FORMATION OF OPEN CLUSTERS

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I. INTRODUCTION

1. Summary of Star Formation

A forming star progresses through several evolutionary stages which are marked by different observational signs that can be identified by different techniques. Stellar birth from interstellar matter occurs in dense, cold clouds of gas due to a local increase in the density and interstellar clouds composed of molecules and grains are the preferential place where star formation can be initiated. The observational indications of this prestellar stage are the emission of millimeter radio waves by the cloud's many molecules and the optical obscuration of the background field stars by the grains mixed with the molecular gas. When fragmentation and condensation mechanisms occur in a dense cloud, the gravitationally collapsing fragments cannot be directly observed at visible wavelengths, because their light is blocked by the dust grains which heat up and radiate in the infrared. Thus the various protostellar stages are essentially studied using infrared techniques. Evidently, the spectral energy distribution of the protostars depends on their evolutionary stage and, globally speaking, one can say that the maximum of the infrared emission moves towards the short infrared wavelengths as the protostar evolves. A tentative coherent stellar evolutionary scenario may be given for the radio and infrared sources directly connected with the star and cluster formation:

1) molecular and dust cloud
2) hydroxyl and water maser sources
3) compact H II regions
4) luminous infrared sources, protostellar objects
5) infrared sources of lower luminosity, pre-main sequence stars still shrouded from view by the dark material

James E. Hesser (ed.), Star Clusters, 169–190.

6) pre-main sequence stellar objects, as the T Tauri stars (late F to middle M spectral types, $M \leq 2\ M_{\odot}$), the Herbig-Haro objects (T Tauri precursors?) or the Herbig Ae/Be stars (B1 to F8 spectral types, $2 \leq M/M_{\odot} \leq 8$).

Several recent reviews of star formation were published in the IAU Symposium No 75 held in Geneva in 1976. These papers give a general view of the scenario for star formation from molecular clouds to the zero-age main sequence.

2. Molecular Clouds, H II Regions, Young Open Clusters : An Overview

The principal constituent of the dense, cold clouds from which stars are formed is hydrogen in the diatomic molecular form. Unfortunately, direct determinations of the H_2 density in molecular clouds are difficult because of the lack of spectroscopic features of this molecule. However, a few dozen types of molecules have been discovered in the interstellar gas, and studies of the physical parameters of the clouds are possible using molecules such as CO, OH, CS, H_2CO, C_2H, HCN, etc. Carbon monoxide is by far the best for studying molecular clouds. Indeed, CO is several orders of magnitude more abundant than any other molecule observed in the radio region and is thus more easily detected than many other interstellar molecules. A good tracer for the molecular gas should correlate well with the invisible H_2, and an ideal tracer is obviously one whose density relative to H_2 is constant. Thaddeus (1977) reviewed the observational determinations of the CO/H_2 ratio in dark nebulae and dense molecular clouds and gave a representative value of $6 \cdot 10^{-5}$, which is not known to much better than a factor 3. However, determinations of this ratio in the solar neighbourhood (e.g. Encrenaz et al., 1975; Tucker et al., 1976) converge towards a value of $12 \cdot 10^{-5}$.

The radial distribution of CO in the Galaxy was established by Gordon and Burton (1976). They found that molecular clouds are concentrated in the $4 \leq R \leq 13$ kpc region of the Galaxy, i.e. in the region where spiral arms are developed. The maximum of the concentration is observed at R = 5.7 kpc. From this CO distribution, Guibert et al. (1978) have calculated the radial distribution of H_2 for three models bracketing the range of possible variations of the CO/H_2 ratio with the galactocentric distance. They found that the surface density of H_2 does not follow that of neutral hydrogen, i.e. hydrogen exists primarily in molecular form in the interval $4 \leq R \leq 8$ kpc. Because of the fact that star formation will essentially occur in molecular clouds, one can expect that star cluster formation will be particularly effective in the same galactocentric interval. This point of view is in qualitative agreement with the results by Serra et al. (1977). Their far infrared (115-196 μm) observations of the diffuse emission from the galactic plane are indicative of a larger star formation rate per unit mass of interstellar gas in the inner region of the Galaxy.

https://doi.org/10.1017/S0074180900091828 Published online by Cambridge University Press

The H II regions in our Galaxy, observed in both the optical and radio wavelength ranges, define a large-scale spiral structure in which the sun is located between two major arms, Sagittarius-Carina and Perseus (Georgelin and Georgelin, 1976). Small H II regions, like Ori OB1, are located between the main spiral arms and represent O-star formation in the interarm region (Mezger and Smith, 1977). As shown by Moffat and Vogt (1973), many young clusters and other young optical tracers (supergiants, Be-type stars, Wolf-Rayet stars, cepheids) are located in the interarm region between the Sagittarius and Perseus arms, suggesting that some recent activity of star formation was going on there (Wielen, 1973; Forte and Muzzio, 1976). Smith et al. (1978) identify three major regions of O-star formation: the main spiral arms, the regions between the main spiral arms and the region around the galactic center. By supposing that the ratio of low-mass stars to O-stars is the same everywhere in the Galaxy and that the rate of O-star formation is proportional to the number of Lyman continuum photons emitted by the ionizing stars of H II regions, they found that the present rate of star formation is 5 $M_\odot$/yr for the whole Galaxy, of which 74 % occurs in the main spiral arms, 13 % in the interarm region and 13 % in the galactic center.

Finally, note that the galactic region of good optical observability for the open clusters is up to 3 kpc from the sun, thus the cluster content of the galactic region of high formation rate ($4 \leq R \leq 8$ kpc) is poorly known. On the other hand, the nearest region of O-star formation is the Orion nebula located at 400 pc from the sun, and the nearest molecular cloud where B-star formation is detected (the Taurus dark cloud) is located at 140 pc from the sun. This means that direct observation of low-mass star ($M/M_\odot < 1$) formation associated with O- and B-star formation is extremely difficult. In any case, there is no physical basis for arguing that low-mass stars cannot form in the same regions where high-mass stars are formed (Evans, 1978).

II. MECHANISMS OF CLUSTER FORMATION

Star and cluster formation arise after collapse of a part of an interstellar cloud. The criterion for gas cloud collapse, in its simplest form, is known as the Jeans criterion: an isothermal spherical cloud is gravitationally unstable to collapse if its mass is larger than the critical Jeans mass $M_J \sim T^{3/2}\ \rho^{-1/2}$ where T is the temperature and ρ the density. The collapse may be <u>spontaneous</u>, resulting from the loss of some of the internal energy of the cloud, be it thermal, magnetic or turbulent in origin. The alternative category is <u>stimulated</u> collapse, which occurs if some external force alters the equilibrium of the cloud. Various compression mechanisms of interstellar clouds are invoked to trigger star and cluster formation, and they are reviewed in this section.

1. Galactic Spiral Shocks

The theory most widely accepted for the maintenance of large-scale spiral structure in galaxies is the density-wave theory developed by Lin and Shu. Interstellar gas streaming into the density wave spiral arms is compressed and star formation is initiated. According to the models by Roberts and Yuan (1970), the factor of compression decreases with increasing galactocentric distance, the value at the sun's distance being approximately 5 to 10. Mezger (1975) estimated that the efficiency of star formation through compression by density waves is about 1 %. Recently, Wielen (1973), Grosbøl (1977), Forte and Muzzio (1976) and Palous et al. (1977) have investigated the migration of young stars or clusters in a spiral field, in order to determine the places of formation and to check the density-wave theory. The results are that the majority of the young objects seem to be born in the spiral arms. But the youngest clusters studied by Forte and Muzzio and the youngest nearby cepheids studied by Wielen are born probably in the interarm region. The Grosbøl's models indicate that about 20 % of the stars studied (216 B0-A0 stars younger than $300 \cdot 10^6$ yr) were formed outside the arms. Note that the essential difficulties in these calculations are the errors in the ages and the kinematical parameters of the objects studied. Also the exact shape of the spiral pattern is not known.

Bash et al. (1977) studied the connection between the galactic density wave, the molecular clouds, star formation and open clusters. Their results are: 1) among 63 open clusters whose earliest stars range from O5 to B4, associated CO emission is detected only if the cluster contains main sequence O-stars (i.e. clusters younger than about 10^7 yr); 2) the terminal velocity (the largest positive radial velocity) of the CO line profiles over a large run of galactic longitude agrees with the value of the orbital velocities of ballistic particles 30 million years after their birth in the two-armed spiral shock wave. These two results agree with each other if about 20 million years elapse between the time an interstellar cloud passes through the spiral shock wave and the time stars begin to form in the cloud. Note that Woodward (1976) predicted a time scale of only 10 million years from shock-wave passage to star formation. In addition, Bash et al. derive a total number of clusters younger than 10 million years in the Galaxy ($2 \leq R \leq 16$ kpc) of $1.7 \cdot 10^4$ and an average surface density of open cluster birthrate in the galactic region $4 \leq R \leq 11.4$ kpc of $1.5 \cdot 10^{-12}$ pc^{-2} yr^{-1} (with an uncertainty of about a factor of 10).

2. Cloud-Cloud Collision

According to Loren (1976) and Loren and Vrba (1979), star formation may be triggered by the compression created by the collision between two separate molecular clouds. This idea comes from the study of NGC 1333, a complex reflection nebula embedded in a large dark cloud.

Optical and infrared studies of this cloud reveal several protostars, pre-main sequence or early-type stars (Strom et al., 1976b). Radio observations of the CO emission show two velocity components at 6.3 and 8.3 km/sec. The gas between the two clouds is compressed to a higher density and temperature than its surroundings. The prediction of a dense core in the region of overlap is supported by the detection by Lada et al. (cited in Loren and Vrba, 1979) of formaldehyde emission lines which are excited only at higher densities. Stars can be born from this compressed gas and it is possible that a chain of increasingly aged stars would be observed. The most recently formed are the most highly obscured stars, which are only observed as infrared sources, and the stars in the NGC 1333 nebulosity are older, formed earlier in the collision, and optically observed as a small cluster which illuminates the reflection nebulosity. Another possible example of cloud-cloud collision triggering star formation is an anonymous dark cloud in Cassiopeia in which is embedded the Ae star LkHα 198 (Loren, 1977). The mass estimates for the two colliding clouds are 440 and 250 $M_\odot$.

3. Shock by an Expanding H II Region

The Lyman continuum radiation from a group of OB stars existing in some part of a molecular cloud will dissociate, ionize and heat the neutral and molecular hydrogen via the propagation of ionization and dissociation fronts. The ionization front will move outwards and the heated gas will expand since the pressure in the surrounding cool gas is only 1 % of the pressure in the ionized region. This expanding shell crashes into the surrounding molecular cloud at a speed of about 5 to 10 km/sec, fast enough to create a shock wave which moves through the cool gas, compressing it (Spitzer, 1968). As the shock wave plows into the molecular cloud, it picks up material in a layer behind it. After a sufficient amount of material is accumulated in this thin dense layer between shock and ionization fronts, it may become unstable to gravitational collapse and the final disruption of the layer results in the exposure of a new cluster. Details of the gravitational collapse and fragmentation of compressed gas behind isothermal shock were given by Elmegreen and Lada (1977), Elmegreen and Elmegreen (1978b) and Nakano (1978). Recent observations were presented by Habing et al. (1972) on NGC 7538, by Mezger and Smith (1977) on the IC 1805-IC 1795 and Orion regions, by Elmegreen and Lada (1976, 1978) on M17 and NGC 281, and by Loren and Wooten (1978) on IC 1848.

4. Compression by an Expanding Supernova Remnant

The expanding shell of a supernova pushes ahead and collects in a compressed form the interstellar gas in its surroundings. When the accreted mass is sufficient, a new cluster could be formed by condensation and fragmentation (Öpik, 1953). According to Berkhuijsen (1974), the Ori-Gem Loop is a supernova remnant with a radius of 60 pc, shell thickness 20 pc and age one million years that may be the largest and oldest known SNR. Superposed on the ring, and at independently determined distances which are compatible with the distance of the ring, are five optically observed H II regions, including four in which the exciting stars have been identified as objects in the spectral range O7-B0.5. Herbst and Assousa (1977) studied the case of the CMa R1 association which is located on the outer edge of a ring of optical and radio emission having a radius of about 30 pc. These features can be explained as a SNR with an age of about $5\cdot10^5$ yr. On the basis of an optical and infrared study, Herbst et al. (1978) attribute an age of about $3\cdot10^5$ yr to the association. It is suggested by the authors that a supernova explosion has triggered the formation of these stars (the earliest star is a B0-type). The association presently observed should continue to reflect the expansion of the SNR and an accurate kinematical study should be done to test this formation hypothesis. An expanding neutral hydrogen shell in the direction of Cep OB3 was examined by Assousa et al. (1977). The expansion velocity, 35 km/sec, and the radius, 53 pc, imply that the feature is a SNR with an age of about $4.3\cdot10^5$ yr. The younger subgroup of Cep OB3 has a comparable age, and they suggest that this is an example of supernova-induced star formation. In addition, the pulsar PSR 2223+65 may be a remnant of the supernova event.

III. BIRTH OF CLUSTERS FROM MOLECULAR CLOUDS

Molecular clouds are observed which are the actual progenitors of future clusters. On the other hand, newly formed clusters allow the estimation of the global characteristics of the parent clouds. The birth of clusters from these clouds will be presented here in the framework of a classification of the molecular clouds based on their total mass: 1) the globules and small clouds (total mass up to some hundreds of solar masses), 2) the dark cloud complexes (total mass up to some thousands of solar masses), 3) the giant molecular clouds (total mass up to some tens of thousands of solar masses). A similar classification was proposed by Mezger (1975).

1. Globules and Small Dark Clouds

Bok (1977) reviewed the properties of large globules which may be connected to star formation. There are approximately 200 large globules known within 500 pc of the sun. Thus, the estimated total number in our Galaxy is at least $2.5\cdot10^4$. Globules may be associated with dark nebulae complexes as in the case of the many globules in the Southern Coalsack (Bok et al., 1977), but they also may be isolated objects, like Barnard 335, or associated with a reflection nebula, like Lynds 810. Radio astronomy has contributed largely to the knowledge of the physics of large globules (Dickman, 1977). The essential results are: 1) the globules' temperatures are low, generally in the range of 7^{o}K to 15^{o}K, 2) the

https://doi.org/10.1017/S0074180900091828 Published online by Cambridge University Press

masses vary from about ten to several hundreds of solar masses, 3) the radii vary from about one pc to some tens of pc.

An essential question about large globules is: are they contracting towards protostars and clusters? The observed velocity spread, derived from the widths of the CO spectroscopic features, is on the order of 1 km/sec. It seems improbable that turbulence could be the cause of such a velocity spread because considerable heating would then take place, whereas the observed temperatures are very low. In addition, the total negative potential energy of the globules from their mass and radii is larger than the total positive kinetic energy from their internal temperature. Thus, it is strongly supported that collapse of the large globules is the dominant phenomenon responsible for the observed velocity spreads. The strongest confirmation of the hypothesis that Bok globules are currently collapsing to form stars would of course be to find some cases where a new star or a small cluster of stars is in the process of being born. Herbst and Turner (1976) seem to have found such a case with the globule L 810 which appears to have embedded within it a young, fairly hot star and possibly even several such stars.

A possible further evolution for the large globules is the formation of a small cluster of total mass up to at most several hundreds of solar masses. Aveni and Hunter (1969, 1972) detected such clusters in the case of the BM And complex (estimated mass 100 $M_\odot$), which also contains a T Tauri-like star, and of a region called van den Bergh 80 (estimated mass 85 $M_\odot$). Another case is the L 1551 dark cloud (Strom et al., 1976a) which contains two very young T Tauri stars and three Herbig-Haro objects (estimated mass 100 $M_\odot$: Knapp et al., 1976). Another small dark cloud (L 43) was recently studied by Elmegreen and Elmegreen (1979) who performed CO and near infrared observations. It is a filamentary cloud that has evolved to the point where it contains a central condensation with an estimated mass larger than 14 $M_\odot$. Two faint red stars may be associated with the cloud and may even be formed in the condensation. A limiting case for the category of small dark clouds is the molecular cloud surrounding NGC 7023, a reflection nebula illuminated by a B3-type star and associated with a small cluster having an estimated mass of 150 $M_\odot$ (Aveni and Hunter, 1969). The estimated total mass of the molecular cloud is 600 $M_\odot$ (Elmegreen and Elmegreen, 1978a).

It is important to note that the earliest star observed in the various examples given above is always of spectral type later than O. Thus it seems that the formation of star clusters from small dark clouds does not result in O-type stars.

2. Dark Cloud Complexes

Between the small dark clouds and the giant molecular clouds, which will be treated in the next paragraph, can be classified molecular clouds

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with a mass of some thousands of solar masses. Star formation in dark cloud complexes does not seem to form O-type stars. This fact is highly strengthened by the work of Myers (1977) who pointed out that radio continuum sources from stars earlier than B1 embedded deep inside the cloud are absent in most of the dark clouds. A large number of pre-main sequence intermediate or low mass stars (T Tauri, Herbig Ae/Be of Herbig-Haro objects) are observed throughout those of the clouds where star formation is active. Extremely young open clusters are observed optically or with infrared techniques within some of these dark clouds, such as in Ophiuchus or IC 5146. In other cases no dense cluster is associated with the cloud, but star formation of low and intermediate mass stars appears through the whole cloud as in the Taurus complex.

2.1 The Ophiuchus Dark Complex

Mezger and Smith (1977) reviewed the properties of this often investigated example of an optically opaque cloud where a star cluster is being formed deep inside. Since their review, important new studies have been performed and it is interesting to summarize anew the characteristics of this dark cloud.

Radio observations. Encrenaz et al. (1975) gave a detailed CO-map of the central part of the cloud and established curves of iso-visual extinction by star counts. They estimated a total mass of gas of about 2000 $M_\odot$ in the region where infrared sources are located. Myers et al. (1978) compared their observations of H, OH, H_2CO, CO and NH_3 with those of SO, HCO^+ and HCN. They found a spatial hierarchy of three sizes: 1) about 0.1 pc for molecular transitions which require a high density for observation, 2) about 1 pc for molecular transitions which require a lower density for observation (CO, OH, H_2CO), 3) about 6 pc for H. The molecular maps indicate 4 separate fragments, most of the mass being in 2 fragments. At a radius of about 1 pc, the molecular cloud has a mass of about 450 $M_\odot$, in excess over its Jeans mass by a factor of about 5.

Infrared observations. Vrba et al. (1975) discovered 67 point sources at 2.2 μm brighter than the magnitude K = 10 in an area of 0.2 square degrees (radius of about 0.7 pc). They represent the brighter members of a young cluster obscured by dark cloud material. They derived for this Ophiuchus cluster a luminosity function not varying from that characterizing other young clusters. Elias (1978b) performed a near infrared survey at 1.6 and 2.2 μm of a large field (18 square degrees). Nearly 400 sources brighter than K = 7.5 were detected. Among these sources, the infrared-bright stars associated with the dark cloud are strongly concentrated around the same region studied by Vrba et al. (1975). Fazio et al. (1976) found 3 far infrared (40-250 μm) sources which can be identified with 3 early B-type stars. Two of these objects are associated with compact H II regions (Brown and Zuckerman, 1975). There are no strong far infrared sources in the central regions of the cloud other than those identified with known early-type stars. This indicates both that there are no heavily obscured B stars in the cloud which have not been identified and that there are no other high luminosity objects.

T Tauri Stars. Rydgren et al. (1976) studied 15 T Tauri stars in the Ophiuchus cloud, confined to an area of about 5 square degrees around the central nebulosity. Thus, it seems that formation of intermediate and low mass stars occurs up to a large distance from the central core of the cluster in the Ophiuchus cloud.

2.2 The IC 5146 Dark Complex

IC 5146 is a very young open cluster whose earliest member, a BOV-type star, excites and illuminates an emission-reflection nebula which is surrounded by a shell of obscuring matter connected to a filamentary dark cloud complex. Thus, the overall appearance of this dark cloud is strikingly similar to that of the Ophiuchus cloud. Elias (1978a) studied this cloud and its surroundings using near infrared photometry. Three young objects were detected in the survey: the B0 star mentioned before, a known Ae-type star and a previously unidentified object which appears to be a heavily obscured FU Orionis star located in the dark cloud far away from the nebula.

Lada and Elmegreen (1979) found that the dark cloud contains 3 relatively intense CO bright spots which probably indicate the presence of embedded, newly formed stars. The total mass of the cloud complex is about 2500 solar masses. Signposts of massive (i.e. O-type) star formation such as H_2O masers, compact continuum and bright infrared sources seem to be absent, suggesting that IC 5146 is a region where the formation of stars of later type (i.e. B and later) is occuring. According to Lada and Elmegreen, the H II region is beginning to disrupt the molecular cloud, thus IC 5146 appears to be a more evolved star-forming cloud than Ophiuchus.

2.3 The Taurus Dark Complex

This dark cloud may be the nearest (140 pc, Elias, 1978c) major aggregate of dust and gas in which star formation is currently in progress. Numerous T Tauri stars and some Herbig-Haro objects in this complex provide evidence of this (Rydgren et al., 1976; Elias, 1978c). Clark et al. (1977) studied the kinematics of the cloud in CO spectral lines. Three out of 8 observed regions have localized multiple velocity components, which are interpreted as indicating fragmentation and resultant orbital motion of parts of the clouds.

The comparison of the Taurus and Ophiuchus complexes is fruitful. T Tauri stars are observed in the two regions, but the Ophiuchus region contains very red objects surrounded by reflection nebulae and such objects appear absent from Taurus. In contrast Herbig-Haro objects are found in Taurus but not in Ophiuchus. In Ophiuchus, one observes about 20 B- or A-stars in the immediate vicinity of the dark cloud, whereas in

Taurus there are only two or three early-type stars. On the other hand, the Taurus cloud appears far more patchy and fragmented than the cloud in Ophiuchus. Star formation in Taurus has been more widespread, but has generally resulted in stars of lower mass than in Ophiuchus and there is no newly formed cluster in Taurus.

3. Giant Molecular Clouds

H II regions are the best optical indicators of star formation. Indeed, clusters containing O-type stars are surrounded by giant H II regions. It must be noted that their characteristics depend only on these most luminous stars which account for only a few percent of the total mass content of a cluster. Thus, any determination of the star formation rate based on the stellar content of H II regions depends strongly on the adopted luminosity function. The molecular clouds in the vicinity of well known giant H II regions associated with very young clusters are complex and often extremely large (total mass up to several 10^4 and even several 10^5 solar masses). Here, it is only the principle and consequences of the sequential formation of OB subgroups from giant molecular clouds which will be reviewed.

The formation of new stars following the compression of a molecular cloud by an expanding H II region (Elmegreen and Lada, 1977) or by an expanding SNR (Öpik, 1953) requires in both cases the anterior existence of one star or a subgroup of massive stars. On the other hand, the newly formed OB stars will be able to trigger the formation of another OB subgroup by the same compression mechanisms. Thus, a step-by-step process for the formation of OB subgroups could be developed in stellar associations. The observation that some nearby OB associations contain distinct, spatially separate subgroups of OB stars which lie along the galactic plane in a sequence of monotically changing age led Blaauw (1964) to suggest that star formation did in fact occur in sequential bursts during the lifetime of the corresponding primordial clouds. Recent radio and infrared observations of these regions suggest furthermore that the sequence of decreasing stellar ages may be extrapoled to cloudy regions where the most recent epochs of massive star formation are known to be occuring. Mezger and Smith (1977) distinguished star formation in an interarm cloud complex such as the Orion region and in a main spiral arm such as in the IC 1805-IC 1795 complex. In both cases O-type stars are produced, but a large number of such bright stars reach the main sequence nearly at the same time in main spiral arm OB associations while, in interarm OB associations, there is a rather long time delay (of the order of the main sequence lifetime of O stars) between the formation of O stars in adjacent subgroups. Warren and Hesser (1978) attribute ages of 7.9, 5.1, 3.7 and 0.5 million years to the 4 subgroups of the Orion association first described by Blaauw (1964), i.e. an approximate age interval of 3 million years. In the case of the IC 1805-IC 1795 region, there is an evolutionary sequence of 3 groups of OB stars (IC 1805, IC 1795 and the infrared region W3) whose ages differ by less than one million years.

The sequential formation of massive stars by shock in an expanding H II region or by supernova cascade offers an alternative possibility (with respect to the density wave theory) to explain the spiral structure of galaxies. Gerola and Seiden (1978) used the mechanisms of self-propagating star formation to study the possibility that the large-scale spiral arms in a galaxy may be induced by purely local processes. In their models of differentially rotating galactic disks, the stochastic self-propagating star formation is able to generate large-scale spiral features that appear very similar to those of real galaxies, in particular with respect to the density and pitch angle of these features.

On the basis of observations of the various OB associations where sequential formation occurs, Elmegreen and Lada (1977) pointed out that most O-stars appear to form in compressed cores at the edge of giant molecular clouds. This fact could mean that O-star formation may require an externally applied pressure force. On the other hand, stars of later spectral type and lower mass seem to be able to form anywhere within the entire extent of a cloud complex.

IV. THE FRAGMENTATION PROCESS AND THE INITIAL MASS FUNCTION (IMF)

The initial mass function of stars is one of the fundamental parameters for the study of galactic evolution. However, we know very little from observations about the IMF in distant parts of the Galaxy. Even in the solar neighbourhood, the IMF is rather uncertain for all mass ranges (Audouze and Tinsley, 1976). The IMF could result from an opacity-limited hierarchical fragmentation (Hoyle, 1953; Rees, 1976; Silk, 1977). In a collapsing cloud, fragments may themselves be liable to further break-up if the gas can lose enough internal energy for the Jeans mass to decrease as the density rises. If cooling were efficient, collapsing clouds would undergo hierarchical fragmentation into progressively small masses, and this process would terminate only when individual fragments become opaque enough to trap their radiation. Evidently, the physical situation is not so simple, and the actual models of cloud fragmentation take into account the accretion mechanisms (Larson, 1978) and the inelastic collisions between fragments (Silk and Takahashi, 1979).

1. Observational Determinations of the IMF: an Overview

Salpeter (1955) used the observed luminosity function for the solar neighbourhood and theoretical evolutionary times to derive an IMF which may be approximated by a power-law: $\xi(\log M) \sim M^{-x}$ or $n(M) \sim M^{-(x+1)}$ where $\xi(\log M)$ is the number of stars per unit logarithmic mass interval and $n(M)$ is the number of stars per unit mass interval. The value of the

https://doi.org/10.1017/S0074180900091828 Published online by Cambridge University Press

exponent x was 1.35 for masses between 0.4 and 10 solar masses. Audouze and Tinsley (1976) give an IMF with several power law segments: $x = 2.6$ for $2 \leq M/M_\odot \leq 20$, $x = 0.25$ for $0.4 \leq M/M_\odot \leq 1$ and $x = 1.3$ for $0.2 \leq M/M_\odot \leq 0.4$. Scalo (1978) obtained an IMF with a variable exponent $x = -0.94\ (1 + \log M/M_\odot)$ which varies from 0 at 0.1 $M_\odot$ to −2.8 at 100 $M_\odot$. Mayor and Martinet (1977) derived a rather moderate value $x < 1$ for the slope of the IMF in the range $1 \leq M/M_\odot \leq 2$. Very recently, Lequeux (1979) has again determined the IMF for the solar neighbourhood, using complete samples of stars extracted from various catalogues and evolutionary models with mass loss. He found that the IMF per unit surface of the galactic disk can be represented approximately by

$$1.3 \cdot 10^{-3}\ (M/M_\odot)^{-2} \text{ stars yr}^{-1}\text{ kpc}^{-2}$$

per unit interval of log M, for $2.5 \leq M/M_\odot \leq 100$. Thus, it is considerably steeper than Salpeter's IMF which was poorly determined for high masses.

2. Observational Determinations of the IMF : in Open Clusters

In connection with the formation of open clusters, an important point is to know whether the observed mass spectrum of open clusters has the same slope as the IMF for the solar neighbourhood. From the studies by Jaschek and Jaschek (1957) and Sandage (1957) one may conclude that there is a satisfying agreement between Salpeter's IMF and the IMF of clusters, at least in the range $1 \leq M/M_\odot \leq 10$. On the contrary, Taff (1974) found a slope $x = 1.74$ for $M/M_\odot \gtrsim 0.75$, on the basis of a sample of 62 open clusters observed in multicolour photometry. Van den Bergh and Sher (1960) derived luminosity functions for the low-mass stars in open clusters and find that the increase towards low masses observed by Salpeter does not continue in the case of clusters for $M/M_\odot < 0.8$. Van den Bergh (1961) suggested that either the luminosity function of star formation now contains less faint stars than it did originally, or that the IMF in associations is steeper than in open clusters. Scalo (1978) concluded that the mass spectrum of field stars and open clusters do not differ significantly within the current uncertainties in the range 1-10 solar masses, but that observational indications for a deficiency of low-mass stars ($M/M_\odot \lesssim 1$) exist in some clusters. Smith et al. (1978) argue that massive stars $\gtrsim 1\ M_\odot$ form together with OB stars in clusters and associations and that low-mass stars $\lesssim 1\ M_\odot$ appear to form rather continuously in dense molecular clouds. They feel that this hypothesis of star formation explains the observed position of the low-mass turn-over of the cluster IMF.

However, the position of this turnover may not be considered as definitively established because the determination of the luminosity function of clusters is subject to many observational biases. In particular, every cluster studied by Artyukhina and Kholopov (references cited by Kholopov, 1969) exhibits at least two main regions, a nucleus and a corona. The ratio of the corona radius to the nucleus radius ranges from 2.5 to 10. Generally, only the cluster nucleus is taken into account for the cluster studies and this biases the cluster luminosity functions because in almost all cases the cluster coronas contain a larger percentage of low mass stars than the cluster nucleus (cluster dynamical evolution). Moreover, the study of the low-mass IMF in very young clusters is difficult because these stars are in the pre-main sequence stages for which mass attribution is very hazardous.

For these reasons, the Pleiades is a good case to study the low-mass IMF in a cluster. Hartmann (1970) obtained, for the stars more massive than about one solar mass, an IMF similar to the Salpeter's IMF. On the other hand, flare activity is a priori a good criterion for Pleiades membership because more than 80 % of the flare stars with known proper motions can be considered as cluster members (Haro and Chavira, 1969). Almost 500 flare stars are at present known in a circular region of radius $2^{\circ}.5$ (Haro, 1976). Moreover, the total number of flare stars in the same region may be estimated to about 1000 (Mirzoyan et al., 1977) and the estimated luminosity function has a maximum in the range $17 \leq m_{pg} \leq 18$, which corresponds to $M_V = 10^{m}.5$ ($M/M_{\odot} = 0.4$). This value is only an upper limit because the entire surface of the cluster was not covered by the surveys and more complete surveys will detect essentially low-mass stars (see also the paper by van Leeuwen in this volume). Another representative case of cluster for which a selection bias has given a wrong picture of the luminosity function is NGC 752. From the study by Johnson (1953) it was generally assumed that the main sequence of this cluster does not continue down to $M_V = +4$. But, on the basis of new photoelectric measurements of member stars (according to their proper motions), Grenon and Mermilliod (1979) showed that the main sequence of NGC 752 continues down to $M_V = +4$ and that this cluster must not be considered as a typical example of the non-formation of low-mass stars in an open cluster.

Evidently, differences in the luminosity functions probably exist from cluster to cluster as noted by van den Bergh and Sher (1960), a slope different from that of the Salpeter's IMF could be observed in open clusters, and a low-mass turnover of the cluster IMF inevitably exists for some masses. But presently, taking into account the uncertainties on the IMF of both field stars and open clusters, the deficiency of low-mass stars in open clusters may not be considered as a general property of open clusters.

3. Calculations of the IMF in Clusters from Theoretical Models

Various attempts to describe the observed IMF from theoretical models have been made in recent years (see Table). We see that these predictions are all able to predict the observed increasing number of stars with the decreasing mass in the high-mass part of the IMF. The

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Authors	Characteristics of the model	mass spectrum
Cloud collisions		
Field and Saslaw (1965)	Inelastic collisions of clouds with a unique speed	$x \cong 0.5$
Penston et al. (1969)	Inelastic collisions of clouds with velocity distributions	$x \cong 0.5$
Taff and Savedoff (1973)	Collisions of clouds with probalistic coalescence	$x \cong 0.5$
Arny and Weissman (1973)	Coalescence during the collapse of a cluster of protostars	$x \cong 0.5$
Cloud fragmentation		
Reddish (1969)	Fragmentation of an isothermal cloud of solid hydrogen grains	$x \cong 1.1$
Reddish (1975)	Fragmentation by H_2 formation on the grain surfaces	correct shape
Larson (1973)	Step-by-step probalistic fragm. of an isoth. collapsing cloud	correct shape
Larson (1978)	3-dim. calcul. of the fragm. of an isoth. collapsing cloud	$x \cong 1$
Silk (1977)	Radiation effects of fragments on the minimum Jeans mass	$x \cong 1.3$
Silk and Takahashi (1979)	Fragm. of a collapsing cloud modeled by the coagul. theory	$x \cong 0 - 1$

predicted exponents are in the range $0 < x < 1.5$. This range of values does not overlap the more recent observational determinations of the IMF exponent for the massive stars (e.g. $x = 2$ by Lequeux, 1979). This is not surprising because particular conditions (compression of the interstellar clouds are required to form O-type stars (see previous section). Some of the theoretical x values could be representative of the low-mass star formation in open clusters. Indeed, there is some observational evidence (e.g. Audouze and Tinsley, 1976) that the low-mass part of the IMF has an exponent x in the range predicted by the various models.

V. SOME OTHER PROPERTIES OF OPEN CLUSTERS CONNECTED WITH STAR FORMATION

1. Spread in Age

Apparently, all the stars in a cluster do not have exactly the same age. For example, the age spread in NGC 2264 may be estimated to be almost 10 million years (Warner et al., 1977). This fact is important for the study of the properties of very young clusters. In particular, it is clear that the IMF of a very young cluster varies with time, if the age spread depends on stellar mass. Work by Iben and Talbot (1966) and Williams and Cremin (1969) has suggested the question "do low mass stars form first?". This was discussed following the review by Mezger and Smith (1977) at IAU Symposium No 75. No conclusive answer has yet been given to this question.

2. Stellar Duplicity

A fact which is generally not mentioned when determining a luminosity function is that the components of double or multiple stars are not separated. Mermilliod (1979) deconvolved the luminosity function of Praesepe by assuming that the vertical dispersion above the main sequence in the observational HR diagram is entirely due to duplicity. The deconvolved luminosity function becomes steeper. Thus the behaviour of the IMF through the Galaxy depends also on the behaviour of the rate of binary stars in the same regions. Our knowledge of this rate is extremely incomplete and in particular we do not know anything about the large-scale variation of the rate of low-mass binary stars through the Galaxy. In the case of B-type stars in the Bright Star Catalogue, Burki and Maeder (1977) found a constant frequency of binary stars with the galactic longitude (about 40 %) and Crampton et al. (1976) found that the percentage of known or suspected binary stars in 6 open clusters (α Per, Pleiades, M 39, IC 4665, NGC 2516, NGC 6475) is approximately constant (40-50 %). In any case, if the IMF is used to study processes of cloud fragmentation, the frequency of secondary components in multiple systems ought to be taken into account.

3. Cluster Size and Birth-places of Stars in Clusters

The size of very young clusters was used by Burki and Maeder (1976) to examine the dependence of the Jeans radius R_J for cluster formation with the galactocentric distance R. It was shown that the size of the clusters younger than 15 million years varies strongly with R in the observable part of the Galaxy. The means of the cluster diameters are 4.7 pc at R = 8.5 kpc and 9.9 pc at R = 11.5 kpc, the variation being especially pronounced beyond 11 kpc. This variation was interpreted in terms of an increase in R_J with R. This could be due to the decrease with R of both the mean molecular gas density and the compression efficiency of the mechanisms initiating star formation, such as galactic shock waves for example.

By using the very complete UBV study by Moffat and Vogt (1974), Burki (1978) examined the birth-places in open clusters of stars brighter than $M_V = 0$ (i.e. $M/M_\odot \geq 4$). It was found that, in the youngest of these clusters (age $\leq$ 5 million years), the ratio of star numbers $N(M \geq 20\ M_\odot)/N(M \geq 4\ M_\odot)$ is, on the average, more than 2.5 times larger in the outer regions of the apparent cluster surfaces than in the central regions. In an isothermally collapsing cloud, the critical Jeans mass is thought to

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increase with the distance to the cloud centre due to the decrease in stellar density. Thus, qualitatively speaking, the more massive stars would form preferentially in the outer regions of a collapsing cloud. In addition, according to the picture that O-type stars are formed near the edge of giant molecular clouds (see section III), it is possible to observe that O-type stars are more dispersed than B-type stars on the apparent surface of newly formed clusters.

4. Dependence of the IMF on the Galactocentric Distance

Shields and Tinsley (1976) observed that the equivalent width of the Hβ emission from H II regions in spiral galaxies increases with distance to the nucleus. They interpret this W(Hβ) gradient in terms of a radial gradient in the temperature of the hottest exciting stars. Thus, the upper stellar mass limit may increase with radius in galaxies. This result is in agreement with the fact that the exponent x of the upper part of the IMF in very young clusters may decrease with increasing distance from the galactic centre (Burki, 1977). These results may be connected to the abundance gradients across the galactic disk, because most of the chemical enrichment in the Galaxy is believed to be due to stars with initial masses larger than 10 solar masses.

5. Are all Stars Formed in Clusters?

Roberts (1957) and Miller and Scalo (1978) have shown that the great majority of, if not all, O-type stars are formed and are still present in clusters and associations. As we have seen, particular conditions of external compression on giant molecular clouds may be necessary in order to form O-type stars. Thus, these high-mass stars are formed in clusters and associations, together with stars of lower mass. Wielen (1971) and Miller and Scalo (1978) found that only a small fraction of field stars are former members of now dissolved open clusters. This may be explained by the fact that certainly many small groups or clusters may dissolve during the early stages of evolution or practically at the moment of their formation. Such stars are formed in clusters but immediately become field stars. Nevertheless, if stars later than O-type are formed in clusters like Ophiuchus and in small groups like NGC 7023, they can apparently also be formed more or less individually as in the Taurus dark cloud.

Acknowledgments: This work was supported in part by the Bourse Plantamour-Prévost of the Geneva University.

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DISCUSSION

BOK: I might mention that in one globule we have, in addition to what you have, two Herbig-Haro objects shooting out of it. The photograph is in the *Pub. Astron. Soc. Pacific* for October and November 1978.

CUDWORTH: In view of what we heard this morning about the Pleiades diameter, I wonder how many of the diameters on the plot that you showed (cluster diameter vs. galactic center distance) are really reliable, and are we to believe any of that in view of what we heard this morning?

BURKI: We have used Trumpler's diameters (Lick Obs. Bull. 14, 154) and have shown (*Astron. Astrophys.* 51, 247) that the measurements of the cluster angular diameters by different authors always show good internal consistency and are very well correlated with Trumpler's determinations. On the other hand, the problem of the extended corona observed in the case of the Pleiades is much less important in the case of the extremely young clusters, because they are not yet dynamically evolved.

SCHMIDT-KALER: Is it possible that the dependence of Trumpler's diameters on the distance from the galactic center is due to a selection effect? The clusters which are observed in the direction of the center are observed against a heavy background of stars, and those which are observed in the anticenter direction are observed against a rather sparse background.

BURKI: If such an effect exists, it must affect the old clusters more than the young ones because of the existence of a corona. We found just the opposite effect, i.e. only the diameter of the youngest clusters increases with the galactocentric distance.

LYNGA: Returning to what you said about galactic shock waves and the formation of clusters, this was a thing that I dealt with a little bit yesterday, too. Although there are different papers that you referred to that might be very conscientiously made, their results are not very convincing. I think you expressed it that some clusters are formed inside spiral arms and some are formed between spiral arms. This refers particularly to two papers where it was clusters that had been formed a certain time ago and they would face backwards in their galactic orbits.

BURKI: They are papers by Forte and Muzzio (1976) and by Palous *et al.* (1977).

LYNGA: There were also other papers that concerned the individual stars and Cepheids. And they all get results which are pretty well, "some units are forming in spiral arms, others between spiral arms". My point is that we should not let the theoreticians believe that the observations show that everything sort of backs up the density wave theory. Because it doesn't quite, does it?

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FREEMAN: Lets go back to this question of the change of diameter of clusters with galactocentric distance. I'll ask you if you think the galactic tidal field might have some role in this? Because the way the galactic tidal field would drop as you go outwards, if the tidal field is important in determining the size of a region that forms a cluster, then that's exactly what you would expect: an increasing size of cluster as you go out further from the galaxy. I wonder how important the tidal field really is in setting the size of a region that becomes a cluster?

BURKI: The tidal radius increases with galactocentric distance, but newly formed clusters are not yet affected by this fact. Thus, the increase of the cluster diameter observed in extremely young clusters is connected with cluster formation processes. This problem was examined by Burki and Maeder (1976).

MAEDER: The age of these clusters are smaller or, at most, of the same order of the crossing time, so it is unlikely that dynamical effects could influence the diameter very much.

FREEMAN: The age I don't think matters here, because what I'm trying to say is, if you have a region that is larger than the local tidal radius for that particular density and that location in the galaxy then the thing won't collapse in the first place.

FITZGERALD: I have the impression from the graph of diameter vs. galactocentric distance that the effect depended extremely heavily on just two points and is not statistically significant.

BURKI: No, it is not determined from two points. The mean diameter at 8 kpc from the galactic center is 5 pc, and the mean diameter at 11 kpc from the galactic center is 10 pc. The difference is statistically significant.

HARWARDEN: Could we see the slides of the diameters again, please?

BURKI: Yes. On the first slide (clusters younger than 10^7 y), we see the increase of the mean diameter with the galactocentric distance. On the second slide (clusters older than 10^7 y), this effect has disappeared.

HODGE: This new slide makes me wonder whether you haven't lost the effect. If this is older than ten million years, that includes a tremendous range in age and you can loose the effect due to the fact that the older clusters are smaller and have a different radial distribution in the galaxy. The reason I wonder about that is in the Magellanic Clouds we found twenty years ago that the old clusters show what your first slide showed: they get larger as you go out from the center, and I was alarmed to discover that you don't find that for our Galaxy. Now I'm wondering if maybe it's not still true but lost.

FEAST: Just wondering if there mightn't be an effect by the fact that some of this material would be different in the northern or southern hemisphere? The southern hemisphere would influence the results toward the galactic center in the inner part of the galaxy.

His plate material was probably different.

BOK: In the south he used, I think, the *Franklin Adams Charts*, and in the north I don't know what he used.

BURKI: Such an effect would affect all the clusters and we do not observe it in the case of the clusters older than 10^7 y.

BOK: One thing I think I should urge all of you to add to this list that you have here of references, you must add all of you IAU Symposium 87. There is all the information about molecules, molecular clouds and all the radio attitude closely spelled out there. So everyone in this room ought to purchase a copy of IAU Symposium 87.

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