Star Clusters: Wonderful Tools to Study the Galactic Structure and Star Formation

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Abstract

The open star clusters are among the valuable objects in the Galaxy and are being used to analyze the large-scale properties of our Galaxy. Observational evidence indicates that the formation of star clusters has been efficient all along the life of our Galaxy. As a consequence, we find star clusters with ages ranging from a few Myr to the age of the Galaxy (few Gyr). This makes star clusters natural laboratories where we can test the theory of stellar evolution and star formation. All the relevant parameters like age, distance and interstellar reddening can be determined more accurately for star clusters than for single stars, therefore the star clusters are best tools to study the galactic structure. Determination of their mass function provides constraints on the theory of star formation in open clusters. On the other hand studies related to the spatial structure and stability of galactic open clusters help to understand the cluster formation processes in our Galaxy, since these depend upon physical conditions of the molecular clouds from which star clusters are formed. Some of the inferences obtained by us about galactic structure and star formation in open clusters are described here.

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.

Galactic (Open) Clusters contain from few tens to several hundred of stars, usually in an unsymmetrical arrangement. Four open clusters, the Pleiades and Hyades in the constellation of Taurus, Praesepe (the Beehive) in the constellation cancer and Coma Berenices have been known from earliest times.

Open clusters are strongly concentrated near the plane of the Milky Way. They form a flattened disk like system about 1000 light-year thick with a radius (around sun) about 15,000 light years. The linear diameter of open clusters ranges from ~75 light years to ~ 5 light years. In the center of each cluster, the stars may be only 1 light year apart. The density can be ~100 times that of the solar neighborhood. In a few open clusters, such as the Pleiades nebulosity is a prominent feature, which indicates that the parent molecular cloud is still associated with the cluster. These clusters show a large range in the masses of member stars ranging from ~80 M⊙ (in young clusters having age ~ 1Myr) to ~0.5 M⊙ in the oldest (age ~ 1000 Myr) open clusters.

Why Open Clusters are Important?

There are a number of reasons why open clusters are useful to study galactic structure and stellar evolution.
1. Distances can be determined more accurately for clusters than for single stars.

2. Young clusters contain luminous stars and thus can be observed at large distance.

3. Young open clusters are best traces of the youngest component of the disk.

4. Age estimates for clusters are better known than for single star.

5. Another fundamental parameter, interstellar reddening, is accurately measurable towards the direction of the cluster as compared to single stars.

6. Star clusters constitute a principal link between the theories of stellar evolution and observable universe. They provide template to test the theoretical stellar evolutionary models.

7. The older open clusters provide a measure of the minimum age of the galactic disk, whereas the younger open clusters provide an opportunity to study the star formation process in molecular clouds which are considered to be the birth places of star clusters.

Open Cluster and Galactic Structure

The study of the spatial distribution of interstellar matter is important for many investigations of galactic and extragalactic objects. A dust cloud can be recognized by the fact that the absorption, $A_V$, is higher behind the cloud than in front of it. Therefore, the distribution of reddening material can be obtained from the variations of $A_V$ with distance in different areas of the sky.

Since the distances and the interstellar extinction obtained from photometric observations of star clusters are more reliable than those from individual stars, we have used the interstellar extinction and distances of 462 star clusters to study the distribution of interstellar matter within a few kiloparsecs (1 parsec = 3.26 light years) of the Sun (Pandey and Mahra 1987).

The interstellar absorption $A_V$ in the galactic plane at 1 and 2 kpc is plotted as a function of galactic longitude in Fig. 1. The plots show a sinusoidal variation of absorption $A_V$ with galactic longitude. Maximum absorption occurs towards $l \sim 50^\circ$ and minimum towards $l \sim 230^\circ$.

![Fig. 1: Absorption $A_V$ at 1 kpc (left panel) and at 2 kpc (right panel)]
In Fig. 2 we plot the values of $z$ (the vertical distance of the objects from the formal galactic plane) for which the absorption is maximum as a function of longitude and we found that in the longitude range $l$~350º-130º the layer of maximum absorption lies above the galactic plane, while in the longitude range $l$~130º-350º the layer of maximum absorption lies below the galactic plane. The striking feature of figure is that the value of $z$ for which absorption is at a maximum, shows a sinusoidal variation with longitude with a symmetry around $z = -10$ pc and we can conclude that the Sun is situated about 10 pc above the plane of symmetry defined by the interstellar matter. Another conclusion drawn is that the plane defined by the interstellar matter is inclined to the formal galactic plane at an angle of 0.º8± 0.º2 and the upward tilt is maximum towards longitude $l$~60º.

**Fig. 2:** The plot of $z$, the distance from the galactic plane for which absorption is at maximum against the longitude.

Similarly, the distribution of young open cluster (Pandey et al. 1990a) shown in Fig. 3 indicates that the open clusters are unevenly distributed with respect to the formal galactic plane. The distribution of young open clusters also shows approximately a sinusoidal variation with galactic longitude. We find that (Pandey et al. 1990a) the young open clusters within 6 Kpc of the Sun define a plane of symmetry inclined to the formal galactic plane by an angle of 0.º3 ± 0.º1 and the upward tilt is maximum towards $l$~60º. The Sun is found to be situated at a distance of 20 ± 5 pc above the plane of symmetry defined by young open cluster.

**Fig. 3:** Running mean latitude, $b$, as a function of longitude. The error bars represent the standard error of the mean.

Distribution at right angle to the galactic disk indicates that the 99% of the open clusters are located within a distance of 290 pc of the plane of symmetry (Pandey et al. 1988).
The Role of Open Star Cluster in Star Formation History

Open clusters represent a large range in age from very young (~1Myr) to the age of the galaxy (~10000 Myr). An analysis of observed open cluster indicates that the number of clusters decreases with age. This has been attributed to a process of dynamical dissolution of clusters.

The majority of stars in our galaxy are formed in giant molecular clouds. The theories based on current observations indicate that stars form 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 leads to the birth of a group of protostar within the cloud known as star cluster. The distribution of stellar mass just at the termination of the fragmentation process is known as Initial mass function (IMF). The matter converted into stars is known as the star formation efficiency (SFE).

Recent 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 Myrs (Pandey and Mahra, 1986), leads to an interesting problem for star formation studies.

Young star clusters (age <100 Myrs) are found embedded in dust and gas clouds and it is assumed that with time the gas and dust in these clouds shall either be used up in star formation or shall be dispersed away by radiation pressure due to massive stars present in these systems. Therefore the presence of variable amount of unused gas and dust is expected inside the boundaries of young open clusters, consequently a non-uniform interstellar extinction is observed in such clusters. The gas removal time, the time scale over which the unused gas is removed from the vicinity of newly formed star and the SFE are the most important parameters which decide whether a newly formed star cluster will be bound or unbound system.

Because of remains of the parental molecular clouds in the young open clusters a non-uniform interstellar extinction is observed in such clusters. This property of star clusters was used to study the gas removal time and it was found that the gas removal time should be ~100 Myrs (Pandey et al. 1990c). If the gas removal time is as large as 100 Myrs, the clusters having SFEs ~15% may also produce bound clusters.

The Average Formation Time of a Bound Open Cluster

We found that 50% of the clusters which are formed from clouds having masses ~10^4 M☉ produce a bound cluster whereas most of the clusters formed from clouds having masses ~10^5 M☉ will be unbound (Pandey et al. 1990c). Elmegreen and Clemens (1985) found that the ratio \( \tau / f \) (the fraction of the total number of clouds that produce bound clusters) is ~10^9 years. Therefore, if 50% of the clouds having masses 10^4 M☉ produce a bound cluster, the value of \( \tau \) comes out to be ~5x10^8 years (Pandey et al. 1990b, c). Presence of non-coeval star formation in young open clusters, spread over 10^7 - 10^8 years, has also been indicated by Sagar (1985).

Recently we have studied an interesting cluster NGC 7654. The colour-magnitude diagram (CMD) of NGC 7654 is shown in Fig. 4. The distribution of stars in the CMD
indicates the star formation within the cluster is not coeval and has a large age spread (30 to 100 Myr) (Pandey et al. 2001). This gives observational support to our earlier work (Pandey et al. 1990c).

Now the question arises, which stars form first? In a recent study of the cluster NGC 7654 we found that formation of massive stars took place sequentially, in the sense that low mass stars formed first. The star formation history in the cluster NGC 7654 supports the conventional picture of star formation in clusters that 'low mass stars' form first and that star formation continues over a long period of time. The star formation within the cluster was terminated with the formation of most massive star in the cluster. In literature we find several observational supports for the conventional theory, including the study of the Hyades and Pleiades by Herbig (1962), which revealed low mass (< 2 M$_\odot$) 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 dominates these clusters. In the case of NGC 3293 Herbst and Miller (1982) also found 2 M$_\odot$ stars on or near the ZAMS with the presence of massive O stars in the cluster. However, this conventional scenario is in contradiction with some recent observations which showed that star formation does not cease after the formation of most massive star in the cluster (Hillenbrand et al. 1993, Massey et al. 1995, Pandey et al. 2000).

**Boundaries of Open Clusters**

The stability of open clusters in the Galaxy also depends upon its structure. Kholopov (1969) pointed out that clusters have two regions, the nucleus and the extended region known as corona. 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. 1990b). In a recent detailed study of 38 open clusters we further confirm the presence of corona around the open clusters (Nilakshi et al 2002).

The nucleus of the cluster contains relatively bright and massive stars, consequently nucleus is a well studied region of the cluster. However the coronae of star clusters, which generally contain large number of faint stars, have not been studied in detail. In fact the spatial distribution of these faint and low mass stars (~1 M$_\odot$) defines the actual boundary of
the clusters and consequently has an important bearing on the studies related to the IMF, the structure and evolution of the open clusters.

**Study of Coronal Regions**

Extensive studies of the coronal regions of the open clusters have not so far been carried out mainly because of non-availability of observations in a large area around open clusters. Now with a combination of charge coupled devices (CCDs) mounted on the Schmidt telescope, such extensive studies of coronae of star clusters are possible. Keeping importance of corona of star clusters in mind we embarked to carry out extensive studies of coronal regions using a large format (2K x 2K) CCD mounted on the Kiso Schmidt telescope (Japan) which gives about 50 arcminute square field. We have observed a sample 10 open clusters from the Kiso Schmidt. Detailed analysis of two clusters namely NGC 7654 and NGC 663 has been carried out which indicates presence of corona in both of the clusters.

The effect of mass segregation, in the sense that massive stars tend to lie near the cluster center whereas low mass stars occupy more extended distribution in the cluster, is observed in both the clusters. It is important to know whether mass segregation is an imprint of star formation or it is due to dynamical evolution of the cluster. If stars in a cluster have a uniform spatial distribution at the time of formation, then with time the dynamical evolution leads to equi-partition of kinetic energy in cluster members. This yields smaller velocities for massive stars and relatively larger velocities for low mass stars which ultimately changes the spatial distribution of stars in a cluster. The time required for the equi-partition of the energy is called dynamical evolution time. It is of the order of about 50 Myr for these two clusters. Since the age (~20 Myr) of the cluster NGC 663 is less than the dynamical evolution time, we conclude that mass segregation is an imprint of star formation in some open clusters (Pandey et al 2002).

**References**