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Star formation in the region of young open cluster - NGC 225

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Abstract. NGC 225 is believed to be a 120 Myr old open cluster located at $\sim$ 650 pc. Eight stars with H_α emission are found to be located around the cluster, of which two are probable Herbig Be stars, indicating a very young age for the cluster. To explore whether the Herbig Be stars, which are pre-main sequence (PMS) stars are part of this cluster, we re-estimated the cluster parameters using optical (UBV)pg and 2MASS JHK photometry. We combined the above data to detect the presence of any possible PMS stars in the cluster region. Among the identified 28 proper motion members, 15 stars were found to have near-infrared (NIR) excess indicating that they are PMS stars. Also, most of the upper MS stars were found to show NIR excess suggesting that the brighter proper motion member stars have not yet reached the MS. PMS isochrones were used to estimate the age of stars with NIR excess and is found to be between 0.5–10 Myr. Thus, the cluster NGC 225 is a very young cluster, younger than 10 Myr and its age is not 120 Myr as previously believed. We propose that a recent star formation has resulted in the formation of NGC 225, two Herbig Be stars, stars with H_α emission, dust lanes and nebulosity in the vicinity of the cluster.

Keywords : open cluster, pre-main sequence star, Isochrone fitting

1. Introduction

Young open star clusters are excellent testing ground to study the formation and evolution of early type stars. Massive early type stars spend very small time ($\sim$ 1-3 Myr) in the

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pre-main sequence (PMS) phase. These early type stars, in their PMS phase, generally show Balmer emission lines, presence of large reddening and associated nebulosity. They are known as Herbig Ae/Be stars (Herbig 1960). Accurate estimation of the ages and masses of these stars are required to understand the evolution and disruption time-scales of circumstellar disks/envelopes in these stars. If these stars are associated with a cluster, then their properties can be estimated more accurately, as the values of distance, reddening and age of the cluster can be extended to the star. In this paper, we study a case, where two Herbig Be stars (LKH_α 201 and BD $+61^o$ 154') are found to be located within the field of an open cluster (NGC 225). A direct connection between them is thought to be unlikely since the cluster is estimated to have a turn-off age of 120 Myr (Lattanzi et al. 1991). On the other hand, the DSS image of the cluster field shows the presence of nebulosity suggesting a recent event of star formation in the cluster vicinity. This, along with the presence of two Herbig Be stars and a number of stars with H_α emission, in the cluster field suggest that the cluster may actually be young. The cluster does not have any red giants and hence the turn-off age estimation may be considered as unreliable. Thus it is necessary to re-estimate the cluster parameters. Subramaniam et al. (2005 & 2006) showed that it is important to combine the optical and NIR data of stars in young clusters to understand the star formation history of the cluster region. If there is any recent star formation in the region of NGC 225, then there could be more PMS stars in the cluster field, other than the Herbig Be stars. These PMS stars, even if they do not have prominent H_α emission, can still be identified by the presence of NIR excess. Thus, in this study we have re-estimated the parameters of NGC 225 by combining the optical and NIR photometry. We try to address the following questions: How old is NGC 225? Are the Herbig Be stars possible members of this cluster? Are these likely to be born out of the same star formation event?

2. Previous studies

NGC 225 is an open cluster situated at RA = 0h 43.4^m, DEC = $+61^o$ 47' (J2000.0) in the Cassiopeia constellation. When Caroline Hershel discovered this cluster in 1784, her brother William included it in his Catalog as H VIII.78. This cluster is also known as Sailboat Cluster. It has a visual magnitude of 7.0. Hoag et al. (1961) obtained photoelectric and photographic photometry of stars in the filed of the cluster. Lattanzi et al (1991) studied this cluster and estimated its parameters. They measured proper motions of 289 stars, out of which, 28 are found to be members of the cluster. The cluster NGC 225 is found to be at a distance D= 525±73 pc, young (120 Myr), having a colour excess of $E(B-V)$= 0.25±0.08, moderately obscured and with a marked differential reddening. The ratio of total to selective visual extinction was found to be R_v= 4.9±1.3. The value $R_V \sim 3.1$ - 3.2 applies to the diffuse interstellar medium, whereas, a value of ~ 5 is more appropriate for the outer cloud dust situated in those more obscured regions around molecular clouds. The average value of $E(B-V)$ is found to be 0.26 ± 0.14 mag. A runaway candidate has been identified in this cluster and a real deficiency of less massive stars seems to be present. They suggested that the differential reddening and the

large value of R_V is due to a dense dust strip crossing the cluster NGC 225. Even though they concluded that the differential reddening in NGC 225 is caused by dust between us and the cluster, and it is not due to the dust within, Lattanzi et al. (1991) suggested that one should rely on IR photometry, particularly KLMN bands to obtain a final answer. In this study, we take help of the 2MASS JHK photometry to understand the reason for the dust properties in the cluster.

In his study of spectra of Be and Ae type stars, Herbig (1960) found a B type star with emissions and nebulosity (BD $+61^o154$'; MWC 419) in the northwestern edge of the cluster NGC 225. This star was found to show H_α emission with P-cygni type of profile and it was also detected by IRAS, though the estimated flux is unreliable. Herbig (1960) mentioned that the cluster lies partly in a dust lane with faint extensions of nebulosity to the south and east of the star. The only evidence available at that time about its membership in NGC 225 comes from the proper motion of a number of stars in the region determined by Lee (1926). Though the results of Lee (1926) have to be taken with some caution, it was found that the proper motion of MWC 419 does not differ markedly from those of many cluster stars. On the other hand, Lattanzi et al. (1991) considered this star as a field Be star. Herbig (1960) obtained slitless spectra of stars within $22'$ of the above star and found 7 stars to have H_α line in emission. These stars are shown in figure 2 of Herbig (1960). It can be clearly seen that stars with H_α emission surround the cluster. Nebulosity can be seen towards the north of the cluster. All these suggest that the cluster region has experienced a recent star formation and the cluster seems to be surrounded by very young stars. If the cluster is also part of this recent star formation, the cluster should be very young. Recently Manoj (2004) estimated the age of some Herbig Ae/Be stars and one of the candidates studied was BD $+61^o$ $154'$. He estimated the age of this star to be 0.3 Myr. The 2MASS JHK photometry indicates that this star has considerable NIR excess (Manoj 2004).

LKHα 201 is another B2 Ve spectral type star near the field of the open cluster NGC 225. It is cataloged by Herbig and Bell (1988) as possible background Be star and rejected by The et al. (1994) as a Herbig Ae/Be star because of the absence of excess at FIR bands. This star was considered as a possible Herbig Be star candidate by Hernandez et al. (2004). They found that the star shows some characteristics typical of PMS stars. The emission at Hα, Hβ and Fe II have been observed in its spectrum. This star exhibits high reddening ($A_V > 5$) and an anomalous extinction law ($R_V > 3.1$) which would be expected if the star is embedded in a molecular cloud. On the other hand, this star and other two stars with H_α emission have been found to have proper motion larger than those for the cluster members.

3. Optical photometry of NGC 225

The UBV photographic (UBV)pg data for the cluster NGC 225 were obtained from WEBDA database (http://www.univie.ac.at/webda/). These are the data of 289 stars

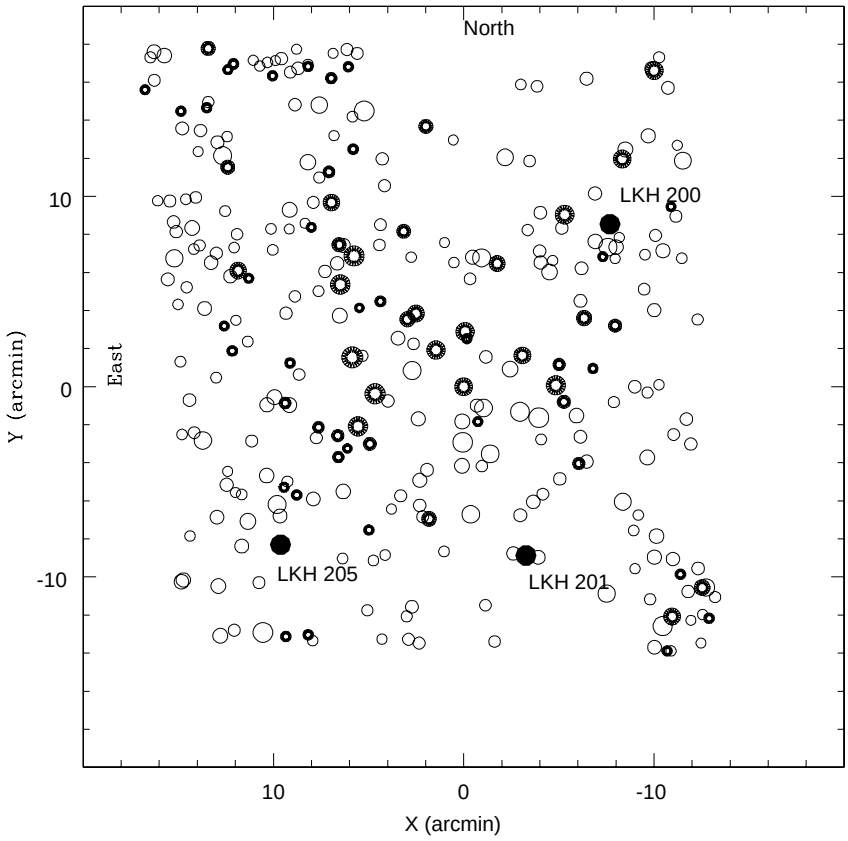

Figure 1. The observed region of the cluster NGC 225. Open circles with extra thickness are stars with NIR excess. Stars with H_α emission are shown as filled circles and are labelled.

published in Lattanzi et al. (1991). The cluster field for which optical data is available is shown in figure 1. There are 289 stars shown in the figure. The Herbig Be star, LKH_α 201 and other two stars (LKH_α 200 and 205) with H_α emission are shown as filled circles. Stars with NIR excess are shown with spikes. It can be clearly seen that stars with NIR excess are distributed all over the cluster field. The location of BD $+61^o$ $154'$ could not be shown in the figure as the X,Y position given in WEBDA does not match the location of this star in the finding chart of Herbig (1960). We have taken the photometry of this star from Lattanzi et al. (1991). Photometry is also available from Ponomareva (1983), where U,B,V magnitudes of 273 stars have been presented.

The colour-magnitude diagram (CMD) of all the 289 stars is shown in figure 2. A poorly defined and broad MS can be found in the CMD. Zero Age MS (ZAMS) is over

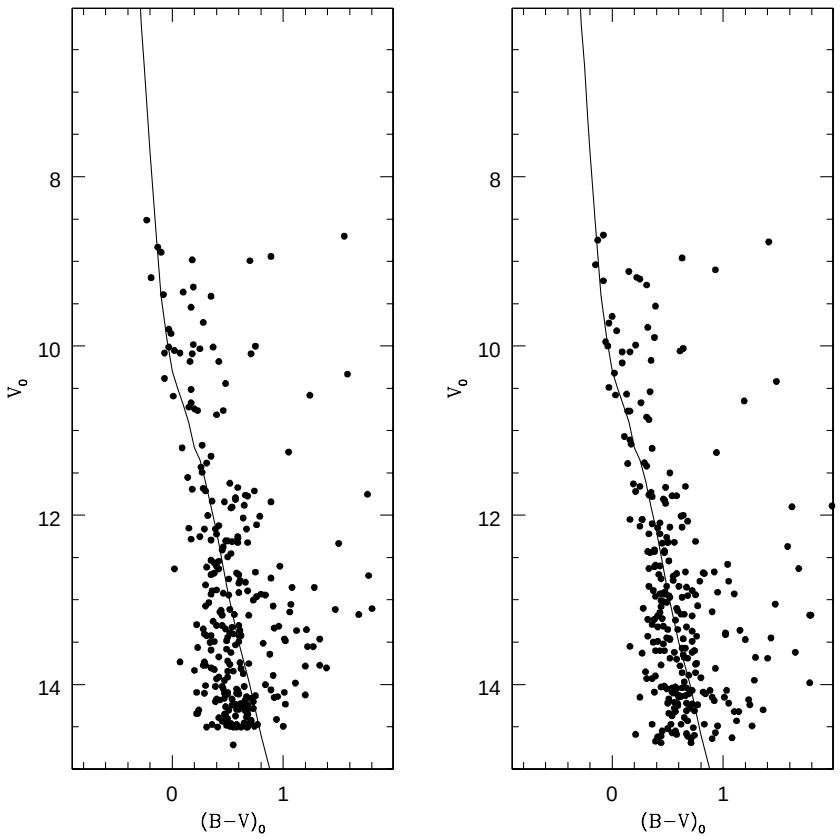

Figure 2. The reddening and extinction corrected CMD of 289 stars from Lattanzi et al. (1991) is shown in the left panel, whereas the right panel shows the same for stars from Ponomareva (1983), along with the ZAMS fitting. The estimated distance modulus is 8.8 mag from both the data sets.

plotted on the CMD, as shown in the left panel of figure 2. The CMD obtained from Ponomareva (1983) is shown in the right panel of figure 2. The reddening value of 0.27 mag (E(B−V)=0.27) is assumed as given in WEBDA. The reddening value of 0.29 is found to fit the right panel CMD, but is within the error of the estimation, that is, 0.02 mag. The value of A_V comes out to be 0.85 mag, assuming a value of 3.1 for R_V. After reddening correction, the main-sequence is fitted with the ZAMS (Schmidt-Kaler 1982) as shown in figure 2. The distance modulus is estimated to be 8.8 mag. This corresponds to a distance of 575 ± 120 pc. The distance to the cluster is estimated as $D = 525 \pm 73$ pc by Lattanzi et al (1991). Dias et al. (2001) estimated the parallax to some stars in the cluster using Tycho data. This was found to be 2.28 mas, which corresponds to a

distance of $\sim$ 440 pc. Dias et al. (2001) have found about 19 probable candidates in the cluster based on Tycho data, which is much less than the number of members found by Lattanzi et al. (1991). It can be seen the distance estimate to the cluster takes a range of values, basically because the cluster has very less number of stars. Though there are indications of a higher value of R_V in this region, as the evidences are non-conclusive, we use the value of 3.1 for this study.

4. JHK photometry and infrared excess

The optical data is cross-correlated with the 2MASS image to identify the common stars in both the data sets. We identified and obtained the NIR counterparts for 289 stars. Stars with errors less than 0.2 mag in J,H,K are considered for this analysis. Thus the J, H, K magnitudes were combined with the present (UBV)pg for the stars. The (J−H) vs (H−K) colour-colour diagram is plotted as shown in figure 3. The location of Be stars, Herbig Be stars, along with the location of MS stars, giants and T-Tauri stars are indicated in the figure. A prominent feature seen is the presence of a large number of stars showing NIR excess. These stars are located below the T-Tauri location (dashed line) indicating that these stars are more massive and probably belong to the class of intermediate mass PMS stars. In order to group these stars, we have shown the typical location of Be stars (Dougherty et al. 1994) and Herbig Ae/Be stars (Hernandez et al. 2005). The star 4012 (LKH$_\alpha$ 201) belongs to the location of Herbig Ae/Be stars. We plotted stars with NIR excess in the optical V vs (B−V) CMD and these stars are found to be scattered in the CMD. Also, the ZAMS was found to pass through many of the bright NIR stars. This indicates that no clear main sequence can be defined for the cluster. Lattanzi et al. (1991) found 28 stars to be cluster members, based on proper motion data. After combining the NIR data, it was surprising to find that 15 stars were found to have NIR excess, among the 28 member stars. These stars are shown as bigger dots in figure 3. Thus, more than 50% of member stars in the cluster have NIR excess, suggesting their PMS status. This clearly shows that the cluster is very young. The CMD with only cluster members is shown in figure 4. Stars with NIR excess are shown as dots. It is evident that all stars in the upper MS have NIR excess. This suggests that all these stars are still in the PMS phase. Thus the upper MS of the cluster as seen in the CMD may only be an approximate sequence and not the true MS. In this context, the age given in Lattanzi et al. (1991) seems to be over estimated (turn-off age of 120 Myr). The turn-off age may be unreliable due to the absence of red giants in the cluster.

Stars with H$_\alpha$ emission and the two Herbig Be stars were found to have NIR excess. The star LKH$_\alpha$ 201 is found to be located within the Herbig Ae/Be box, confirming its nature of being a Herbig Be star. Stars LKH$_\alpha$ 200 and 205 are located just outside the box and closer to the T-Tauri line. The location of BD $+61^o$ $154'$ is peculiar. This star occupies the right extreme of the figure, but above the T-Tauri line. A large circumstellar reddening due to the nebulosity around the star could be the reason for its peculiar

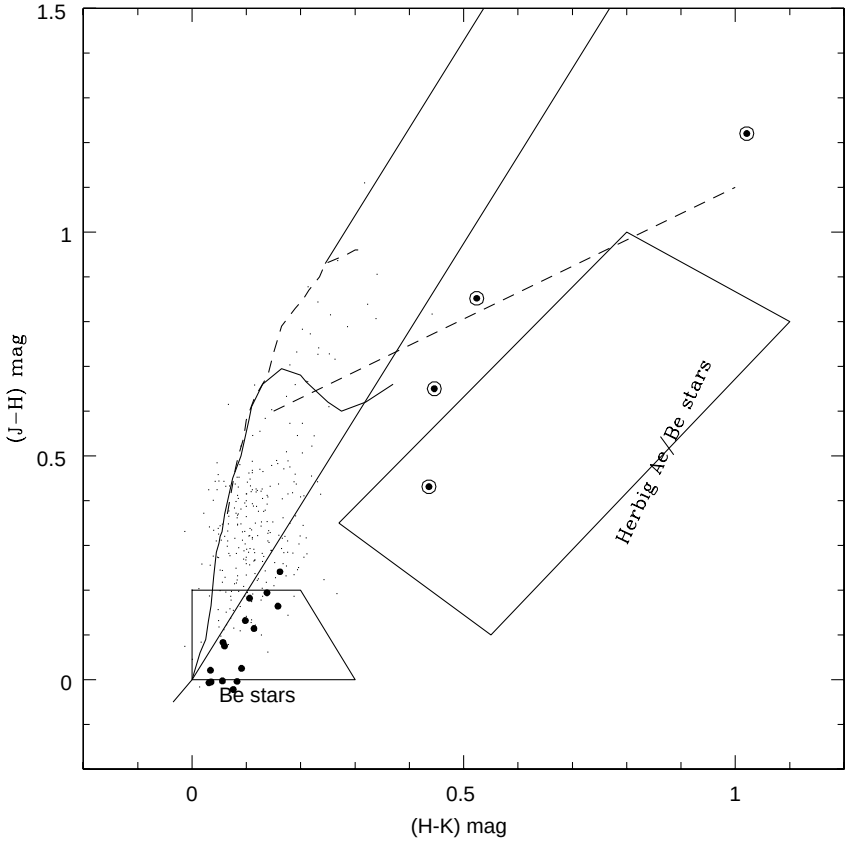

Figure 3. The NIR colour-colour diagram for stars in the region of the cluster is shown. The location of Herbig Ae/Be stars and classical Be stars are indicated. The bigger dots are cluster members with NIR excess. The encircled stars are LKH$_\alpha$ 201 (within the box of Herbig Ae/Be stars), LKH$_\alpha$ 200 and 205 (above and below the dashed line) and BD $+61^o$ 154' (right most star, above the dashed line).

position. A better estimate of its reddening may be required to establish its actual position in the figure.

5. Estimation of turn-on age

The age of the PMS stars are determined by fitting theoretical PMS isochrones (Siess et al. 2000) to the CMD. The age as estimated from the PMS stars is known as turn-on age of the cluster. The PMS isochrones are fitted to the cluster CMD as shown in figure 5.

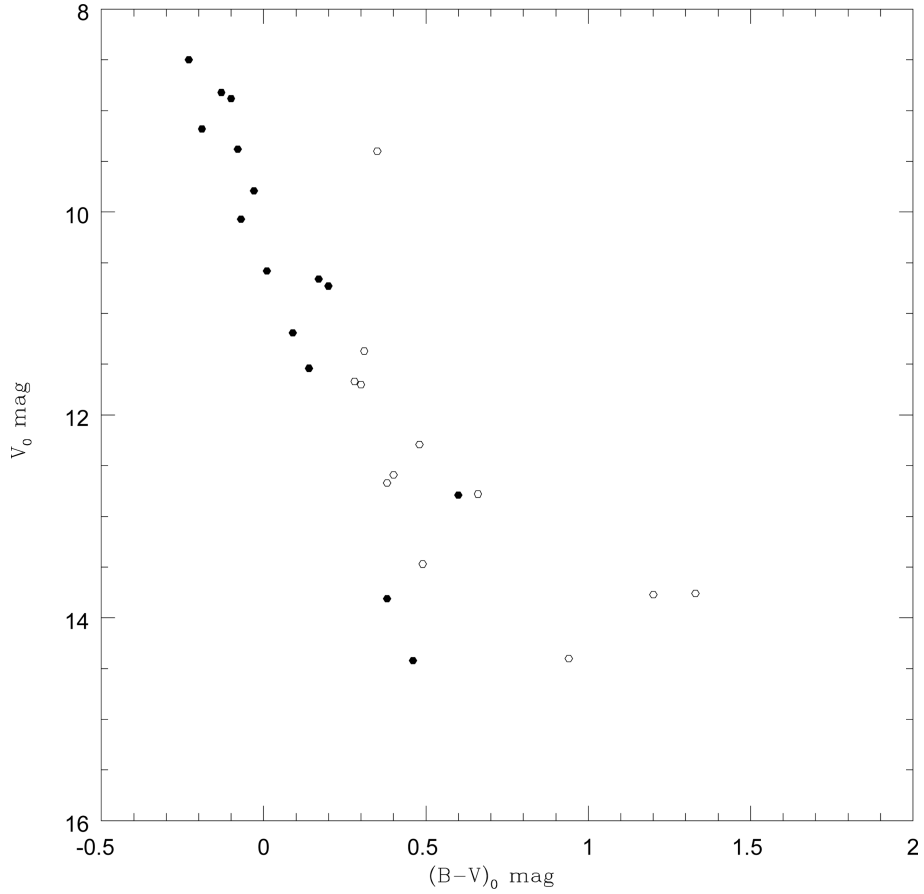

Figure 4. Of the 27 cluster members, stars with IR excess are shown as filled circles. This gives a clear indication about the inability to define a main sequence, which in turn leads to the fact that the cluster is young.

The isochrones for ages 0.5, 1.0, 1.5, 3.0, 5.0, 7.5 and 10 Myr are shown. It can be seen that the upper MS stars are found to have ages between 1- 10 Myr. Thus the brightest members of the cluster are found to be younger than the fainter members. The youngest member is found to be older than 0.5 Myr, indicating that the cluster is unlikely to be younger than 0.5 Myr. Also, there are no PMS stars older than 10 Myr, suggesting that the cluster is unlikely to be older than 10 Myr. Thus the PMS age or the turn-on age of the cluster is between 0.5 – 10 Myr. Thus the cluster is found to be very young, young enough to host PMS stars including Herbig Be stars, H_α emission stars and nebulosity.

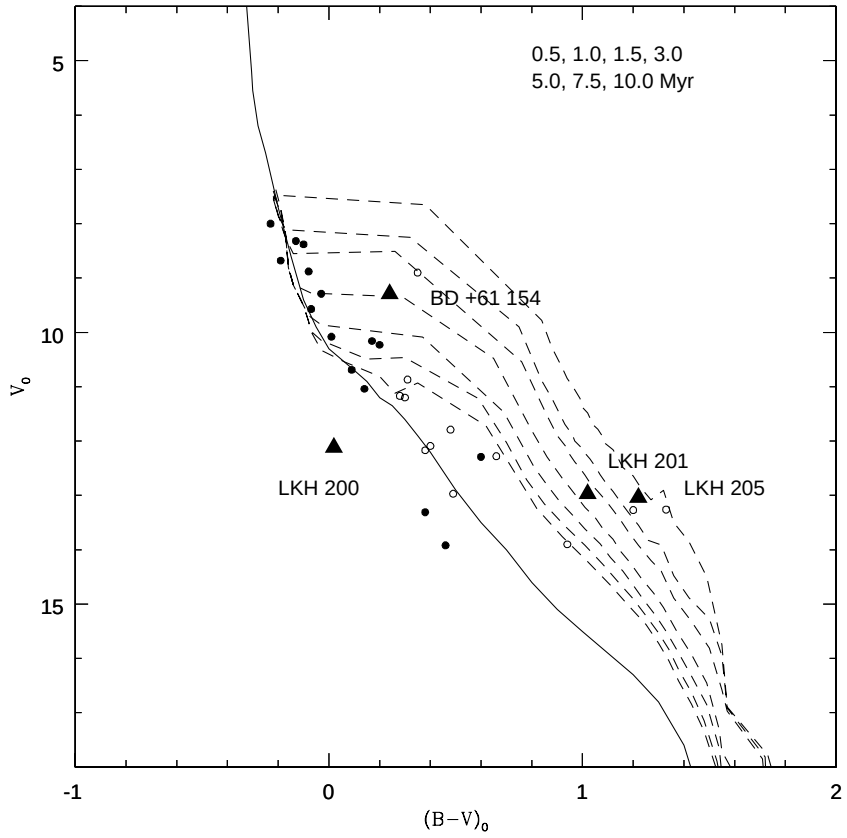

Figure 5. Pre-MS isochrones of different ages are fitted which gives the turn-on age of the cluster as 0.5 - 10 Myr. The ages of LkHα201 and BD $+61^o$ 154' is found to be 1.5 - 3.0 Myr. LKH$_\alpha$ 205 is estimated to be between 0.5 - 1.0 Myr. LKH$_\alpha$ 200 may be a foreground star.

6. Independent estimate of distance to the Herbig Be stars

The spectroscopic data for LkHα201(HBC 7) were taken from Hernandez et al. (2004). The FITS image of the spectrum in the range 3700 – 7600 Å is available from the web site (http://cfa-www.harvard.edu/youngstars/jhernand/haebe/principal.html). We used this spectrum to estimate the reddening towards the star. This spectrum was dereddened by comparing it with a standard spectrum of star of spectral type, B1.5, taken from Jacoby et al. (1984). From Lattanzi et al. (1991), the optical data of LkHα201(HBC 7) is taken as V=14.32, B−V=1.29. We estimated the colour excess for the star by spectroscopic matching in the blue region as $E(B-V) = 1.6 \pm 0.1$. Hence the value

of $A_V = 3.1 * 1.6 = 5.0$ mag. The extinction corrected magnitude is calculated to be 9.3 mag. The spectral type is found to be B2 from Hernandez et al. (2004) and the corresponding value of absolute magnitude for a star having the above spectral type is -1.9 mag. Therefore the distance modulus of the star is $10.9\pm$ 0.2. Large error in the estimation of distance modulus comes from the estimates of reddening. Thus a good estimate of distance to the star is not possible, but the estimated range is around 1500 pc. The distance to the star is found to be 850 pc from Hernandez et al. (2004). This star is more likely to be located behind the cluster.

The other Herbig Be star, BD $+61^o$ $154'$ is a brighter star and hence HIPPARCOS parallax is available as 3.34 ± 1.63 mas (Perryman et al. 1997). This corresponds to a distance of 300^{+285}_{-100} pc. Despite the large error, this Herbig Be star can be considered to be located at the distance of NGC 225. If we consider both the stars to be at the same distance as NGC 225, these stars can be placed on the cluster CMD so that their ages can be estimated. The PMS isochrones indicate that the age of both the Herbig Be stars lie between 1.5 - 3 Myr. We also tried to include the other two stars with H_α emission, in the cluster CMD. The age of LKH$_\alpha$ 205 is estimated to be between 0.5 - 1.0 Myr. LKH$_\alpha$ 200 is found to be located to the left of the MS, suggesting that this may be a foreground star. This indicates that three of the four H_α emission stars are very likely to have been formed along with the cluster NGC 225, especially since the cluster is found to be very young (1 - 10 Myr), instead of 120 Myr.

7. Conclusion and Discussion

The open cluster NGC 225 is studied using optical (UBV) and 2MASS (JHK) photometry to detect the presence of possible PMS stars in the cluster region. 15 stars out of 28 stars ($\sim$ 54% stars), identified as proper motion members, are found to show IR excess. Most of the upper MS stars are found to show IR excess. The first conclusion is that the brighter stars have not yet reached the MS. The sequence seen in the CMD is not the true MS, could only be considered as an approximate MS. The PMS isochrone fitting indicates that the turn-on age lies between 0.5- 10 Myr. Thus the main result of the study is that the age of the cluster NGC 225 is not 120 Myr, as previously estimated by Lattanzi et al. (1991). This study again shows that it is important to combine the optical and NIR data to estimate the parameters of young clusters. The age as well as the distance estimates make a possible association of two Herbig Be stars with this cluster, though the distance estimates to the cluster as well as the Herbig stars have large errors. The young age of the cluster also explains the presence of nebulosity and dust lanes near the cluster as well as the presence of stars with H_α emission. Assuming that the Herbig Be stars are part of this cluster, the age of LkHα201 and BD $+61^o$ 154' were estimated to be between 1.5 - 3.0 Myr. Therefore these stars are probably in the final stage of their PMS evolutionary phase.

A large number ($\sim$ 7) of stars are found to show H_α in emission in the vicinity of NGC

225. It will be interesting to find whether these stars also belong to the Herbig Be class by identifying these stars and studying their spectral and other properties. Their radial velocity estimates also might help in finding whether they belong to the same group.

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