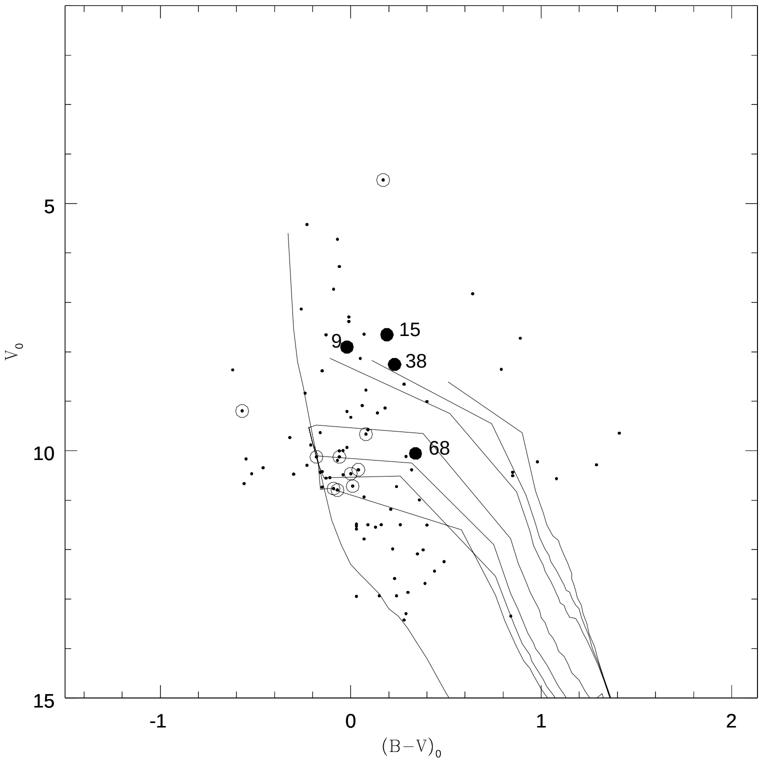

Figure 8. Pre-MS isochrone fittings for the CMD of the cluster Be 87. The isochrones for the ages, 0.15, 0.2, 0.25, 0.5, 1, 1.5 and 2 Myr are shown.

By cross-correlating the optical (Dupuy & Zukauskas 1976) and NIR data of the cluster field, 114 stars were identified to have both data. NIR colour-colour diagram is plotted as shown in Fig. 10. 33 stars were found to be located below the reddening vector and 15 stars having higher (H−K) were grouped as candidate pre-MS stars. No star with H_α emission is observed in this cluster.

Assuming $E(B-V)$ as 0.45 mag and R_v as 3.1, colour correction and extinction correction were done and the resulting CMD is shown in Fig. 11. We re-estimated the DM as 11.2 ± 0.2 mag. The distance obtained is 1737.8 ± 175 pc. The pre-MS isochrones for the ages 0.5, 1, 1.5, 2, 3 and 5 Myrs are plotted. The presence of pre-MS stars in these isochrones shows that the pre-MS stars have an age range of 0.5-5 Myr. Most of the pre-MS stars are younger than 2 Myr and only four stars were found to be older than 5 Myr. This indicates that the star formation started 5 Myr back, but was very active for the last 2 Myr. The turn-off age of the cluster obtained by the previous study is 10 Myr or less (Dupuy et al. 1976). The turn-off age estimation is difficult and inaccurate due to the absence of evolved stars. It is quite likely that the turn-off age of the cluster

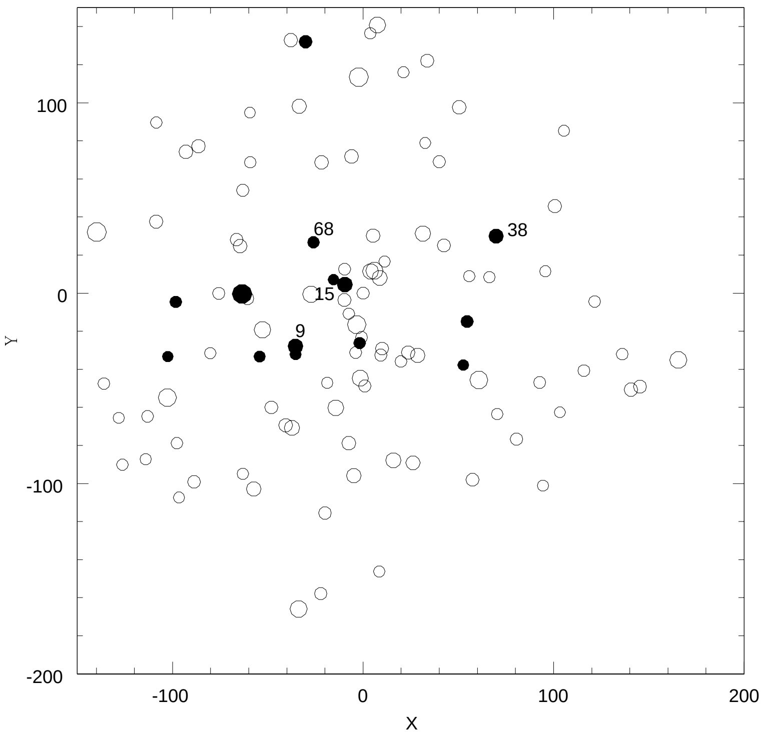

Figure 9. Cluster field of Be87 showing pre-MS stars and normal stars separately. The symbols have the same meaning as in Fig. 3.

is 5 Myr, which is the time when the star formation started. The turn on age is less than 1 Myr. Thus the duration of star formation in this cluster is about 5 Myr.

We compared the location of pre-MS stars in the cluster field, as shown in Fig. 12. It can be seen that the pre-MS stars are distributed across the cluster field and do not show any central concentration.

3.5 Berkeley 86

Berkeley 86, a young open cluster, is one of the three nuclei of the OB association Cyg OB 1. The core of this cluster is located at $l = 76^\circ.7, b = 1^\circ.3$. Optical photometry was carried out in UBVRI bands by Deeg & Ninkov (1996) and Massey et al. (1995). They found the cluster to be a young one with a turn-off age of 5 Myr, reddening of 1 mag and an initial mass function close to the Salpeter value. Be 86 hosts the famous eclipsing binary system V444 Cygni (Forbes 1991). Stromgren photometry was obtained by Delgado et al. (1997) down to V=19 mag, from which they estimated an age of 8.5

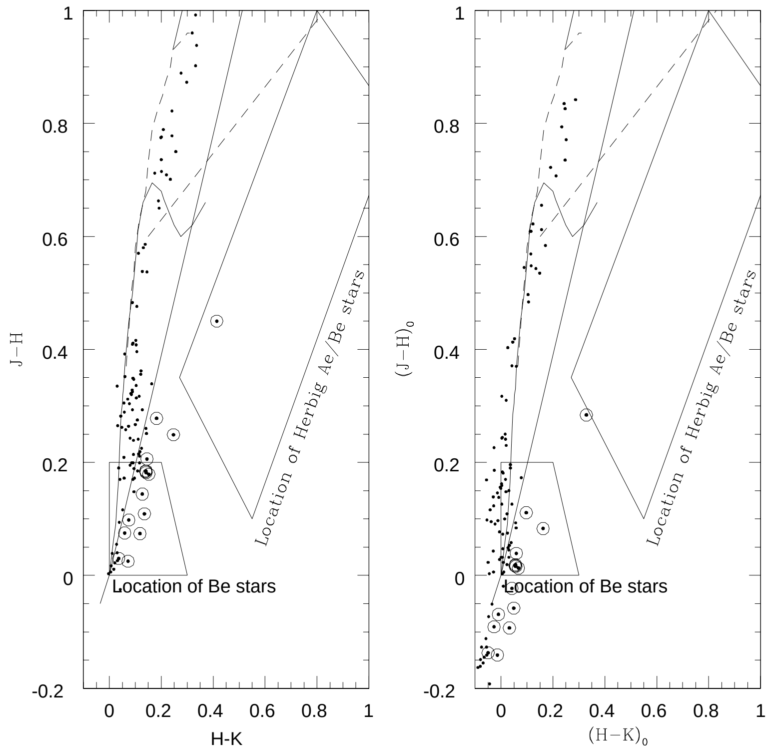

Figure 10. NIR colour-colour diagram for the cluster Biurakan 2. Symbols and panels have the same meaning as in Fig. 1.

Myr and a distance of 1659 pc. Forbes (1981) found Be 86 to lie at a distance of 1.72±0.20 kpc with a reddening of E(B−V)=0.96±0.07 mag. The cluster is located in the Orion spiral feature and is a possible member of the Cygnus OB 1 association at 1.8 kpc. An age of 6 Myr was estimated based on the earliest spectral type of O9. Vallenari et al. (1999) studied about 2000 stars in the field of Berkeley 86 down to K $\sim$ 16.5 mag using near-infrared photometry in J and K bands. They have found a number of pre-MS stars from (V−I) vs (I−K) plot and J vs (V−J) diagram. They do not estimate the ages of their candidate pre-MS stars. According to WEBDA cluster contains 3 Be stars.

From the field of Be 86 about 191 stars are identified with V, (B−V), (U−B), J, H, K magnitudes. Optical data is taken from WEBDA (Deeg & Ninkov 1996). NIR colour-colour diagram is plotted for the identified stars as shown in Fig. 13. 36 stars are found to be located below the reddening vector, showing IR excess. 27 stars are found to have more IR excess (large (H−K) magnitude) and could be candidate pre-MS stars. Three more stars are located below the reddening vector (not shown in the figure) with very large (H−K) value. These stars are located in HAeBe location, could be probable HAeBe stars. The stars 9 and 26 (Forbes 1981) for which H_α emission was observed are

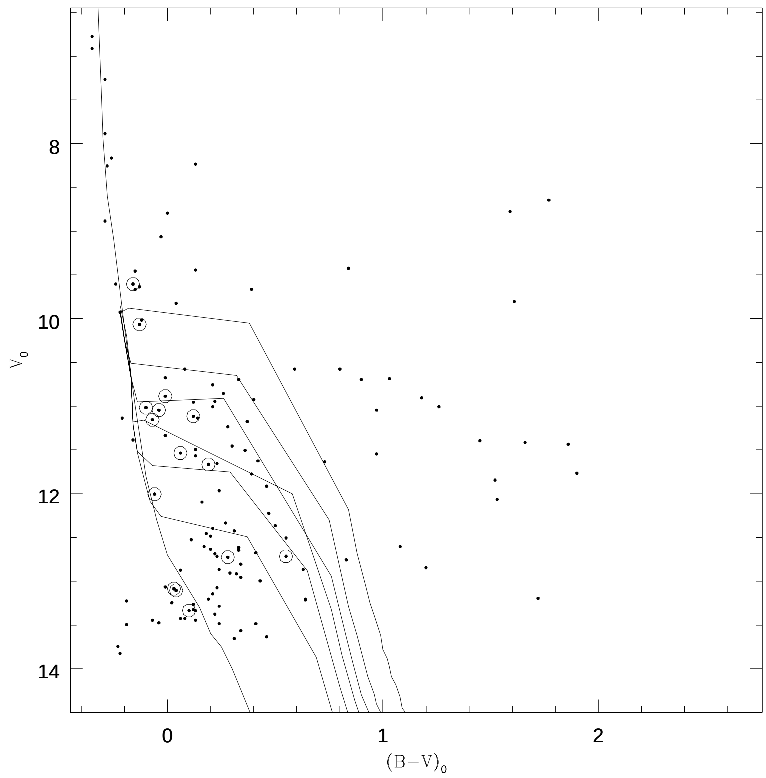

Figure 11. Pre-MS isochrone fittings for the cluster Biurakan 2. Isochrones for ages 0.5, 1, 1.5, 2, 3 and 5 Myr are shown.

shown as filled and labeled circles. In the reddening corrected figure (right panel), these stars occupy the CBe location.

For the identified stars reddening and extinction correction are done by assuming $E(B-V)$ as 0.95 mag and R_v as 3.1. The resulting CMD is shown in Fig. 14. We re-estimated the distance as 1585±160pc. In the CMD, many stars fainter than $V_0 =$ 14 mag and having IR excess are located to the left of ZAMS. These may be field stars or stars with different reddening. The turn-off age of the cluster is 6 Myr (Forbes et al. 1992). Pre-MS isochrones of ages 0.25, 0.5, 5, 7.5 and 10 Myrs are shown. The pre-MS stars are distributed in two age groups. The younger group is found to be younger than 1 Myr, while the older group is as old as or older than 5 – 7 Myr. It is quite likely that the star formation in this region started around 5 Myr and had a relatively low level star formation till 1 Myr. The cluster region has experienced vigorous star formation in the last 1 Myr. The duration of star formation is about 5 Myr, which is similar to the cluster, Biurakan 2. Star 9 lies on the 0.25 Myr pre-MS isochrone and 26 is located on the 0.5 Myr isochrone. Thus these stars are could be younger than 1 Myr, which makes

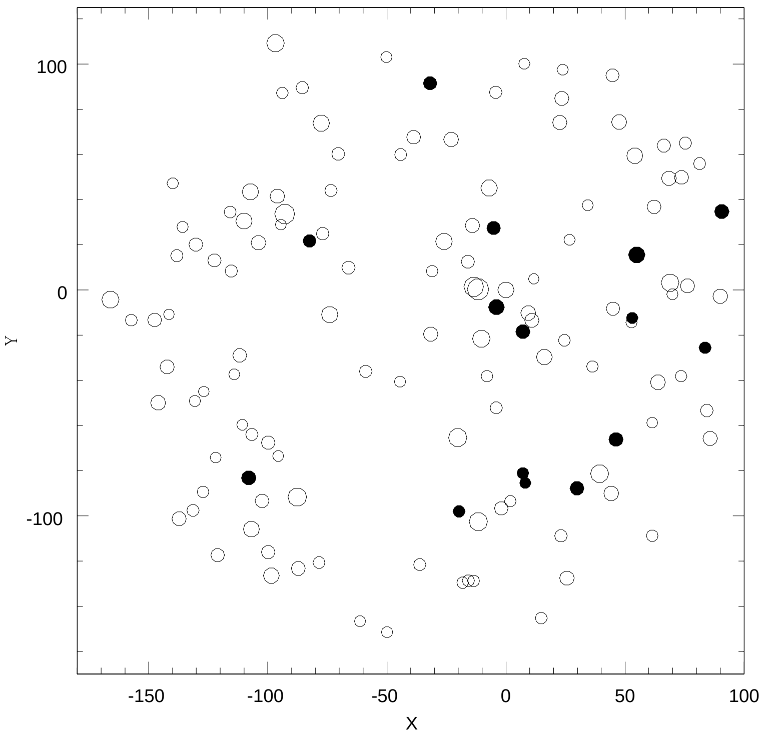

Figure 12. Cluster field of Biurakan 2 showing pre-MS stars and normal stars separately. The symbols have the same meaning as in Fig. 3.

them as candidate HAeBe stars. Otherwise, these stars could be 5 Myr old or slightly older, which would make them as candidate CBe stars. The Pre-MS stars are found to be distributed throughout the cluster field, as shown in Fig. 15.

4. Spectroscopic detection of emission line stars

The spectroscopic observations of the emission stars in clusters have been obtained using the HFOSC instrument available with the 2m 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.iia.res.in/). We have used slitless spectroscopic technique to identify emission stars in a cluster (Subramaniam et al. 2005). The log of observations of individual clusters in the slit-less mode is tabulated in Table 1. Slit spectra for identified emission stars were taken using Grism 7 (3800Å–6800Å) and 167 μ slit combination in the blue region which gives an effective resolution of 1330. The spectra in the red region were taken using Grism 8 (5800Å–8850Å) 167 μ slit setup, which gave an effective resolution of 2190. The CCD used was a 2 K $\times$

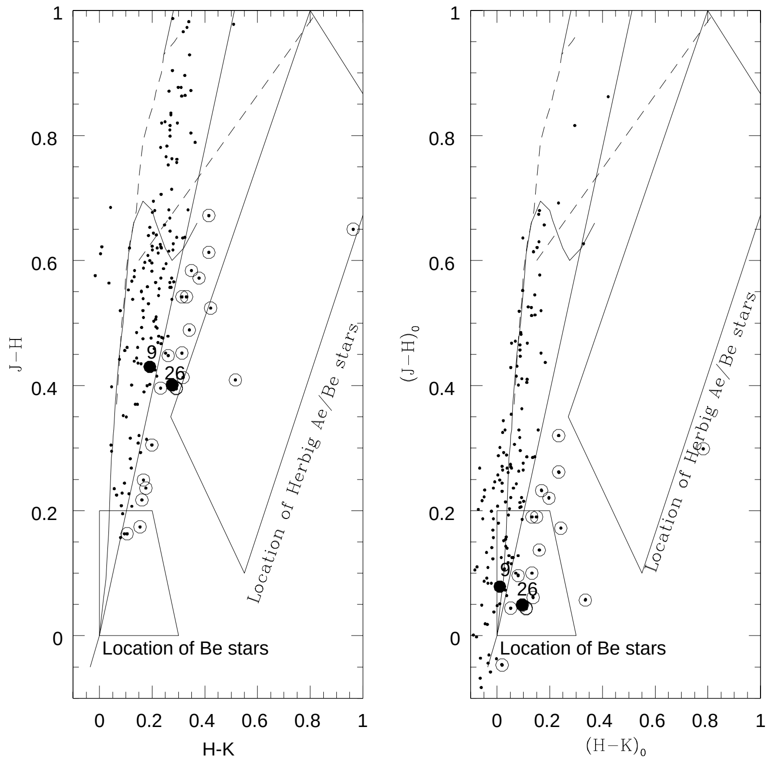

Figure 13. NIR colour-colour diagram for the cluster Be 86. Symbols and panels have the same meaning as in Fig. 1.

4 K CCD, where the central 500 × 3500 pixels were used for slit spectroscopy. The log of observations of the identified emission stars in the slit mode is tabulated in Table 2. All the observed spectra were wavelength calibrated and corrected for instrument sensitivity using IRAF tasks. The spectrophotometric standard, BD +284211, was observed on corresponding nights and was used for flux calibration. The resulting flux calibrated spectra were normalised and continuum fitted using IRAF tasks. The spectra are shown in Figs 16 (blue region) and 17 (red region). Fig. 18 shows the spectra of 4 stars which show prominent lines in the red end of the optical spectrum. The spectral properties of stars in four clusters are discussed below.

NaI lines (5890, 5896Å), Telluric O_2 bands (6867, 7600Å) and TiO molecular band (6080-6390Å) can be seen the spectra of emission stars in all the clusters.

IC 4996: The H_α profile of star 23 (GSC 03151-00898) shows emission in absorption feature and has OI(8446 Å) line in emission.

NGC 6910: Star 181 has H_α and OI (8446Å) lines in emission. The H_α profile is

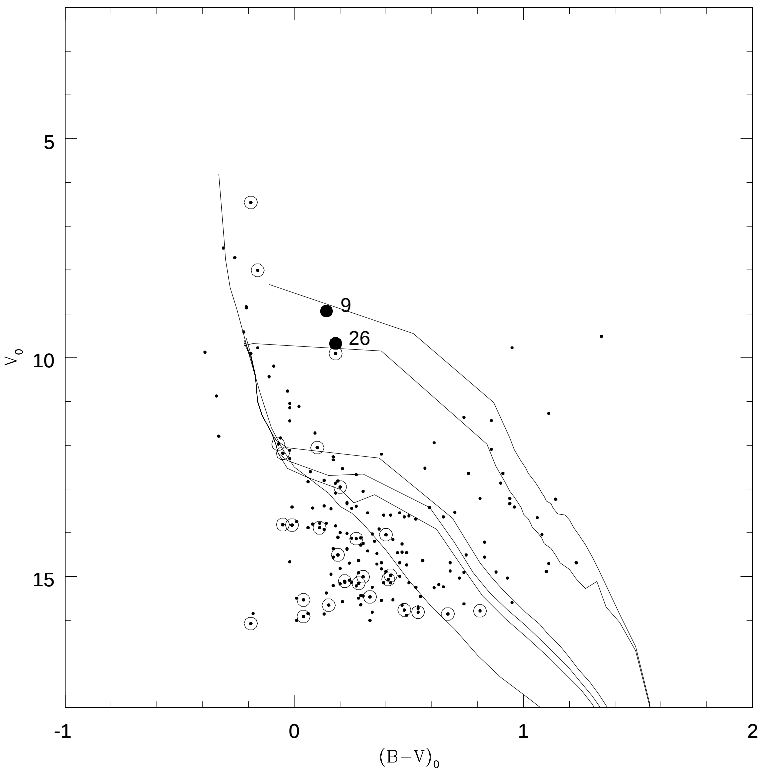

Figure 14. Pre-MS isochrone fittings for the cluster Be 86. The isochrones for the ages, 0.25, 0.5, 5, 7.5 and 10 Myr are shown.

found to show an asymmetry in profile with a definite V/R ratio. Star numbered 26 has an emission in absorption feature for H_β and H_δ profiles.

Be 87: Star 9 (B0.5Ve; GSC 02684-00007) shows double peaked emission for H_α profile along with H_γ and Paschen 14 line in emission. Spectral lines like OI (8446Å), Calcium triplet (8498, 8542, 8662Å) and FeII line (6384Å) are seen in emission. Star 15 has an equivalent width of -3.5 and -32.89 for H_β and H_α profiles respectively, which is the highest among these 9 emission stars. Intense emission can be seen for spectral lines like OI (8446, 7771Å), Paschen lines (P14(8598Å), P12 (8750Å)), Calcium triplet(8498, 8542, 8662Å) and FeII lines (6384, 5316, 7712Å). For star 38, (B2IIIe; GSC 02684-00004) only H_α is seen in emission among the group of Balmer lines. Faint emission features of OI, FeII(4351, 4620Å) and Calcium triplet are seen. He lines (4922, 4471, 4026, 5876, 6678Å) are seen in absorption. For star numbered 68, the H_α profile is seen in double peaked emission while H_β is seen in absorption. The spectrum is more or less featureless with tentative emission in OI (7772, 8446Å), Calcium and Paschen lines.

Table 1. Log of observations of individual clusters in the slit-less mode.

Date of observation	Cluster	Filter/ Grism	Exposure Time	RA hh:mm:ss	Dec deg:mm:ss
30-10-2003	IC 4996	R	5	20:16:30	+37:38:00
		R/Gr5	60		
		R/Gr5	300		
22-11-2004	NGC 6910	R	5	20:23:12	+40:46:42
		R/Gr5	60		
		R/Gr5	180		
	NGC 6910	R	10		
		R/Gr5	600		
15-07-2005	NGC 6910	R	10		
		R/Gr5	600		
22-11-2004	Berkeley 87	R	5	20:21:42	+37:22:00
		R/Gr5	120		
		R/Gr5	480		
15-07-2005	Berkeley 87	R	10		
		R/Gr5	900		
21-07-2006	Berkeley 87	R	10		
		R/Gr5	900		
27-06-2005	Berkeley 86	R	10	20:20:24	+38:42:00
		R/Gr5	600		
08-06-2004	Berkeley 86	R	30		
		R/Gr5	300		
		R/Gr5	600		

Be 86: For star 9, the H_α profile is found to show a double peak profile with the red region intense over violet. Balmer lines other than H_α are in absorption. He lines (4922, 4471, 4026, 5876, 6678Å) are seen in absorption. For the star numbered 26 intense emission can be seen for spectral lines like OI (7254, 8446Å), Paschen lines (P14 (8598Å), P12 (8750Å)), Calcium triplet (8498, 8542, 8662Å) and FeII lines (6384, 5316, 7712Å). P15 (8545Å), CaII (8542Å) lines and P13 (8665Å), CaII(8662Å) are blended due to the low resolution of the spectrum. In the blue region (3700-4500Å), Balmer lines other than H_α and H_β (core emission) are seen in absorption.

4.1 Estimation of stellar and disk properties

The equivalent width and FWHM of the spectral lines are estimated from a Gaussian fit, using routines in IRAF. The FWHM of H_α is corrected for instrument line width using comparison lines. The rotation velocity has been calculated using the formula,

$$VSini = c * FWHM/(2\lambda_0 * (ln2)^{(1/2)})$$

where c is the velocity of light, λ_0 is the central wavelength of the spectral line. The rotation velocity estimated using H_α emission line profile gives the rotation velocity of the disk while that from HeI (4471 Å) absorption line profile gives the stellar rotation

Table 2. Log of observations of emission stars in clusters (slit spectra).

Date of observation	Cluster	Star	Grism/ Slit	Exposure Time	RA hh:mm:ss	Dec deg:min:ss
15-06-2005	IC 4996	23	Gr7/167μ	600	20:16:29.05	+37:38:53.9
			Gr8/167μ	600		
29-07-2005	NGC 6910	26	Gr7/167μ	900	20:23:09.76	+40:45:53.7
			Gr8/167μ	900		
		181	Gr7/167μ	900	20:23:11.82	+40:43:28.8
			Gr8/167μ	900		
09-10-2005	Berkeley 87	9	Gr7/167μ	600	20:21:29.72	+37:26:25.1
			Gr8/167μ	600		
		15	Gr7/167μ	900	20:21:33.59	+37:24:51.7
			Gr8/167μ	900		
		38	Gr7/167μ	900	20:21:59.9	+37:26:25.1
			Gr8/167μ	900		
		68	Gr7/167μ	900	20:21:28.9	+37:26:19.9
			Gr8/167μ	900		
27-06-2005	Berkeley 86	9	Gr7/167μ	900	20:20:10.55	+38:37:29.8
			Gr8/167μ	900		
		26	Gr7/167μ	900	20:20:22.78	+38:38:12.3
			Gr8/167μ	900		

Table 3. Estimated parameters of 9 emission stars. The age estimated assuming them to be pre-MS stars is tabulated in column 3, while the age, assuming them to be MS stars is tabulated in column 4. The Spectral type is estimated from the photometry (column 5). The H_α EW is in column 6. The stellar rotation velocity is estimated from the FWHM of He I (4471 Å) and disk rotation velocity from H_α are in columns 7 and 8.

Cluster	Star	Age (pre-MS)	Age (MS)	Sp. type	Eq.width	Disk velocity kms^{-1}	Star velocity kms^{-1}
IC 4996	23	0.5	7	B2.5	-18.99 ± 1.13	268 ± 6	301 ± 5
NGC 6910	26	-	7	B2.5	-9.24 ± 0.45	228 ± 5	234 ± 6
	181	0.5	7	B5	-29.25 ± 2.09	339 ± 36	224 ± 3
Be 87	9	0.2	2	B1.5	-22.87 ± 1.22	352 ± 8	266 ± 7
	15	0.1	2	B1.5	-32.89 ± 1.87	196 ± 3	264 ± 3
	38	0.2	2	B1.5	-7.29 ± 0.46	199 ± 7	229 ± 5
	68	0.5	2	B9	-6.84 ± 0.23	353 ± 7	99 ± 5
Be 86	9	0.25	6	B2.5	-4.83 ± 0.14	367 ± 1	383 ± 3
	26	0.5	6	B4	-19.02 ± 1.1	151 ± 6	491 ± 5

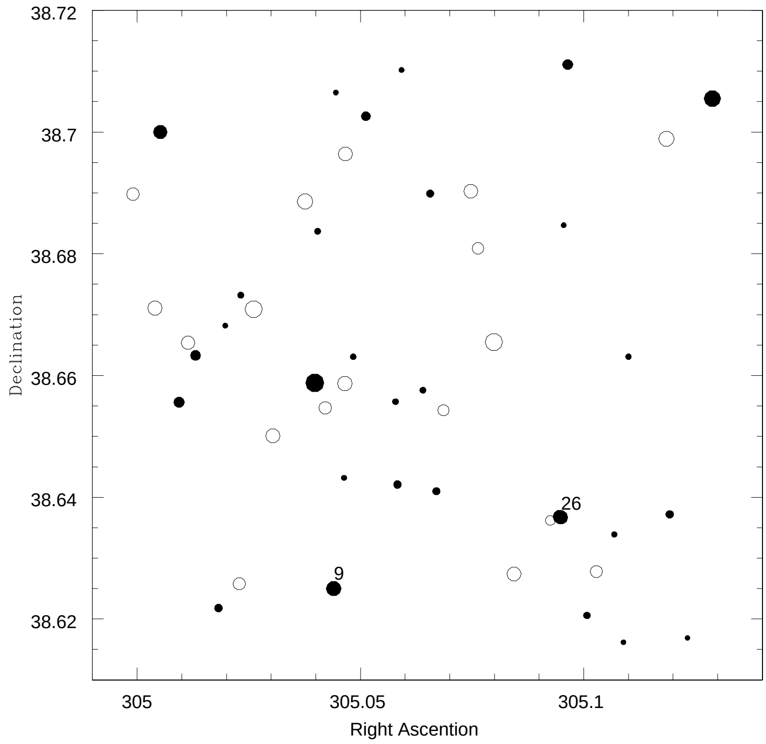

Figure 15. Cluster field of Be 86 showing pre-MS stars and normal stars separately. The symbols have the same meaning as in Fig. 3.

velocity. The estimated parameters are tabulated in Table 3. Many of the previous estimates of the spectral types indicate some of the emission stars to be giants. We have tried to classify the stars according to their photometry. The estimated spectral types are given in Table 3. It is evident from the optical CMDs that all the emission stars are located either on the MS or very close to the MS. Also they are not located near the turn-off of the MS, but well below the tip of the MS. This indicates that none of the stars are evolving to the giant phase from the MS. Thus, we consider the luminosity class to be V for all the emission stars.

The estimated rotational velocity of the star, as well as the disk is basically the V$\sin i$, which is the projected component. In general, we expect the disk to trail behind the star, but we can see that in certain cases the rotational velocity of the disk is higher than that of the star. The stars 181 (NGC 6910), 9 (Be 87) and 68 (Be 87) have disk velocity higher than the star. All the three stars have either double-peaked H_α or asymmetric profile. In principle, one has to de-convolve the peaks and then estimate the individual FWHM. Since the spectral resolution is poor, we are unable to deconvolve the profile. Thus, we

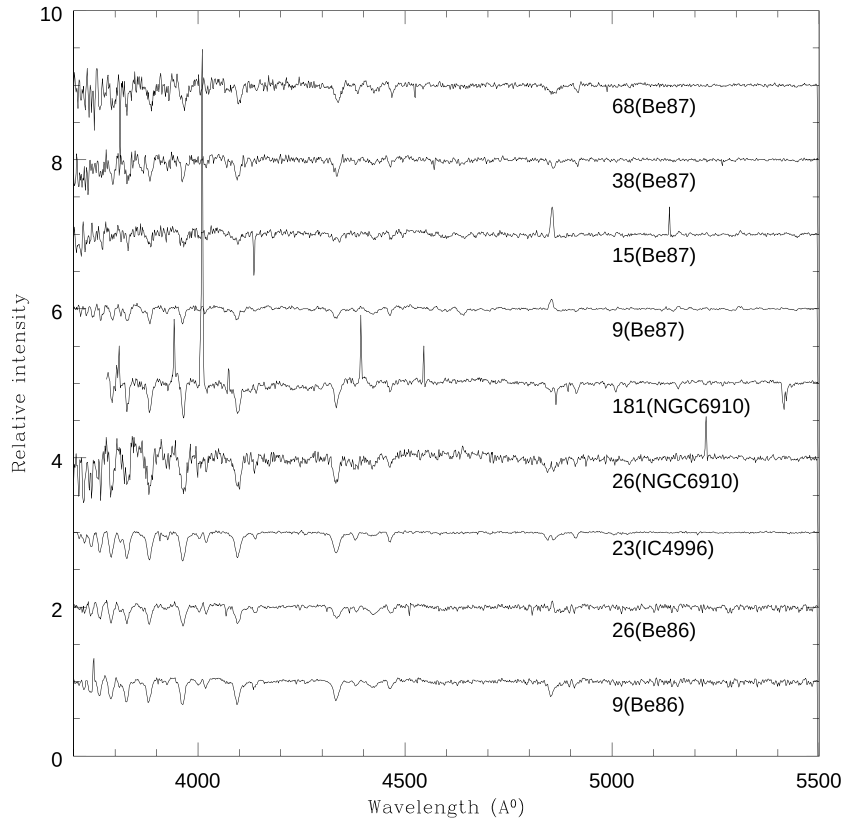

Figure 16. Flux calibrated, normalised, continuum fitted spectra of 9 Be stars in blue region.

have over estimated the disk velocity. Thus, excluding these three cases, the rest of the stars show faster rotation, when compared to the disk.

It will be interesting to study the relative rotational velocity between the disk and the star. Since the projection angle will contribute identically to both the velocities, the relative velocity is assumed to be independent of the projection angle i. This relative velocity could be a function of spectral type and hence we consider 5 stars which are of similar spectral type. The stars considered are the emission stars Be 87(38), NGC 6910 (26), Be 87(15), IC 4996(23) and Be 86(9). We have estimated the difference in rotation velocity between the star and the disk and it is plotted against the rotation velocity of the star (Fig. 19). The stellar rotational velocity is found to be between 200–400 km s^{-1}. The two stars in Be 86 have relatively large velocities (one is of later spectral type). The disk is found to lag behind the star by 0 - 40 km s^{-1} for four stars, For one star, the disk is slower by 68 km s^{-1}. This star happens to have the highest value of equivalent width for H_α, which indicates a heavier disk.

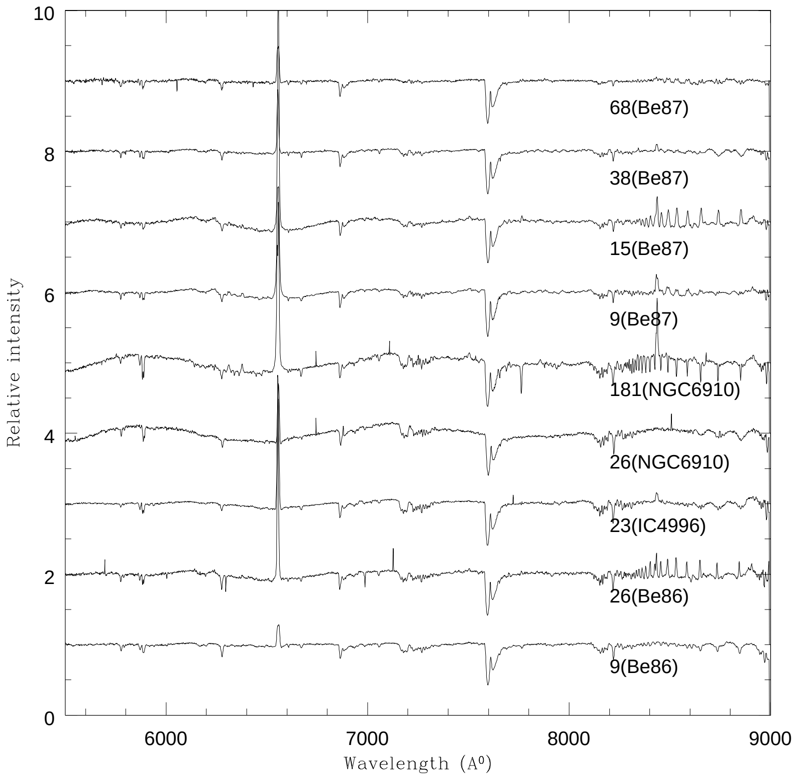

Figure 17. Flux calibrated, rormalised, continuum fitted spectra of 9 Be stars in red region.

We find that out of the 9 emission stars, most are likely to be CBe stars. There may only be at the most one-two HBe candidates, if at all. Also, the rotational velocity of the emission stars are in the range of those of the CBe stars, supporting their CBe nature. We see that the CBe phenomenon starts very early in the evolution of these stars, by about 2 − 7 Myr. Since these stars are well below the turn-off of the cluster, the CBe phenomenon starts much before the star evolves from the MS.

Capilla et al. (2000) found that younger clusters (age $\leq$ 10 Myr) do not contain Be stars. Clusters in the age interval 10-30 Myr are rich in Be stars. Almost all of them are of spectral types earlier than B5, while late-type Be stars are scarce. These results point towards an evolutionary interpretation of Be phenomenon, in the sense that Be stars are close to the end of their MS life time. Capilla et al. (2000) did not find any Be stars in NGC 6910. The clusters studied here all have a turn-off age less than 10 Myrs and they are found to have 9 emission stars which are likely to be CBe candidates. Two stars are of spectral type B5 and one of B7, which indicates the possibility of late type Be stars present in young clusters which in turn means that the CBe phenomenon need not be an evolutionary effect. Fabregat (2007) suggested that CBe phenomenon is an evolutionary

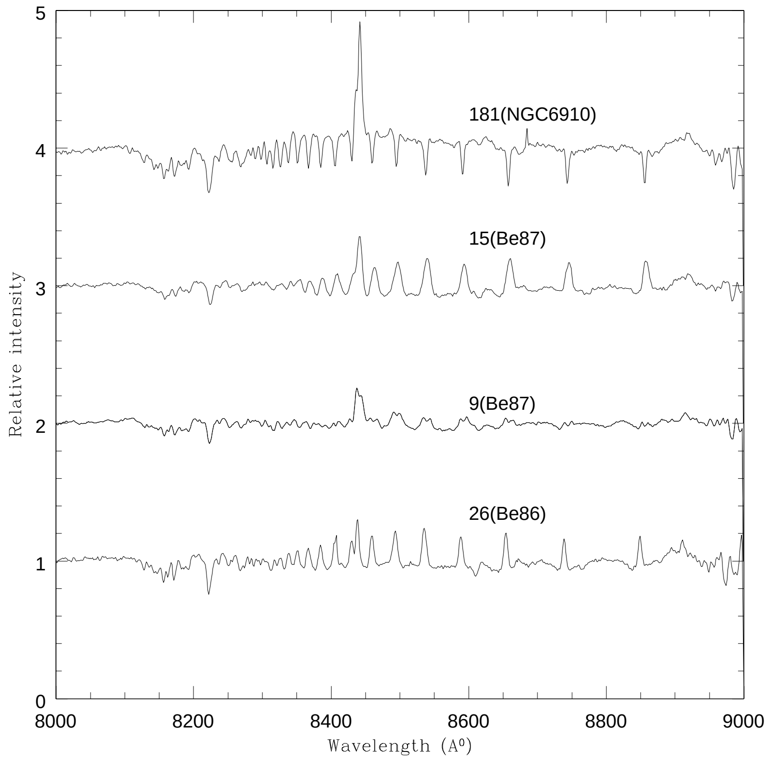

Figure 18. Spectra showing 3 stars with emission lines and 1 star with absorption lines in red end of the optical spectrum.

Table 4. The estimated duration of star formation in the five clusters.

Cluster	Turn-on age (Myr)	Turn-off age (Myr)	Duration of star formation (Myr)
IC 4996	0.5	7.5±3	7(continuous)
NGC 6910	0.5	6.5±3	7(continuous)
Berkeley 87	0.2	∼2	2 (continuous)
Biurakan 2	0.5	∼6	5 (continuous/recurrent)
Berkeley 86	0.2	∼6	6(continuous/recurrent)

effect appearing at the second half of the life in the MS of a B star. But this study suggests that CBe phenomenon can happen during the core burning initial phase in the MS life time of the star.

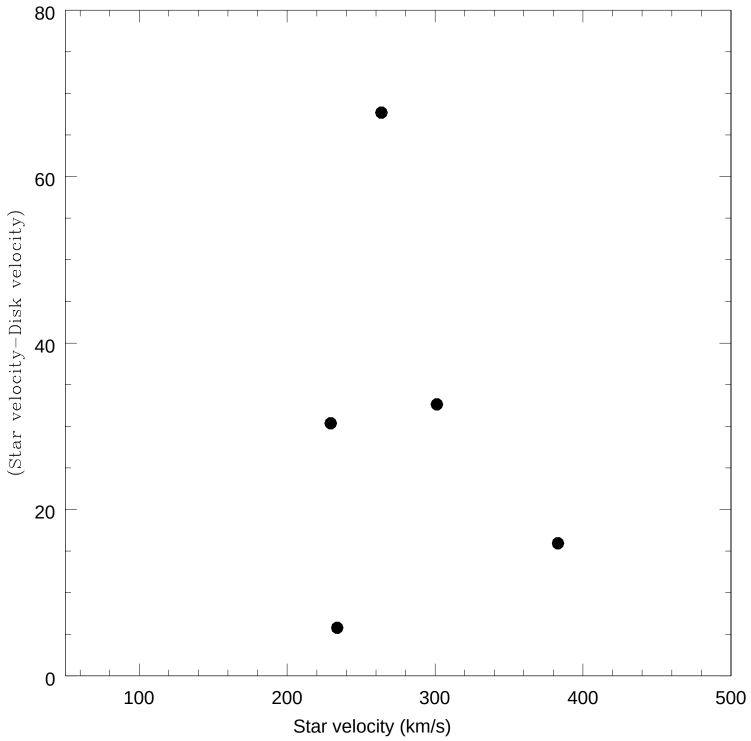

Figure 19. The relative rotational velocity between the star and its disk is plotted against the rotational velocity of the star. The velocities are plotted for the emission stars Be 87(38), NGC 6910 (26), Be 87(15), IC 4996(23) and Be 86(9), in the order of increasing stellar rotational velocity.

5. Location of clusters and direction of star formation in the Cygnus region

In the Cygnus OB region, 5 clusters are studied. The estimation of the turn-off age and turn-on age of the clusters along with their distance provides a reasonable interpretation about the direction of propagation of star formation in the Cygnus OB star forming complex. The longitude and distance to the cluster is used to derive their location in the Cartesian Coordinate system as shown in Fig. 20. The estimated duration of star formation in the clusters studied are tabulated in table 5. The location of clusters along with their age is used to understand the star formation. This region, located between the galactic longitudes $l = 70° - 80°$, has eight more open clusters, for which reliable distance and age estimates are available. We include these clusters also, as shown in figure 21, to understand the star formation. The clusters included are Collinder 419, Collinder 421, Ruprecht 172, NGC 6913, NGC 6871, Biurakan 1 and ASCC 111. The first four clusters

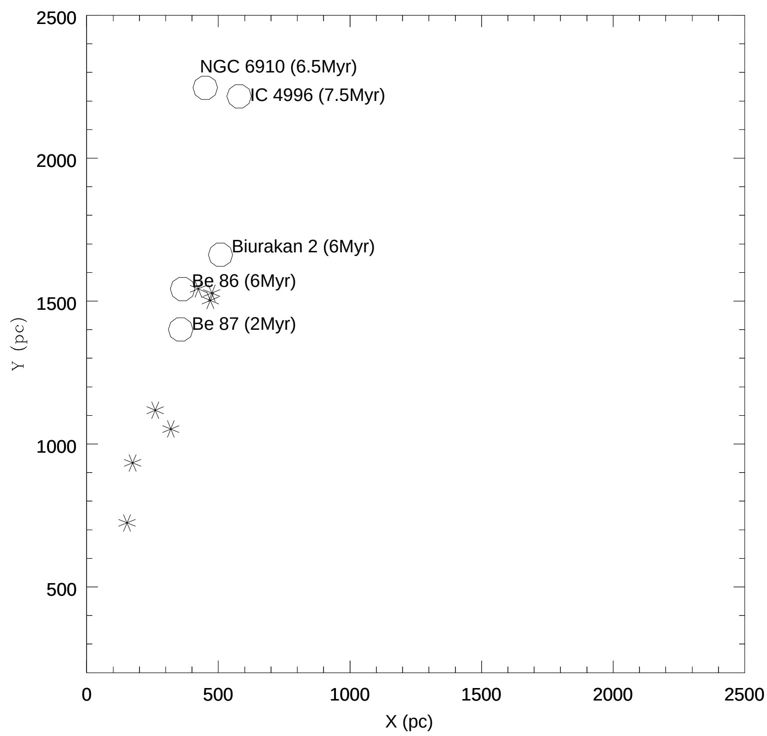

Figure 20. Location of clusters in the Cygnus region. The labeled open circles along with their turn-off ages, indicate clusters studied here. The asterisks indicate clusters present in the region, but not studied here.

are located closer to us, closer than 1200 pc and the rest of the three clusters are located very close to Be 86, Be 87 and Biurakan 2 . The ages as given in WEBDA for these three clusters are 9 Myr, 18 Myr and 11 Myr, respectively.

We interpret this figure keeping in mind that there may be significant error associated with the estimated distance. The clusters can be grouped into three groups, the first one is located around 1 kpc, the second group is located at $\sim$ 1500 pc and the third group, beyond 2000 pc. The farthest group consists of two clusters, NGC 6910 and IC 4996. Both the clusters seem to have similar star formation history. The second group seems to indicate a vigorous star formation, where the relatively older clusters, Biurakan 2, NGC 6871, Biurakan 1 and ASCC 111 could have formed first, then Berkeley 86 and very recently, Berkeley 87. In both the groups, the duration of star formation is about 5 – 7 Myr. We estimate a short duration for the star formation, 2 Myr, in the case of Berkeley 87. The three clusters studied here indicate an enhanced star formation in the last 1 – 2 Myr. Also, the major star forming region with 6 clusters is located at $\sim$ 1500 pc, and this could be considered as the most active star forming region within the longitude range $l = 70^\circ - 80^\circ$ and located at $\sim$ 1500 pc. No preferential location for the young pre-MS stars were found in the clusters. The emission line stars were found in 4 clusters and one was found to be devoid of such stars. Therefore, all clusters in a star forming complex may not harbour emission line stars. Thus, the recent star formation observed in the Cygnus was started about 2 – 7 Myr ago, depending on the location. This implies that the star formation in large complexes can last up to 7 Myr.

6. Conclusion

The main conclusions of the present study can be summarized as follows:

In the Cygnus region, 93 candidate pre-MS stars and 9 stars with H_α emission spectra are identified in 5 clusters.

The duration of star formation (estimated as the difference between the turn-off and turn-on age) is estimated for five clusters. This indicates that the star formation in the clusters were going on for 2 – 7 Myr. The recent star formation in the Cygnus region started $\sim$ 7 Myr ago.

CBe phenomenon can be found in very young MS stars which are just a few (2–7) Myr old. This indicates that the CBe phenomenon need not be an evolutionary effect.

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