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Near-infrared JH photometry of young open cluster Be 59

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Abstract. We present near-infrared JH photometry and optical slitless spectroscopy of stars in the field of the young cluster Be 59. The $J/(J-H)$ colour-magnitude diagram of the cluster yields a distance modulus of $(m-M)_0$ = 10.0 ± 0.2 mag, which corresponds to a distance of 1.0 ± 0.1 kpc. Using the slitless spectroscopy we identified 9 $H\alpha$ emission line stars in the observed region. The location of $H\alpha$ stars in the CMD indicates that they may be pre-main sequence stars. We have estimated the age of the cluster using the turn-off and turn-on points and is found to lie between ∼ 1 Myr to 4 Myr. Two massive stars (∼ 25 $M_\odot$) in the cluster region have high membership probability which indicates that the low mass stars (∼ 0.8 $M_\odot$) may co-exist with massive stars.

Keywords : Open clusters, Photometry, Extinction, Infrared

1. Introduction

A basic enigma in the study of star formation is the relationship between high and low mass star formation (Megeath 1996). In recent years, much of the interest in star formation has focused an open question: are regions of massive star formation forming low mass stars as well? Therefore, understanding the formation process of stars and their evolution constitute one of the basic problems in astrophysical research. Star clusters are

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important tools to study the star formation process. Young open clusters (age $\leq$ 10 Myr), having just formed from gravitationally bound molecular clouds and still embedded in the parent nebulous regions present an unique laboratory for understanding the process of star formation and the early evolution of stars over a wide mass range as well as the nature of interactions between young stars and the interstellar medium (Scalo 2004).

Young clusters also contain statistically significant samples of Young Stellar Objects (YSOs) of the same parental heritage but of differing mass and evolutionary states (Lada 1993). The interstellar gas and dust associated with the YSOs can absorb and reproduce a substantial fraction of the radiant energy emitted by the embedded stars, as a result, the bulk of the luminous energy of YSOs is often radiated at wavelength longward of 1 μm. Therefore census of these embedded stellar populations using near-infrared (NIR) observations is very useful for investigating the star formation process and early stellar evolution.

Be 59 ($\alpha_{2000} = 00^h02^m13^s$, $\delta_{2000} = +67^{\circ}25^{'}11^{''}$) is a young open cluster located in the Cepheus region (l = 118.^{o}22, b = 5.^{o}00). An approximate age, distance and the reddening ($E(B-V)$) for the cluster Be 59 is estimated to be around 6 Myr, 1 kpc and 1.22 mag respectively (Kharchenko et al. 2005). In the present study, we have carried out NIR imaging of $\sim$ 56 arcmin^2 area and obtained JH magnitudes of 204 stars in the field of Be 59 upto a limiting magnitude of $J \sim 15.5$. We have also used slitless spectra to identify some of the pre-main sequence $H\alpha$ stars in cluster region. The primary goal of the present study is to obtain a census of the cluster population and to investigate star formation processes to study whether this is co-eval or not.

2. Observation and data reduction

2.1 IR data

The JH NIR observations of Be 59 were carried out during 2004 September 24 and 25 with the Himalayan Chandra Telescope (HCT) NIR camera (NIRCAM) equipped with 512×512 HgCdTe array of 18 micron pixel size. For the observations, the NIRCAM was used in the Camera-B mode which has an FOV of $\sim 3.6 \times 3.6$ arcmin^2. Further details on NIRCAM can be found at *http : //www.iiap.res.in/iao/nir.html*. The read out noise and gain are 35.1 e^- and 6.21 e^-/ADU respectively in DCS mode.

The image frames were taken in different filters and in each filter, a number of dithered frames were taken to avoid dead pixels and to generate sky frames. As the chip covers only $\sim 3.6 \times 3.6$ arcmin^2 on the sky, we have observed 8 different regions of the cluster with some overlapping. A number of dark and flat frames were also taken during the observing runs. The log of observations is tabulated in Table 1. The DSS image of the observed region is shown in Fig. 1. Stars observed in $\sim$56 arcmin^2 area of the cluster region are also shown in Fig. 2.

Table 1. Log of observations.

Field	Filter	Exposure (sec)	No. of frames	Date
01	J	2.0	30	24/09/2005
01	H	0.8	35	24/09/2005
02	J	2.0	20	24/09/2005
02	H	0.8	20	24/09/2005
03	J	2.0	20	24/09/2005
03	H	0.8	30	24/09/2005
04	J	2.0	10	24/09/2005
04	H	0.8	35	24/09/2005
05	J	5.0	35	25/09/2005
05	H	3.0	35	25/09/2005
06	J	5.0	35	25/09/2005
06	H	3.0	35	25/09/2005
07	J	5.0	35	25/09/2005
07	H	3.0	35	25/09/2005
08	J	5.0	35	25/09/2005
08	H	3.0	35	25/09/2005

The image frames were reduced using computing facilities available at the Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital. Initial processing of the data frames was done using the IRAF[1] and ESO-MIDAS[2] data reduction packages. Photometry of cleaned frames was carried out using DAOPHOT-II software (Stetson 1987). The PSF was obtained for each frame using several uncontaminated stars. For calibration, we observed AS-13 (Hunt et al. 1998) standard field and calculated the zero point correction. The zero point errors in J and H bands are of the order of 0.04 and 0.07 mag respectively. DAOPHOT errors in J, H bands as a function of J magnitude are shown in Fig. 3. The photometric data along with the position of the stars measured in the cluster are given in Table 2, which is in electronic form. A sample of the full catalogue is shown in Table 2.

2.2 Grism slitless spectroscopy

The cluster was also observed in the slitless mode with the grism as the dispersing element using the Himalaya Faint Object Spectrograph Camera (HFOSC) instrument on 2004 September 22, 2005 January 7–9. This mode of observation using the HFOSC yields an image where the stars are replaced by their spectra. A combination of wide $H\alpha$ filter ($\lambda(\delta\lambda)$ = 6563(440) Å) and Grism 5 (5200 - 10300 Å) of HFOSC was used without any

[1]IRAF is distributed by National Optical Astronomy Observatories, USA
[2]ESO-MIDAS is developed and maintained by the European Southern Observatory.

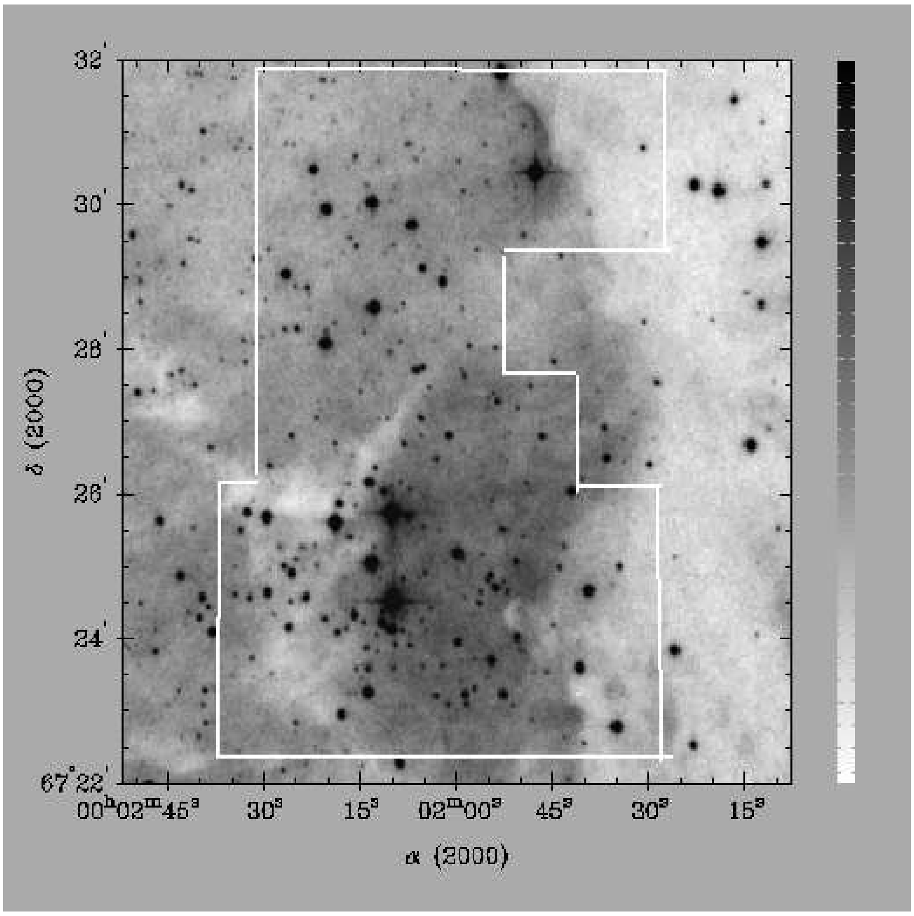

Figure 1. DSS image of the cluster Be 59. The boundary of the observed region in NIR is also marked.

slit. The resolution of grism is 870. The 2K×4K CCD, CCD was used for imaging where the central 2K×2K pixels were used. The pixel size is 15 micron with an image scale of 0.297 arcsec/pixel. We secured three spectroscopic frames of 7 min exposure with grism in and three direct frames of 1 minute exposure with grism out. The co-added spectroscopic frames yield limiting magnitude of about $V \sim 20$ for continuum detection. The slitless spectra thus obtained were used to identify the presence of any emission line stars in the field of the cluster. Since Be 59 is known to be a young cluster, there is a good chance of some of the stars showing emission line feature. The data were reduced following standard procedures with IRAF as described by Ogura et al. (2002). We have detected 14 $H\alpha$ stars in the observed region, however only 9 stars have J and H magnitudes from the present photometry. Relevant information about these 9 $H\alpha$ stars are given in Table 3.

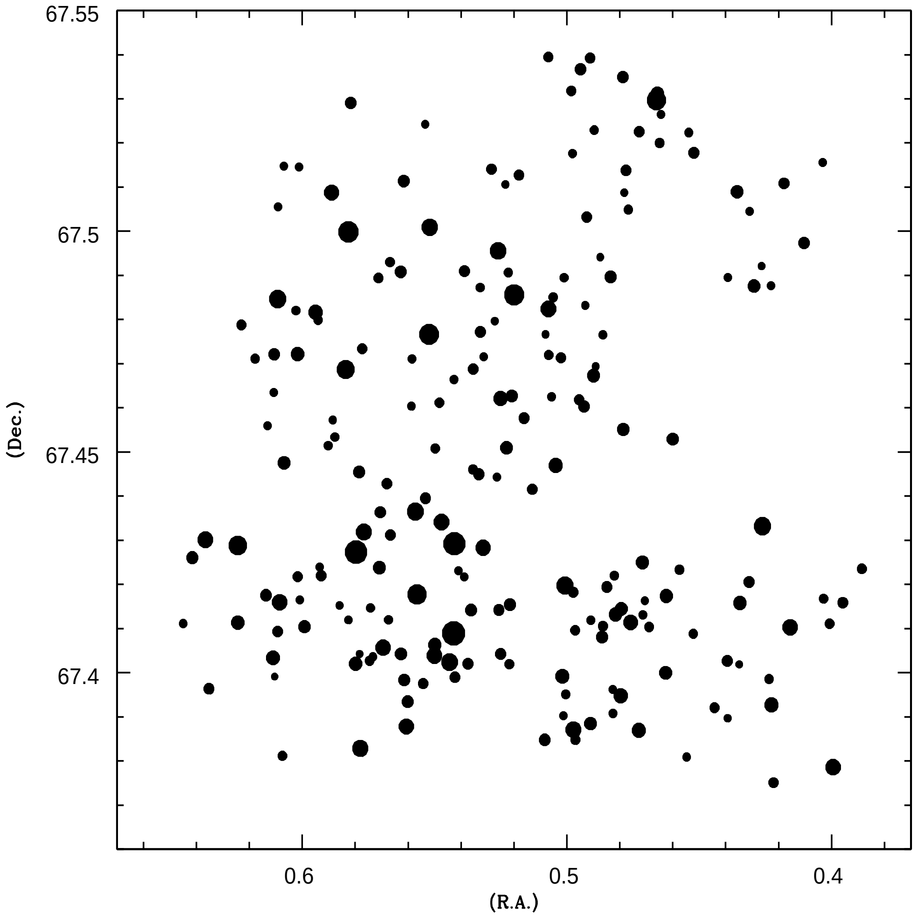

Figure 2. The observed region of the cluster Be 59. The sizes of the dots are according to the brightness i.e. bigger dots represent brighter stars. The RA and Dec are in degrees (J2000).

3. Comparison with 2MASS

We have carried out a comparison of the present data with that available in Two Micron All Sky Survey (2MASS). The difference Δ (2MASS - HCT) in mag as a function of J magnitude is shown in Fig. 4. We have cross identified 129 stars out of 204 from 2MASS data with a positional accuracy of less than 1 arcsec. The comparison indicates rather a large scatter in Δ. The mean value and standard deviation of Δ are -0.03 ± 0.25 mag and -0.01 ± 0.24 mag in J and H bands respectively.

Table 2. Photometric data of the stars in the field of Be 59.

ID	α_{2000} (h:m:s)	δ_{2000} (d:m:s)	J	J_{err}	H	H_{err}
1	00:02:10.27	67:24:32.2	6.86	0.02	6.45	0.02
2	00:02:19.12	67:25:38.4	7.28	0.03	6.87	0.03
3	00:02:19.81	67:29:59.6	8.48	0.01	7.41	0.02
4	00:02:12.50	67:28:35.9	8.63	0.01	8.12	0.02
5	00:02:04.79	67:29:08.2	8.68	0.01	7.37	0.02
6	00:02:13.59	67:25:03.9	9.04	0.02	8.84	0.02
7	00:01:51.88	67:31:46.9	9.12	0.02	8.71	0.02
8	00:02:29.85	67:25:43.8	9.58	0.02	9.38	0.01
9	00:02:20.05	67:28:07.3	9.70	0.01	9.39	0.02
10	00:02:26.23	67:29:04.8	10.03	0.04	9.51	0.05
11	00:02:00.18	67:25:11.2	10.15	0.02	9.60	0.03
12	00:01:42.26	67:25:59.5	10.21	0.00	9.44	0.01
13	00:02:13.74	67:26:11.4	10.35	0.01	10.04	0.01
14	00:02:10.64	67:24:08.6	10.46	0.01	9.98	0.01
15	00:02:06.24	67:29:44.1	10.57	0.02	10.07	0.02
16	00:02:12.43	67:30:03.3	10.70	0.00	10.34	0.01
17	00:02:18.74	67:22:58.3	10.73	0.03	9.99	0.02
18	00:02:18.41	67:25:54.8	10.95	0.01	10.55	0.01
19	00:01:59.41	67:23:13.6	10.97	0.01	10.10	0.01

Table 3. Detected $H\alpha$ emission stars.

ID	α_{2000} (h:m:s)	δ_{2000} (d:m:s)	J	J_{err}	H	H_{err}
39	00:02:00.41	67:23:57.1	12.04	0.01	11.15	0.01
43	00:02:24.43	67:28:19.9	12.26	0.02	11.14	0.03
58	00:01:57.86	67:23:18.6	12.75	0.01	11.75	0.01
67	00:02:15.06	67:29:27.0	13.10	0.03	11.75	0.03
83	00:02:07.85	67:28:38.0	13.53	0.02	12.35	0.02
74	00:02:02.01	67:23:05.3	13.20	0.03	12.00	0.03
91	00:02:06.17	67:24:51.2	13.60	0.08	12.74	0.05
126	00:01:59.25	67:24:34.6	14.27	0.03	13.04	0.02
140	00:01:54.43	67:30:17.7	14.50	0.04	13.49	0.03

4. Analysis and discussion

On the basis of spectral features, NIR excess and colour magnitude diagrams, we can identify PMS stars such as Herbig Ae/Be and classical T Tauri stars within star-forming regions and thus estimate the age of these stars using PMS isochrones. If the cluster age (on the basis of high mass stars) and PMS stars age are more or less the same, it means

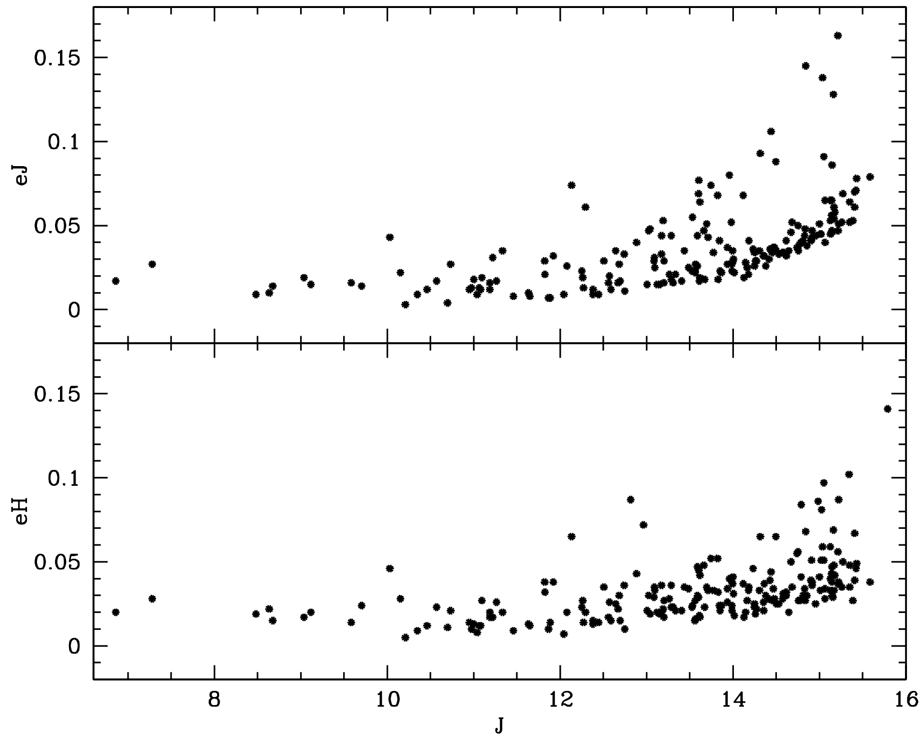

Figure 3. Error in magnitude determination as a function of J magnitude for different pass-bands.

that the high mass stars and the low mass stars (PMS stars) were formed together in the cluster (coeval star formation) otherwise star formation scenario may be different for low and high mass stars.

4.1 Colour-magnitude diagram

NIR observations are very effective for investigating the nature of obscured clusters and the populations of YSOs which are embedded in molecular clouds (Lada 1992). Analysis of the JHK colour-magnitude diagram (CMD) for young stellar objects indicates that it can be a very useful tool for studying star formation. The reason for this is that observations at wavelengths around 1 μm probe the environment close to the surface of a YSO and are therefore sensitive to the presence and structure of any circumstellar material there.

In Fig. 5, we have plotted $J/(J-H)$ colour magnitude diagram for the stars in Be 59 region. In the observed region proper motions are available for five stars in WEBDA

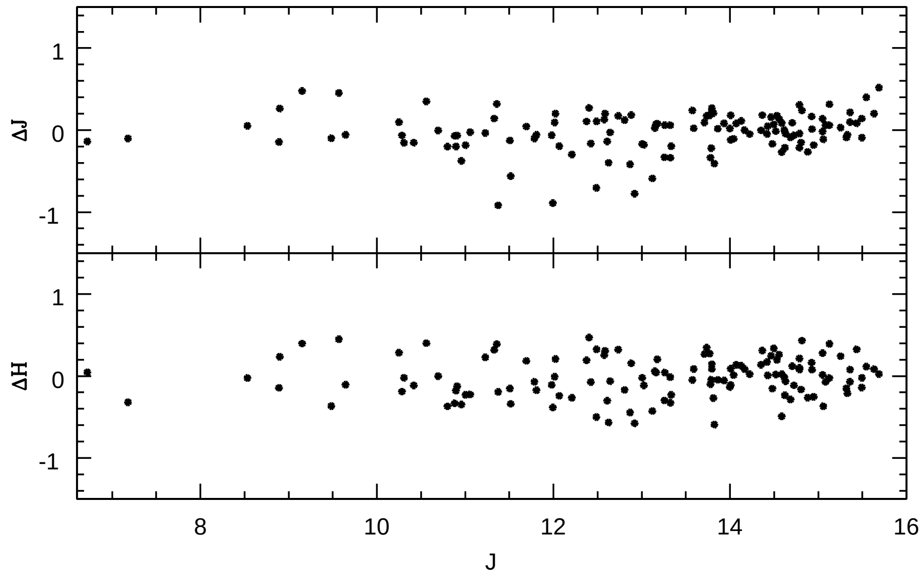

Figure 4. Comparison of HCT infrared photometry with the 2MASS data. The difference Δ (2MASS - HCT) in mag is plotted as a function of J magnitude.

(Mermilliod 1995). The star numbers and membership probabilities taken from WEBDA for five stars are shown in Fig. 5. The $J/(J-H)$ data for star number 3 (membership probability 0.98) is taken from 2MASS catalogue as its measurements were showing large errors. The star number 7 also has high membership probability (0.72). Using the relation $\frac{A_J}{A_V} = 0.265$, $\frac{A_{J-H}}{A_V} = 0.110$, $A_V = 3.1 \times E(B-V)$ and the value of $E(B-V) = 1.22$ (Kharchenko et al. 2005) we overplotted theoretical isochrones by Bertelli et al. (1994) and PMS isochrones by Siess et al. (2000). The comparison yields a post-main-sequence age of $\sim$4 Myr along with an apparent distance modulus $(J - M_J) = 11.0$ mag which in turn gives a true distance modulus $(J - M_J)_0$ of 10.0 mag corresponding to a distance of 1000 pc. Taking into account various errors (e.g. in mean $E(B-V) \sim 0.15$, $J \sim 0.04$, $(J-H) \sim 0.08$), the estimated error in distance modulus is about 0.2 mag which corresponds to an error of about 100 pc in distance determination.

Most of the faint stars ($J \geq 12$ mag) are distributed along a PMS isochrone of 1 Myr indicating that the cluster is young. This makes it a good object for spectroscopic observations. Location of the 9 $H\alpha$ stars on the CMD of the cluster identified in the observed region (see Section 2.2) indicates that these may be PMS stars having age $\sim$ 1 Myr. It is not possible to deredden the stars individually and consequently to estimate the age spread, if any.

The radial extent of the cluster using 2MASS data is found to be around 10 arcmin. The CMD for a reference field (having area equal to the cluster region) located at a

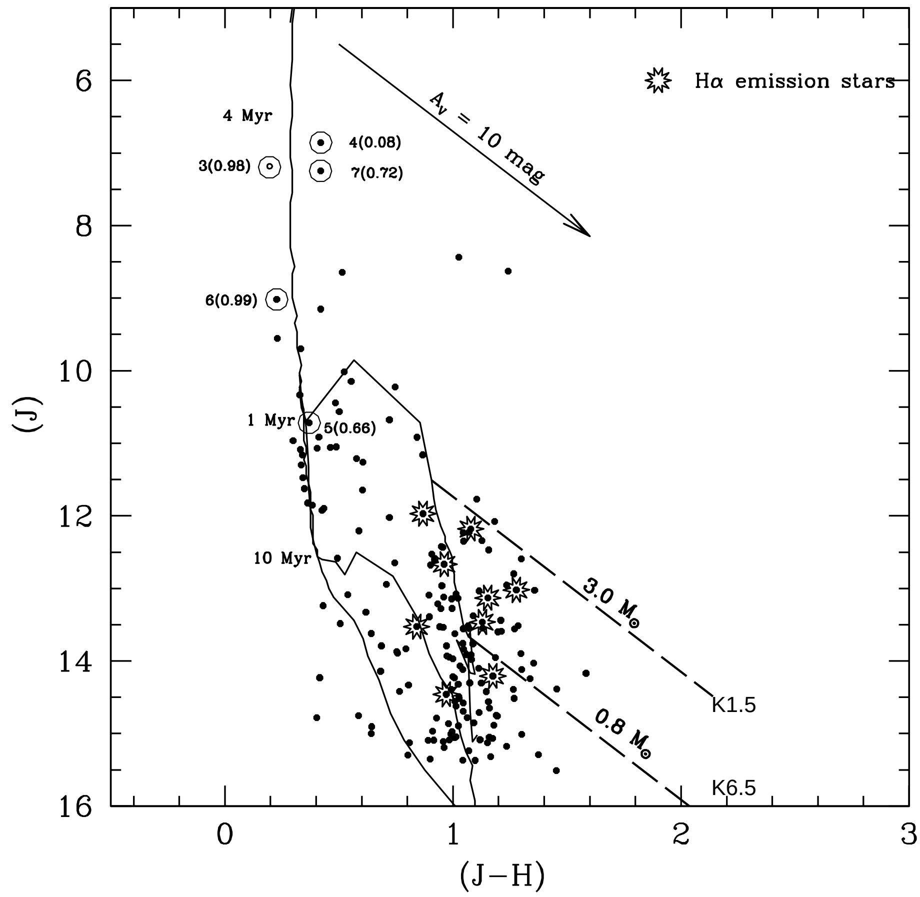

Figure 5. The $J/(J-H)$ colour-magnitude diagram for the observed cluster region. The isochrone for 4 Myr and pre-main sequence isochrones for 1, 10 Myr by Bertelli et al. (1994) and Siess et al. (2000) respectively are also plotted for $E(B-V) = 1.22$ and distance modulus $(J - M_J) = 11.0$ mag. The star numbers are taken from WEBDA. The numbers in parentheses represent membership probability. The dashed oblique reddening lines denote the position of PMS stars of 3.0 and 0.8 $M_\odot$ having age 1 Myr. The star symbols show the $H\alpha$ emission stars detected in our sample and $\odot$ symbols show the five stars identified in WEBDA.

distance of about 20 arcmin from the cluster center towards NW direction is obtained using the 2MASS data and is shown in Fig. 6. A comparison of the field region CMD with the cluster CMD indicates a significant number of PMS stars in the cluster region. The CMD of the cluster region indicates that two massive stars ($\sim 25 M_\odot$), having high membership probability, are likely to be members of the cluster. If these massive stars are members of the cluster, then there is a possibility that low mass stars ($\sim 0.8\ M_\odot$) may co-exist with the massive stars.

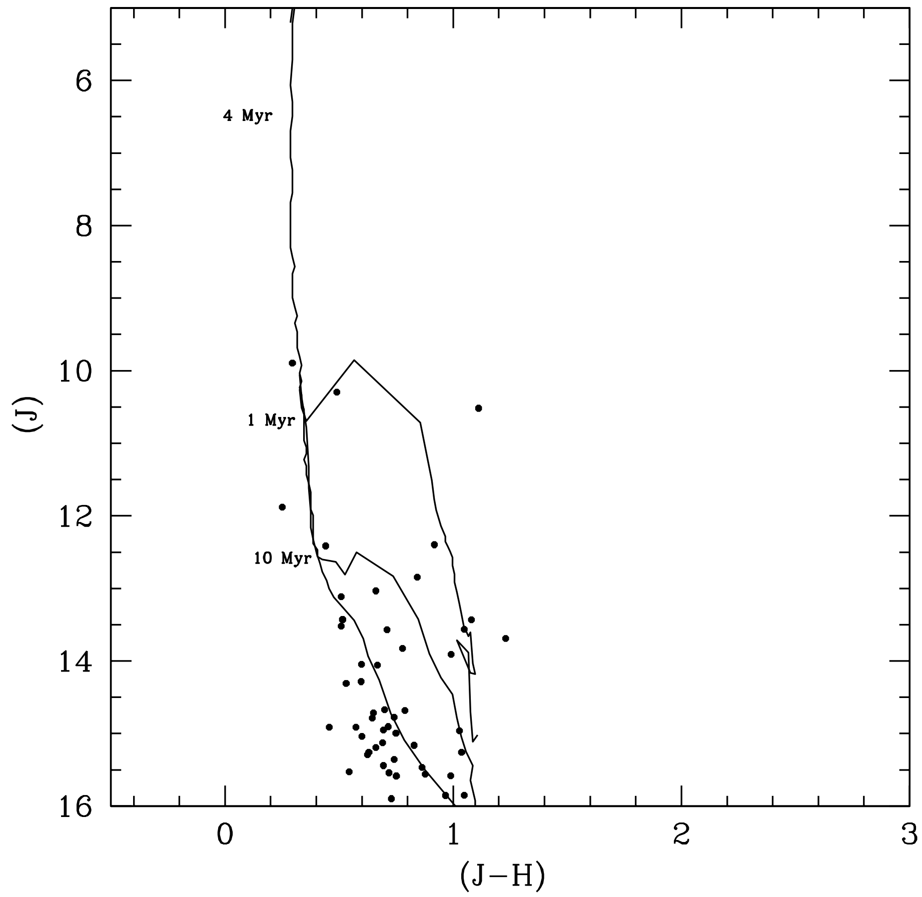

Figure 6. Same as Fig. 5 but for the field region.

It will be worthwhile to compare the statistics of $H\alpha$ stars of Be 59 with other nearby young open clusters. The statistics of $H\alpha$ stars in the case of IC 5146 and IC 348 is given by Herbig & Dahm (2002). Present slitless spectroscopy is expected to be complete upto $V = 19$ mag ($M_V = 4.65$). Our data indicate a surface density of ~ 3 stars/pc^2 (for stars upto $M_V = 4.65$) which is in between the surface densities 4.5 stars/pc^2 (for IC 5146) and 1.1 stars/pc^2 (for IC 348) estimated for the same magnitude limit from the work of Herbig & Dahm (2002). The variation in surface density of $H\alpha$ stars in young open clusters may be due to difference in the age of PMS stars. A careful homogeneous age determination of $H\alpha$ stars is needed to study the evolution of these stars.

Present study of the young cluster Be 59 indicates that the star formation may be non-coeval with an age spread of ~ 4 Myr. It is also found that low mass PMS stars may co-exist with the high mass stars. To study the cluster in detail a multi-wavelength photometric and spectroscopic data in a larger region around the cluster is required.

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