A STUDY OF YOUNG OPEN CLUSTERS

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INTRODUCTION

Star clusters constitute a principal link between stellar evolution theory and the observable universe. The important constraints which can be imposed on the theory of star formation by studies of galactic open clusters are :

- The determination of duration of time over which star formation was active. This can be estimated from the spread in ages of stars in a cluster. This also tells about the disruption time of parent molecular clouds which effects the SFE.
- The determination of duration of epoch during which star formation in open clusters takes place, may provide clue to the problem: "which stars, high or low mass, form first".
- The nature of the MF over the entire region of the cluster and whether it is uniform or shows spatial variation.

Herbig (1962) was the first to speculate that star formation in open clusters might be significantly noncoeval. In Herbig's model, low mass stars form first in a cluster, and star formation continues quiescently in the molecular cloud untill some event triggers the formation of massive stars. The formation of massive stars disrupt the molecular cloud, causing star formation to cease. The time scale of star formation appears to vary from cluster to cluster, as estimated from the length of cluster main sequence. The work of Landolt (1979) and Stauffer (1980) confirms the discrepancy between the "nuclear age" of the Pleiades ($t_n \approx 7X10^7$ years), derived from high mass stars and the "contraction age" ($t_c \approx 2.2X10^8$ years), derived from the photometry of the low mass Pleiades members. Apparently, low mass stars began to form before the appearance of massive stars. In NGC 2264 and 6530 it appears that stars are formed sequentially in mass over a period of 10^7 years (cf. Iben and Talbot, 1966; Adams et al., 1983). Stahler (1985) suggests that the popular idea that star formation has proceeded sequentially from the lowest to highest mass members in open clusters is a consequence of the assignment of pre-main sequence contraction ages to all member stars. However, he supports the basic concept of continuous star formation. Some recent works (cf. Elmegreen and Clemens, 1985; Pandey et al. 1990) have also concluded that the average formation time of a bound cluster may be as large as 10^8 years.

The above discussions indicate that further study of star formation processes in young open clusters, where cluster members have been identified using the proper motion data, would be desirable. To address the aspects raised above, the most suitable objects are moderately young clusters (having age $\approx 5X10^7$ yr). Moderately young clusters are also well suited for studies of the IMF, because their ages being less than the dynamical evolution time (10^8 years) and it is unlikely that a significant number of stars could have escaped from the clusters. In the present work an effort has been made to address the above mentioned aspects of star formation in a few moderately young open clusters. The photometric data of the open clusters used in the present study have been taken from the catalogue of Myakutin et al. (1984).

COMPARISON OF THE INNER AND OUTER CLUSTER REGIONS

(a) HR Diagrams: The boundaries of the clusters have been defined by the locations of the observed member stars in each cluster. Each cluster was then divided into two regions with the criteria that r_{inner} : r_{out} = 1:5 unless mentioned otherwise. HR diagrams of inner and outer regions for each cluster are shown in figure 1. ZAMS was fitted for the entire region. Age estimates for bright MS stars have been obtained using the isochrones given by Barbaro et al. (1969). The pre-main sequence theoretical isochrones have been determined from the models of Iben (1965).

NGC 6913: The HR diagram for the nucleus shows that most of the stars are either evolved or on the ZAMS. However, there are few stars whose position in the HR diagram suggest that they are still in the

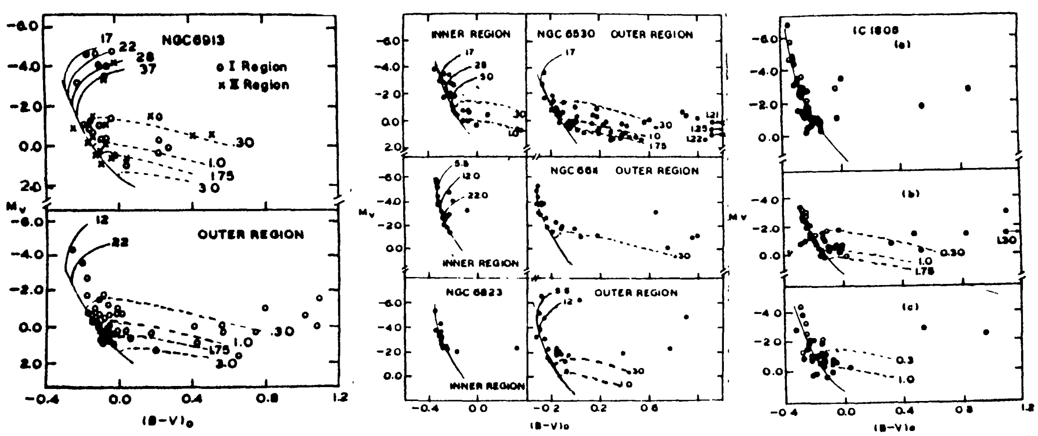

Fig. 1. HR diagram for the cluster members in the inner and outer regions of the clusters. The ZAMS, post MS and PMS isochrones (ages in million years) are also shown.

contraction phase. Evolved stars suggest an age estimate of about $3X10^7$ years. Outer region stars show a well defined main sequence for relatively less bright stars. HR diagram manifests that a large number of stars are still on pre-main sequence (PMS) stage. Theoretical isochrones for the PMS evolution suggest a distribution in the ages of cluster members from 0.3 to $2X10^6$ years. From the HR diagram of coronal stars we find evidence for evolved stars indicating an age of $2X10^7$ years.

NGC 6611: Stars in the nucleus show a well defined main sequence upto Mv $\approx$-1.4 mag. None of the cluster member is in PMS stage. Bright stars indicate an age of $\approx 2X10^6$ years for the cluster. There are very few stars in the coronal reigion. However,the length of main sequence is approximately same as for stars in the nucleus. HR diagram for coronal stars also shows evidence for PMS evolution. Stars having contraction time $t_c \approx 0.3X10^6$ yr are still in the contraction phase.

NGC 6823: The HR diagram of the nucleus shows a well defined upper main sequence. The noticeable feature in the HR diagram of the nucleus and coronal region is that only coronal region shows an evidence for evolved stars and the most massive star is situated in the outer region of the cluster which suggests an inverse mass segregation. This has been discussed in ensuing section. Brighter stars in the coronal region indicate an age of $6X10^6$ yr, whereas PMS stars having $t_c \approx 0.3X10^6$ yr and probably less than this also, are still in the contraction phase.

NGC 6530: The HR diagram of the nucleus manifests that most of the stars are on the MS. If we consider that bright stars having Mv$\sim$ -3.3 mag are evolving off the ZAMS, the age of the cluster comes out to be approximately $2X10^7$ yr. However, Sagar and Joshi(1978) have expressed view in favour of absence of turn off point and assigned a lower limit of $2X10^6$ years for the age of this cluster. A few less massive stars in nucleus show that these are in the contraction phase. The HR diagram of coronal stars indicates that only a few stars are on MS whereas a large number of stars are in the PMS stage having $t_c \approx 0.3X10^6$ yr to $2X10^6$ yr.

IC 1805: This is a large and rich cluster therefore, we have divided it into three regions having radii r1:r2:r3 = 2:4:5. The HR diagram of the innermost region shows a well defined main sequence (MS). There are four stars whose position in the HR diagram is peculier on the basis of stellar evolution. The possibility that these stars are field stars can not be ruled out. The position of only one star in the HR diagram suggest that it is still in contraction phase. Two other clusters NGC 6530 and NGC 6913 also show that a few less massive stars in the nucleus are still in contraction phase. In our notion these stars are located in the outer regions of the clusters which lie in the line of sight of the observer and thus contaminating the sample of inner region. The outer regions also show a well defined lower main sequence. In the outer regions stars having $t_c \approx 0.3X10^6$ yr are still in the contraction phase. The HR diagram of the IC 1805 suggests that some stars in the outermost region are even younger than $0.3X10^6$ yr.

The HR diagrams discussed above indicates that the age of the bright stars is higher than the PMS stars in the outer region.

(b)Extinction: The reddening across all the cluster is found variable which indicates the presence of unprocessed gas and dust within the cluster. The presence of gas suggests a possibility that star formation might still be taking place in these clustres. Extinction in NGC 6530 systematically decreases with increasing distance from the cluster centre while in NGC 6611 extinction is maximum in the nucleus and constant in the outer regions. Other three clusters do not show spatial variation in extinction. Spatial variation of extinction has also been studied in other young open clusters which suggests that most of the clusters do not show any statistically significant spatial variation, i.e., extinction is rather constant throughout the cluster

(c) Mass function: In a few open clusters mass segregation, i.e., massive stars tend to lie near the cluster centre is an established fact (Sagar et al. 1988, and the reference therein). A casual look into the HR diagrams of inner and outer regions of the clusters also indicates that generally massive stars are located in the nucleus. The spatial variation of mass function in young open clusters has been studied by dividing the cluster region into two or three concentric regions depending upon the total number of stars in the cluster so that each region has generally more than 20 stars. The cumulative mass function has been constructed for each cluster by counting the number of stars, N, having masses within the limit of the mass interval, M, and using the relation

$$\log N = -x \log M + \text{const},$$

where, x is the slope of the cumulative mass function. Assuming normal error distribution, statistical significance levels (in %) for difference in the values of x for regions 1 and 2 have been obtained. Except for NGC 6611 and 6823, the statistical confidence level is above 98% in other three clusters. The variation of mass function with the radial distance for each cluster is shown in figure 2, which indicates that the slope of the mass function is steeper in the outer parts of the open clusters except for NGC 6823, which suggests a preferential concentration of massive stars towards the centre than the outer regions of the clusters. The open clusters NGC 6611 and 6823 do not show statistically significant diference in the slope of mass functions for

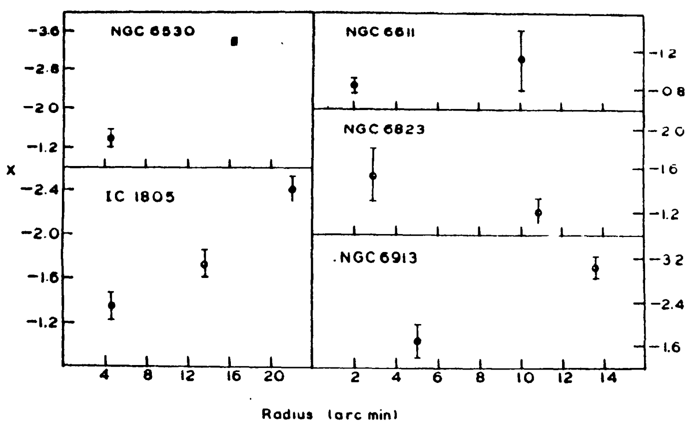

Fig. 2. The spatial variation of mass function in young open clusters.

the inner and outer regions. A possible reason for this could be the completeness limit of the present data (~8 $M_\odot$) in both the clusters.

It is interesting to note that Burki (1978) has found that massive stars ($M>20\ M_\odot$) are formed with lesser degree of central concentration than less massive stars ($20>M/M_\odot>4$) and it is also concluded that the slope of the mass spectrum is steeper in central regions than outer regions of the newly formed clusters. Pandey et al. (1991) have concluded that the results obtained by Burki (1978) do not represent the true spatial variations of mass function in open clusters because his results are based on a small region of clusters. We feel that the results obtained by Pandey et al. (1991), which have been derived from a large region of the clusters, are expected to give a better picture of the spatial variation of the mass function.

DISCUSSION

In the present study of a few young open clusters following aspects have emerged out :

(1) The distribution of the PMS stars in the HR diagram of outer region of the clusters indicates that these stars are significantly younger than the upper main sequence stars.

(2) The lack of concentration of unused gas in the cluster centre.

(3) The slope of the mass function in the outer region of the young open clusters is significantly steeper, which suggests a preferential concentration of massive stars towards the centre than the outer region of the clusters.

A plausible explanation for the above stated conclusions (i.e., 2, 3) may be that as massive stars were formed at the centre, a shock front would have been dissipated outwards. The advancing H II gas could have disrupted small condensations at the centre ($\approx 1\ M_\odot$ easily) before gravitational collapse ensued. The more massive condensations have greater likelihood of being pushed into gravitational collapse by the excess pressure of the H II gas. Thus after the shock front passes, we are left with a lower concentration of small mass stars than large mass stars in the cluster centre (cf. Moffat 1971, and the references therein).

Present work supports the concept of continuous star formation However, it does not support the concept of sequential star formation for the entire cluster. The fact that there is a lack of concentration of gas in the centre and the PMS stars in the outer region of the clusters are relatively younger, suggests that initially star formation takes place in the inner region of the cluster. It is possible that the formation process for less massive stars might have also triggered in the entire cluster region. The statement that low mass stars tend to form first is still valid in a statistical sense since production is heavily weighted towards lower masses. The HR diagrams of inner and outer regions manifest that the formation of less massive stars in the outer regions does not cease even after formation of most massive star in the cluster as is generally believed in sequential star formation process. Stone (1988) in case of NGC 6823, has suggested that the cluster might have experienced atleast two stages of stellar formation, namely, that the nuclear and bright coronal stars were formed some $2X10^6$ years ago, and a second generation of young stars was formed in corona some ~ $0.5X10^6$ years ago.

Since the dynamical relaxation time is always larger than the age of these clusters (Sagar et al. 1988), it is inferred that the observed mass segregation might have taken place at the time of cluster formation. This conclusion is in agreement with the findings of Larson (1982) and Sagar et al. (1988).

ACKNOWLEDGEMENT

AKP is thankful to the Department of Science and Technology (India) and the Organizers for providing grants to attend the Workshop. AKP is also thankful to Drs Roberto C. Dolcetta and Paolo Battinelli for reading manuscript critically and for their useful suggestions and to Dr. Hans Zinnecker for extremely useful discussions. Finally AKP is also thankful to Dr. M.C. Pande, Director, U.P. State Observatory for giving an oppprtunity to attend the Workshop.

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