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Open Star Clusters: Star Formation and Structure

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Abstract. Observational evidences indicate that the formation of open star clusters has been efficient throughout the life of our Galaxy. As a consequence, we find open clusters with ages ranging from a few Myr to few Gyr. This makes open clusters natural laboratories where we can test the theory of star formation and stellar evolution. Study of young open clusters indicates that the star formation in a few clusters is non-coeval and the star formation efficiency depends on the IMF. Our work supports the existence of corona around open clusters. The coronal regions in bound open clusters are dynamically stable in the tidal forces of the Galaxy.

1. Introduction

Star clusters are groups of dynamically associated stars presumably created from the same molecular clouds at about the same time. All the cluster members are therefore located at the same distance, have same primordial chemical composition and move together in the gravitational field of the galaxy. The nucleus (contains relatively bright and massive stars) and the corona (generally contains faint stars) are two main regions in open clusters.

The majority of stars in our galaxy are formed in giant molecular clouds. The theories based on current observations indicate that stars form in a cluster as a result of large scale gravitational instability developed in the central region of the molecular clouds. Instability leads to collapse and breaking into pieces of original clouds. Each sub unit subsequently suffers further collapse and fragmentation leading to the birth of a group of proto-stars within the cloud known as a Star Cluster. The matter converted into stars is known as the Star Formation Efficiency (SFE). The distribution of stellar mass just at the termination of the fragmentation process is known as the Initial Mass Function (IMF). The mass function is often expressed by the power law, $N(\log m) \propto m^{\Gamma}$ and the slope of the mass function is given as:

$$\Gamma = d \log N(\log m)/d \log m$$

where $N(\log m)$ is the number of stars per unit logarithmic mass interval. The value derived by Salpeter (1955) for the slope of IMF in the solar neighbourhood is $\Gamma = -1.35$.

Studies indicate that the probability of formation of gravitationally unbound clusters in our Galaxy is quite high because star formation is a destructive and inefficient process (Lada et al. 1984). However the existence of about 115 gravitationally bound open clusters within 1 Kpc of the Sun having a typical life time of about 100 Myr (Pandey and Mahra, 1986, Battinelli and Capuzzo-Dolcetta, 1991), leads to an interesting problem for star formation studies. The formation of a bound cluster system can be explained on the basis that the molecular clouds from which these are formed are either dispersed slowly after the appearance of the cluster, or the clouds must attain a star-formation efficiency of about 50% if the cloud dispersion is sudden (Elmegreen 1983, Lada et al. 1984). Lada et al. (1984) have theoretically obtained that molecular clouds with SFEs >21% can produce bound open cluster systems if the gas removal time 'τ_g' is considered to be about 5 Myr.

2. Gas Removal Time 'τ_g'

It is believed that the molecular cloud regions are the birth places for star clusters as young stellar systems, e.g., the stars in the molecular clouds in ρ Ophiuchus, heavily obscured cluster members in Ara, stars in the clusters NGC 2024 and NGC 3603 are still embedded in dust and gas clouds and it is assumed that with time the gas and dust in these clouds will either be used up in star-formation processes or will be dispersed away by radiation pressure due to massive stars present in these systems. Therefore, in young open clusters (age< 100 Myr), the presence of a variable amount of unused gas is expected within the open clusters and consequently non uniform interstellar extinction is observed in such clusters. This property of open clusters was used by Pandey et al. (1990a) to study the gas removal time τ_g, which is the timescale over which the unused gas is removed from the vicinity of newly formed stars. From the age dependence of differential extinction, $\Delta E(B-V)[= E(B-V)_{\mathrm{max}} - E(B-V)_{\mathrm{min}}]$, Pandey et al. (1990a) found that the differential extinction shows a systematic variation with age and the gas removal time may be ~ 50 Myr. However, Leisawitz et al. (1989) concluded that clusters older than ~ 10 Myr do not have associated with them molecular clouds more massive than a few times $10^3 M_\odot$.

3. Star Formation Efficiency (SFE) and Age Spread

Since gas removal from the cluster region is a slow process, it is reasonable to assume that young clusters having age ~ 20 Myr may not have lost a significant amount of gas from the system. Using a sample of 11 young open clusters (age ~ 10 Myr) Pandey et al. (1990a) estimated the mass of the gas 'M_{gas}' present in the clusters. The total mass of the stellar content, 'M_*', has been obtained by summing up the masses of individual stars of the cluster. The SFE, defined as $\frac{M_*}{M_* + M_{\mathrm{gas}}}$, obtained for the clusters and it is found that 50% of the clusters which are formed from clouds having masses $\leq 10^4 M_\odot$ are bound cluster whereas most of the clusters formed from clouds having masses $\geq 10^5 M_\odot$ will be unbound (Pandey et al. 1990a). This confirms the findings of Elmegreen (1983) that bound clusters are formed in low-mass clouds (M$\leq 10^4 M_\odot$), where the star formation efficiency is high (Elmegreen and Clemens 1985, Pandey et al. 1990b), while the unbound OB associations are formed in clouds having higher masses ($M > 10^5 M_\odot$).

SFE in a protocluster is a highly time dependent quantity namely the integral of the formation rate upto a given time, if star formation is still going on (cf. Pandey et al.1990b, Zinnecker et al. 1993). Elmegreen & Clemens (1985) and Pandey et al (1990b) found that SFEs are relatively higher in low mass clouds than in high mass clouds. Pandey et al. (1990b) also found that the SFE increases systematically with the slope of the mass function and steeper mass functions favour the formation of bound clusters.

The observed space density of low mass clouds is higher than the cluster- formation rate, which suggests that either low-mass clouds do not form bound clusters or cluster formation time per low-mass cloud exceeds 100 Myr (Elmegreen and Clemens 1985). Elmegreen and Clemens (1985) found that the ratio τ/f of mean timescale for cluster formation, τ, and the fraction f of the total number of clouds that produce bound clusters is ~1000 Myr. Therefore, if 50% of the clouds having mass $\sim 10^4 M_{\odot}$ produce a bound cluster, the value of τ comes out to be 500 Myr.

In the literature we find several observational evidences which support non-coeval star formation in open clusters. The CMD of Pleiades reveals low mass ($< 2M_{\odot}$) stars on the zero-age-main-sequence (ZAMS), despite the fact that their contraction time is much larger than the nuclear burning time of higher mass stars that dominate the cluster (Herbig 1962). Landolt (1979) and Stauffer (1980) also concluded that star formation in the Pleiades cluster has been a continuous process for about 100 Myr. Siess (1997) also found that the morphology of synthetic CMD of the Pleiades can be better reproduced by invoking an age spread of about 30 Myr.

The distribution of stars in the CMD of NGC 7654 indicates that the star formation within the cluster is not coeval and has an age spread ~50 Myr (Pandey et al. 2001). The CMD of NGC 663 (Pandey et al. 2003a) shows that the low mass ($\sim 1M_{\odot}$) stars, which have a contraction time ~50 Myr, are on the MS despite the fact that the cluster has a post-main-sequence-age ~25 Myr. The CMDs of a very young cluster NGC 3603 (Pandey et al. 2000) indicate that most of the massive stars have just evolved away from the ZAMS and that majority of stars have age ≤1 Myr. Still, there are several stars whose age is as high as 5 Myr or more. However, we find some stars on the right side of the lower part of the ZAMS. Eisenhauer et al. (1998) have derived an age of 0.3-1.0 Myr for these stars, which then are non-coeval with the majority of high mass member.

Now the question arises, which stars form first ? In a recent study of NGC 7654 (Pandey et al. 2001), we found that star formation took place sequentially in the sense that low mass stars formed first. The star formation history in the clusters NGC 7654 and NGC 663 (Pandey et al. 2003a) supports the conventional picture of star formation in cluster where 'low mass stars' form first and star formation continues over a long period of time. The star formation within the cluster terminates with the formation of most massive stars in the cluster. In the literature we find several observational supports for the conventional theory, including the study of Pleiades by Herbig (1962) and NGC 3293 by Herbst & Miller (1982).

However, this conventional scenario is in contradiction with some recent observations (e.g., NGC 3603, Pandey et al. 2000; NGC 6611, Hillenbrand et al. 1993; several cluster and OB associations, Massey 1995) which showed that star formation does not cease after the formation of most massive stars in the cluster .

4. Radial Structure

The nucleus and the corona (the extended region of the star clusters) are two main regions in open clusters (Kholopov 1969). The nucleus region of clusters contains relatively bright and massive ($\geq 3M_{\odot}$) stars and consequently it is a well-studied region of the clusters. However, the coronae of star clusters, which generally contains a large number of faint stars, has not been studied in detail. In fact the spatial distribution of these faint and low mass stars ($\leq 1M_{\odot}$) defines actual boundary of the clusters. Consequently coronal regions have very important bearing on studies related to the MF, the structure and evolution of open clusters. Observations of low mass stars (M $\leq 1M_{\odot}$) in the coronae are of critical importance in determining the true shape of the cluster MF (Scalo 1998). From a sample of bound open clusters we found that the corona of these clusters is dynamically stable in the tidal forces of the galaxy (Pandey et al. 1990a). In a recent study of 38 open clusters we further confirm the presence of corona around open clusters and the coronal region of the clusters contain $\sim 75\%$ of the cluster members (Nilakshi et al. 2002). A detailed analysis of the structure of coronae of open clusters helps in understanding the effects of external environment like the galactic tidal field and impulsive encounters with interstellar clouds etc., on dynamical evolution of open star clusters.

Extensive studies of the coronal regions of open clusters have not been carried out so far mainly because of non-availability of photometry in a large field around open star clusters. In view of the above discussions we embarked on to carry out extensive studies of the coronal regions of star clusters using the 2K $\times$ 2K CCD mounted on the Kiso Schmidt telescope (Japan) which gives a $\sim$ 50 arcminute square field.

5. Mass Function

Studies of IMF of star clusters are important to constrain star formation theories and also to understand the early stages of evolution of star clusters. A fundamental question about the IMF is whether the shape of the IMF is universal in time or space. Scalo (1986) in a detailed review of IMF did not find any convincing argument to support a variable IMF. However after a period of twelve years, he cited much evidence against a universal IMF (Scalo 1998). On the other hand Kroupa (2001) and Sagar (2000) indicate a universal Salpeter type MF above M>1 $M_{\odot}$. Zinnecker et al. (1993) mentioned that in the low metallicity environment of LMC, there is a steeper IMF compared to the solar neighbourhood, however with a considerable scatter. Carigi et al. (1995) also suggested that low metallicity regions have proportionately more low-mass stars. On the other hand Massey et al (1995), from a comparison of Galactic and Milky Way OB Association/Clusters found no difference in the IMF slope, and they conclude that the formation of massive stars in clusters proceeds independent of metallicity.

The most important contribution to the studies of IMF in the last twelve years is the advent of CCDs. The CCDs combined with a moderate size telescope are giving deeper insights into low mass stars that can change the scenario of the IMF studies. One of the important studies was by Phelps & Janes (1993) who estimated IMF for eight clusters with age 10-70 Myr. The slope of the mass function they obtained varies from 0.4 to 1.8. However some of the clusters in their sample, as pointed out by Scalo (1998), do not cover a large area. Pandey et al. (1992, 2001) have found that the nature of mass function does not remain the same over the entire region of the cluster and the slope of the mass function steepens as the radial distances increase. Phelps & Janes (1993) have studied the mass function of the young open cluster NGC 663 in a $\sim 20 \times 20$ arcmin^2 region and concluded that the slope of the mass function is flatter than the Salpeter value indicating a lack of low mass stars in the cluster. Recently we have studied the cluster NGC 663 in detail using the 2K $\times$ 2K CCD mounted on the Kiso Schmidt telescope (Japan) and found that the cluster region has a radius $>$ 10 arcmin. For the core, corona and the whole cluster we find the slope of the mass function $\Gamma = 0.87 \pm 0.16, 1.71 \pm 0.25$ and 1.38 ± 0.22 respectively (Pandey et al. 2003b), which indicates that the cluster mass function is steeper in the outer region of the cluster. However the mass function for the entire cluster region is similar to the Salpeter MF.

6. Conclusions

1. Gas removal from the cluster region is a slow process. The average gas removal time must be $\sim$ 50 Myr. Bound clusters form in low-mass clouds ($M \leq 10^4 M_\odot$), while the unbound associations form in clouds having higher masses ($M > 10^5 M_\odot$).

2. The SFE is higher in low mass clouds. The SFE depends on the mass function. If the slope of the initial mass function is steeper, rich clusters with relatively high SFEs will be formed.

3. Star formation in a few young open clusters seems to be a continuous process for about 30-50 Myr.

4. Open clusters have extended regions (corona). The mass function is steeper in the coronal regions compared to that in the nucleus of the cluster.

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References

Battinelli P., Capuzzo-Dolcetta R., 1991, MNRAS **249**, 76
Eisenhauer F., Quirrenbach A., Zinnecker H., Genzel R., 1998, ApJ **498**, 278
Carigi L., Colin P., Peimbert M., Sarmiento A., 1995, ApJ 445, 98
Elmeegreen B.G., 1983, MNRAS **203** 1011

Elmeegreen B.G., Clemens C., 1985, ApJ **294**, 523
Herbig G.H., 1962, ApJ **135**, 736
Herbst W., Miller D.P., 1982, AJ **87**, 1478
Hillenbrand L.A., Massey P., Strom S.E., Merill K.M., 1993, AJ **106**, 1906
Kholopov P. N., 1969, SvA **12**, 625
Kroupa P. 2001, MNRAS **322**, 231
Lada C. J., Margulis M., Dearborn D., 1984, ApJ **285**, 141
Landolt A.U., 1979, ApJ **231**, 468
Leisawitz D., Bash F.N., Thaddeus P., 1989, ApJS **70**, 731
Massey P., Johnson K.E., De Giola-Eastwood K., 1995, ApJ **454**, 151
Nilakshi, Sagar R., Pandey A.K., Mohan V., 2002, A&A **383**, 153
Pandey A.K., Mahra H.S., 1986, Ap. Space Sci. **126**, 167
Pandey A.K., Mahra H.S., Sagar R., 1990a, AJ **99**, 617
Pandey A.K., Paliwal D.C., Mahra H.S., 1990b, ApJ **362**, 165
Pandey A. K., Mahra H.S., Sagar R., 1992, BASI **20**, 287
Pandey A.K., Ogura K., Sekiguchi K., 2000, PASP **52**, 847
Pandey A.K., Nilakshi, Ogura K., Sagar R., Tarusawa K., 2001, A&A **374**, 504
Pandey A.K., et al. 2003a, in preparation
Pandey A.K., Upadhyay K., Ogura K., Sagar R., 2003b, BASI (this volume)
Phelps R. L., Janes K. A., 1993, AJ **106**, 1870
Salpeter E.E, 1955, ApJ **121**, 161
Sagar R., 2000, BASI **28**, 55
Scalo J.M., 1986, Fundam. Cosmic Phys **11**, 1
Scalo J.M., 1998, in *The stellar initial mass function*, Proc. of the 38th Herstmonceux meeting, eds. G. Gilmore, I. Parry, and S. Ryan S.
Siess L., Forestini M., Dougados C., 1997, A&A **324**, 556
Stauffer J., 1980, ApJ **85**, 1341
Zinnecker H., McCaughrean M.J., Wilking B.A., 1993, in Protostars and Planet III, eds E. Lery and J. Lumine, Univ. Arizona Press p. 429