The physics and modes of star cluster formation: observations

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Stellar clusters are born in cold and dusty molecular clouds and the youngest clusters are embedded to various degrees in dusty dark molecular material. Such embedded clusters can be considered protocluster systems. The most deeply buried examples are so heavily obscured by dust that they are only visible at infrared wavelengths. These embedded protoclusters constitute the nearest laboratories for direct astronomical investigation of the physical processes of cluster formation and early evolution. I review the present state of empirical knowledge concerning embedded cluster systems and discuss the implications for understanding their formation and subsequent evolution to produce bound stellar clusters.

Keywords: star formation; cluster formation

1. Introduction

The question of the origin of stellar clusters is an old one. As early as 1785, William Herschel first considered this problem in the pages of these *Transactions* when he speculated on the origin of the clusters Messier 80 and Messier 4 in Ophiuchus. More than two centuries later, despite profound advances in astronomical science, we find that the question of the physical origin of stellar clusters remains largely a mystery. This is, in part, due to the fact that cluster formation is a complex physical process that is intimately linked to the process of star formation, for which there is as yet no complete theory. The development of a theoretical understanding of star and cluster formation therefore depends on first acquiring detailed empirical knowledge of these phenomena. This can be a very difficult task. Consider, for example, the globular clusters, the most massive stellar clusters in our own Galaxy, the Milky Way. These stellar systems are more than 12 billion years old and are no longer formed in the Milky Way. Consequently, direct empirical study of their formation process is not possible. The situation is considerably better for Galactic open clusters. These typically span ages from 1 Myr to 1 Gyr and thus must be continually forming in the Milky Way, making direct observational study of their formation process possible, at least in principle. However, such studies have been seriously hindered by the fact that open clusters are born in molecular clouds and, during their formation and early evolution, are completely embedded in molecular gas and dust. They are thus obscured from view at optical wavelengths, where the traditional astronomical techniques are most effective.

Fortunately, molecular clouds are considerably less opaque at infrared wavelengths and the development and deployment of infrared imaging cameras on optical- and infrared-optimized telescopes during the past two decades has provided astronomers with the ability to detect, survey and systematically study the extremely young embedded stellar clusters within nearby molecular clouds. Such studies indicated that embedded clusters are quite numerous and that they account for a significant fraction, if not the majority, of all star formation presently taking place in the Galaxy. Similarly, as discussed in accompanying articles by de Grijs (2010) and Larsen (2010), young clusters also appear to account for a significant fraction of star formation in other galaxies, such as in the very active and luminous starburst galaxies and in the vigorous star-formation episodes which accompany galaxy mergers and close interactions. In our Galaxy, the embedded-cluster phase lasts only 2–4 Myr and the vast majority of embedded clusters which form in molecular clouds dissolve within 10 Myr or less of their birth. High cluster infant mortality has also been inferred for clusters in other galaxies (see, e.g., de Grijs 2010; Larsen 2010). This early mortality of embedded clusters is likely a result of the low star-formation efficiency that characterizes the massive molecular-cloud cores within which the clusters form. The physical reason for the low formation efficiencies is not well understood and the origin of the massive cores themselves is one of the many mysteries of modern astrophysical research.

The embedded clusters are the primary laboratory for research into the question of the physical origin of stellar clusters. At the present time, the answer to this question is shrouded by the dusty veils of the dark molecular clouds in which stars and clusters are born. The ultimate goal of a theoretical understanding of the physical process of cluster formation is far from being realized. The first step towards achieving this goal is to construct a solid empirical foundation upon which a physical theory can eventually be built. This then requires a detailed understanding of the physical nature of embedded clusters and the environments in which they form. In this article, I will review the empirical knowledge that is setting the stage for the eventual development of a theory of cluster formation. I will describe existing knowledge concerning many of the basic physical properties of the embedded-cluster population, including the cluster mass function, cluster birthrate, structural properties, etc., as well as the nature of the gaseous cloud cores in which they form. I will (at the end) briefly speculate on the implications of these results for understanding the origin of stellar clusters. A more theoretical discussion of possible physical mechanisms for forming such clusters is contained in the accompanying article by Clarke (2010).

2. Demographics of embedded clusters

(*a*) *Definitions*

It is useful to begin any discussion of embedded clusters with the definition of what constitutes such objects. Following Lada & Lada (2003), we first define a cluster to be a physically related group of stars that satisfy the following two requirements. First, the group must have a stellar-mass volume density sufficiently large to render it stable against tidal disruption by the Galaxy (i.e., $\rho_* \geq 0.1$ $M_\odot$ pc^{-3}; Bok 1934) and by passing interstellar clouds (i.e., $\rho_* \geq 1.0$ $M_\odot$ pc^{-3}; Spitzer 1958). A group of only 8–10, 0.5 $M_\odot$ stars within a radius of 1 pc would satisfy this first requirement. Second, the group should contain a sufficient number of members to ensure that, if in a state of virial equilibrium, its evaporation time (i.e., the time

Figure 1. *(left)* Optical and *(right)* infrared view of an embedded Trapezium cluster associated with the Great Orion Nebula. North is on the left, west at the top. (From Lada & Lada 2003.)

it takes for internal, gravitational stellar encounters to eject all of its members) is greater than the typical lifetime of Galactic open clusters of $\sim 10^8$ yr. For a cluster in virial equilibrium, this number is about 35 stars. An embedded cluster is then defined as a cluster that is fully or partially embedded in interstellar gas and dust. The above definition of a cluster includes both gravitationally bound and unbound stellar systems. Bound stellar clusters are those whose total energy (kinetic and potential) is negative. When determining the total energy of a cluster, we take into account contributions from all forms of mass within the boundary of the cluster, including interstellar material. This is crucial in evaluating the dynamical states of embedded clusters, since generally the mass of interstellar material exceeds the stellar mass within the cluster boundaries.

(*b*) *Identification: infrared imaging surveys*

Because most of their members are often optically obscured by interstellar dust, infrared imaging is generally required to identify and investigate embedded clusters. The existence of a cluster is established observationally by an excess density of stars over the background. Consequently, the detectability of a cluster depends on its richness and compactness, the brightness of the cluster members and the density of background objects. Figure 1 shows optical and infrared images of the famous Orion Nebula and its embedded cluster. It clearly illustrates the advantage of infrared imaging for revealing the stellar content of embedded clusters. A number of authors have compiled catalogues of embedded clusters based on infrared observations. Porras *et al.* (2003) compiled a list of 34 clusters, which is likely nearly complete for clusters within 1 kpc of the sun. Lada & Lada (2003) list 76 embedded clusters with well-determined properties within 2.5 kpc of the sun. They estimate that their list is representative but incomplete and that there are likely a total of about 200 such clusters within this volume of space, most of which are unobserved to date. Bica *et al.* (2003) compiled a highly incomplete list containing more than

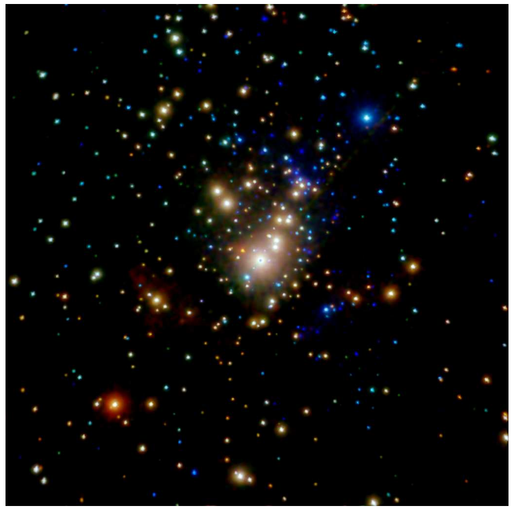

Figure 2. X-ray image of the Trapezium cluster in Orion, obtained with a deep integration using the *Chandra* space observatory. Essentially all cluster members were detected as X-ray sources (Getman *et al.* 2005). North is at the top, west on the right.

300 infrared clusters, stellar groups and candidate clusters, most within about 5 kpc of the sun, some fraction of which are likely embedded. Even cursory consideration of these studies suggests that embedded clusters are quite numerous in the Galactic disc.

(*c*) *Membership: signatures of youth from infrared to X-rays*

Although the existence of a cluster can be established by the increase of source density over the background, identification of the individual members is considerably more difficult, especially for intrinsically faint members whose numbers are only comparable or significantly lower than those of the background/foreground stellar field population. The size of the cluster's membership can be determined statistically through comparison with the background/foreground field-star surface density over the cluster area. However, determining whether or not a specific star is a cluster member requires independent information. Since embedded clusters are very young stellar systems, independent indicators of stellar youth, such as the presence of circumstellar discs, variable emission lines, X-ray emission, etc., can be employed to ascertain membership of individual stars.

For typical embedded-cluster ages of 1–3 Myr, at least half of the members will be surrounded by circumstellar discs, remnants of the star-formation process (e.g., Haisch *et al.* 2001; Hernandez *et al.* 2008). Many of these discs will be accretion discs and exhibit strong, variable hydrogen recombination lines at optical and infrared wavelengths (e.g., Green & Lada 1996; White *et al.* 2007). Infrared spectroscopic surveys, especially those done with multi-object spectrographs, can be used to identify accreting objects in a cluster field. However, such observations can be time consuming and even prohibitive for faint members, which can account for a significant portion of the cluster population.

Circumstellar discs can be detected directly with infrared broad-band photometry as a readily measurable excess above the expected emission from a normal stellar atmosphere. Excesses due to circumstellar discs and envelopes are most robustly measured at longer infrared wavelengths (i.e., $\lambda \geq 2\mu$m). In recent years, the *Spitzer Space Telescope*, operating at wavelengths between 3 and 70 μm, has provided the capability to survey and measure infrared excesses and circumstellar-disc emission with unprecedented sensitivity across the complete mass range of stars in embedded-cluster regions (e.g., Allen *et al.* 2007). These observations are providing the first statistically complete accountings of disc populations in individual young clusters (e.g., Lada *et al.* 2006; Sicilia–Aguilar *et al.* 2006) and important new insights into their structural properties (Gutermuth *et al.* 2009).

Although infrared observations are sufficiently sensitive to detect the presence of infrared excess from stars across the entire spectrum of stellar mass, there are typically many cluster members which have no discs or detectable infrared excess, presumably because these stars have passed quickly through the disc phase of early stellar evolution. As many as 50% of all members of a young cluster may have lost their discs and any other accretion signatures at an age of 2–3 Myr. Observations made from space with X-ray observatories such as the *Chandra X-ray Observatory* have shown that young stars emit X-rays at levels $10^2 - 10^4$ times that of normal stars, particularly during the first 10 Myr of their lives (Feigelson & Prebisch 2005). Such emission appears to be detectable across almost the entire stellar-mass spectrum, whether or not the stars have discs (e.g., Telleschi *et al.* 2007). In principle, X-ray surveys can be used to identify the discless membership of a young stellar population and thus, in combination with infrared surveys, lead to identification of all members of an embedded cluster. For example, a deep *Chandra Observatory* observation of the Trapezium cluster in the Orion Nebula resulted in the X-ray image shown in figure 2, in which all cluster members (with and without discs) are detected as X-ray sources (Getman *et al.* 2005). However, these *Chandra* observations were very deep, and in general the degree to which X-ray surveys can sample the membership of a cluster depends on the sensitivity and depth of the observations. In typical situations, infrared observations are more sensitive to the faintest members of a cluster population (e.g., Winston *et al.* 2007). Nonetheless, to accurately obtain a census of the membership of an embedded cluster requires a varied set of observations and such information is, at the present time, only available for a limited set of clusters.

3. Fundamental physical properties of embedded clusters

(*a*) *Embedded cluster mass spectrum*

The frequency distribution of embedded-cluster masses is a fundamental property of these systems which any physical theory of cluster formation must explain. Lada & Lada (2003) used the data from their cluster catalogue to uniformly derive masses for the known embedded clusters within 2.5 kpc. They then constructed the embedded-cluster mass spectrum (ECMS) and found it to be given by a power law of the form $\mathrm{d}N/\mathrm{d}M \propto M^{-\alpha}$, where $\alpha \approx 1.7$–2.0 for masses in excess of about 50 $\mathrm{M}_\odot$. For a distribution with $\alpha = 2$, the total mass of clusters in any logarithmic interval (bin) is constant. Thus, even though there are many more 50 $\mathrm{M}_\odot$ than

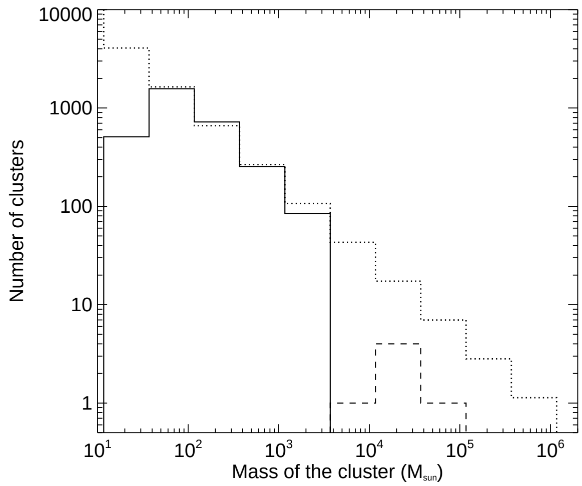

Figure 3. Embedded-cluster mass spectrum for the Galaxy. The scaled ECMS for clusters from Lada & Lada's (2003) compilation of cluster masses within 2.5 kpc is plotted as the solid trace. The predicted ECMS for all masses and a spectral index of $\alpha = -1.7$ is shown as the dotted histogram. Massive embedded clusters from the list of Ascenso (2008) are represented by the dashed trace. (Adapted from Ascenso 2008.)

1000 $M_\odot$ clusters, the very rare 1000 $M_\odot$ clusters contribute the same fraction of the total mass in clusters as the more numerous 50 $M_\odot$ clusters. This, in turn, implies that if a star in the Galaxy is born in a cluster, it is just as likely to form in a 1000 $M_\odot$ as in a 50 $M_\odot$ cluster. The ECMS very likely represents the primordial mass function of Galactic open clusters. In this context, it is interesting to note that a recent attempt to determine the mass function of classical open clusters also produced a power-law relation with an index of $\alpha \approx 2$ (Piskunov *et al.* 2008; see also discussion by Larsen 2010).

Observations also suggest that the ECMS peaks near 50 $M_\odot$and then falls off towards lower masses. Indeed, in a detailed study of all known stellar groups and clusters within 1 kpc of the sun, Porras *et al.* (2003) found that although small stellar ($N_* < 30$) groups greatly outnumber clusters, clusters with 100 or more members account for 80% of the total number of stars contained in both groups and clusters. This is consistent with the notion that most stars that form in the Galaxy form or have formed in embedded clusters with 100 or more members, and these are the clusters with masses of 50 $M_\odot$ or greater.

The most massive cluster in the Lada & Lada (2003) sample was the Orion Nebula Cluster, weighing in at a little above 10^3 $M_\odot$. More massive systems are known to exist, so it seems natural to assume that the lack of massive clusters in the Lada & Lada mass function is not caused by a truncation at high masses but is instead a result of the distance restriction of 2.5 kpc coupled with small-number statistics at higher cluster mass. Recently, Ascenso (2009) compiled a list of known clusters independent of distance in the Galaxy with masses estimated as in excess of 10^4 $M_\odot$. The largest of these appears to be Westerlund 1, whose mass of about 5×10^4 $M_\odot$ approaches that of globular clusters (Brandner *et al.* 2008). Of the nine clusters in her list, six have ages of 3 Myr or less and can be considered as part of the embedded, young cluster population. To estimate the numbers of massive, embedded clusters that may inhabit the Milky Way, Ascenso (2008) scaled the 2.5 kpc ECMS to correspond to that expected for the entire area of the Galactic disc ($R_{\rm MW}$ = 13 kpc). Figure 3 shows the scaled ECMS, along with the six massive clusters from Ascenso's list. The predicted distribution of clusters is also plotted, calculated for a mass spectrum index $\alpha = 1.7$ and normalized to the scaled observed distribution at cluster masses $\leq 10^3$ M$_\odot$(Ascenso 2008). A significant number of young clusters are predicted for cluster masses in excess of $2 - 3 \times 10^3$ M$_\odot$, but only a few such clusters have been identified.

Understanding the nature and origin of high-mass ($M > 10^4$ M$_\odot$) clusters is of considerable interest because observations indicate that such large clusters are a major component of the vigorous star-formation activity in merging and starburst galaxies (e.g., Bastian *et al.* 2005; see also accompanying reviews by de Grijs 2010; Larsen 2010). Are there examples of such clusters being produced in the Milky Way at the present epoch or is the ECMS truncated at high mass? The question of whether there exists a high-mass cutoff or truncation to the ECMS is difficult to answer. There are no known embedded clusters with reliably determined masses in excess of 10^5 M$_\odot$. One would think that such clusters would be easily identified if they existed. However, the predicted numbers are low enough that small-number statistics could be responsible, in part, for the observed lack of such systems in the Galaxy today. The present-day masses of classical open clusters offer additional constraints on the possibility of a truncation of the upper end of the primordial ECMS. For example, consider the most massive open clusters in our Galaxy with ages ≥ 20 Myr. Those systems all have masses $< 10^4$ M$_\odot$ (e.g., Bruch & Sanders 1983; Mermilliod 2000). Recently, astronomers identified three red-supergiant-rich clusters with ages between 10 and 20 Myr and masses between 2 and 4×10^4 M$_\odot$(Figer *et al.* 2006; Davies *et al.* 2007; Clark *et al.* 2009). If the cluster-formation rate were constant over time, figure 4 suggests that we might expect at least 100 objects with masses $\geq 10^4$ M$_\odot$ and with ages of 300 Myr or less. So far, only three such objects are known. Therefore, either the ECMS is truncated at masses $> 10^4$ M$_\odot$ or such clusters did not survive emergence from molecular clouds and dissolved very rapidly into the field.

(*b*) *Ages, birthrates and infant mortality*

The theory of stellar structure and evolution predicts fairly precisely the mass-dependent evolution of stellar luminosities and temperatures with age. This enables the age of a stellar population to be determined by placing the stars on a Hertzsprung–Russell (HR) diagram, which plots the distribution of stellar luminosities versus temperatures. The locations of stars are then compared to the predictions of stellar-evolution theory. This has proved to be a powerful tool for age dating mature clusters whose more massive stars have finished their main hydrogen-burning stage and experience significant luminosity and temperature evolution. However, age dating young, embedded clusters has proved to be considerably more difficult. The reason for this is twofold. First, the majority of stars in an embedded cluster are pre-main-sequence (PMS) stars, that is, stars that have not yet evolved to the point where nuclear burning commences in their interiors. For these stars, the

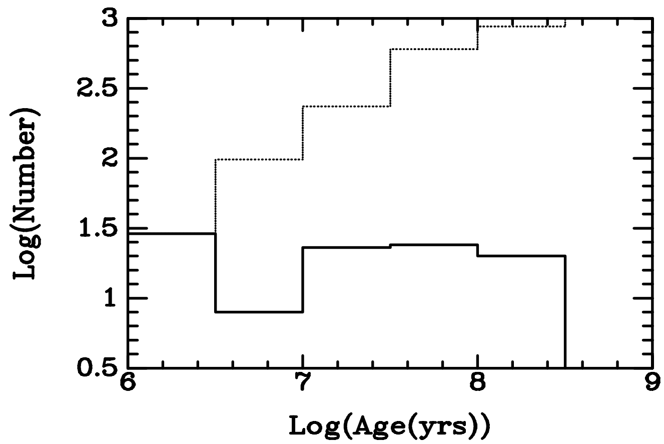

Figure 4. Observed frequency distribution of ages for classical open and embedded clusters within 2 kpc of the sun (solid line) compared to that predicted for a constant rate of cluster formation (dotted line). The discrepancy between the predicted and observed values in the second bin indicates that the vast majority of embedded clusters do not survive emergence from a molecular cloud. (From Lada & Lada 2003.)

theoretical trajectories on the HR diagram can be highly uncertain, especially for stars with ages of 1 Myr or less. Second, it is difficult to measure accurate luminosities and temperatures for PMS stars since they are obscured by interstellar dust, exhibit infrared excess emission and are variable. Nonetheless, a number of embedded clusters have been age dated in this fashion and typical median ages of stellar members in clusters range between 1 and 3 Myr, with the age spread in a given cluster of comparable magnitude to its age (Lada & Lada 2003). These results are consistent with the early work of Leisawitz *et al.* (1989), who found that clusters older than about 5 Myr exhibit no evidence of interstellar molecular gas within or near their boundaries. Thus, the embedded-cluster phase of evolution lasts somewhere between 3 and 5 Myr. [It is interesting to note here that recent analysis using only main-sequence cluster members on the HR diagram by Naylor (2009) yields age estimates 1.5 to 2 times older than derived from the PMS stars.]

Assuming typical ages of embedded clusters of between 1 and 2 Myr, Lada & Lada (2003) estimated their birthrate within 2 kpc from the sun at ≥ 2 to 4 Myr^{-1} kpc^{-2}. Upon emergence from their dusty wombs, embedded clusters become optically visible open clusters. Yet, the embedded-cluster birthrate is an order of magnitude higher than that (0.45 Myr^{-1} kpc^{-2}), estimated for classical open clusters within 2 kpc of the sun (Battinelli & Capuzzo–Dolcetta 1991). The large difference in the estimated birthrates is key in understanding the formation and early evolution of Galactic clusters.

The distribution of ages for a combined sample of embedded and open clusters within 2 kpc is shown in figure 4. Embedded clusters fall into the first bin and classical open clusters have ages that span a range from roughly 10^6 to 10^8 yr. The distribution is surprisingly flat. Also plotted is the predicted age distribution for a constant rate of cluster formation, assuming all clusters can live to ages of at least a few times 10^8 yr. There is a large and increasing discrepancy between the expected and observed numbers. This figure suggests a high infant-mortality rate for embedded clusters. Most of these clusters do not survive emergence from their parent molecular cloud. Roughly 90% dissolve in less than 10 Myr. Less than about 4% of the initial cluster population reach an age of 100 Myr. Lada & Lada (2003) suggest that only the most massive embedded clusters ($M > 500$ $M_\odot$) survive to ages of 100 Myr or more. It has been understood for some time that passing massive interstellar clouds could tidally disrupt open clusters with mass densities ≤ 1 $M_\odot pc^{-3}$ within 200 Myr (Spitzer 1958; Gieles *et al.* 2006). These tidal interactions with giant molecular clouds (GMCs) likely account for the flat age distribution of clusters with ages > 10 Myr. However, the rapid disintegration of most clusters in the first 10 Myr of life requires another mechanism. To understand this process, we need to first understand the conditions under which embedded clusters form.

(*c*) *Association with molecular clouds*

The intimate physical association with interstellar gas and dust is the defining characteristic of embedded clusters. Such objects are immersed in dusty, gaseous material to varying degrees. The most deeply embedded clusters are believed to be the youngest and least evolved objects of this class. They are found within massive, dense structures or cores inside GMCs. GMCs are, along with globular clusters, the most massive objects in the Milky Way. They are complex structures, often defined by long filamentary features. Such clouds are primarily composed of molecular hydrogen gas and characterized by a wide range of gas densities ($10^2 \leq n(H_2) \leq 10^6$ cm^{-3}). Star formation has long been known to take place in the dense ($n(H_2) > 10^4$cm^{-3}) component of molecular clouds (Lada 1992) and this component only accounts for between 1 and 10% of the total mass of GMCs observed in the vicinity of the sun. There are also indications that the star-formation rate in local clouds is closely related to their total content of dense gas (Lada *et al.* 2009). The latter is found in the form of filaments and also in more compact cores. Individual stars can form along dense filaments, usually in compact, dense cores within the filamentary structure.

Clusters of stars typically form in the most massive and dense cores within a GMC. Often, these massive cores are compact structures located at the ends or at an intersection of filaments, as illustrated in figure 5 (Myers 2009). The dense cores that form clusters range in mass from ~ 20 to 2000 $M_\odot$ and have sizes on the order of 1–2 pc in diameter (e.g., Higuchi et al. 2009). The spatial extents of embedded clusters are comparable to the sizes of the dense cores within which they reside. This suggests that the stars may be in approximate virial equilibrium with the gas in the core. The cluster members may thus not be colder dynamically than the surrounding gas. On the other hand, there are some indications that the stars within clusters may have started out dynamically colder than the gas. Starless dense molecular cores, the precursors to individual new stars, are characterized by subvirial velocities in a number of clouds (e.g., Walsh *et al.* 2004; Peretto *et al.* 2006; Lada *et al.* 2008) and protostellar objects have also been found to be spatially more confined than more evolved young stellar objects (e.g., Teixeira *et al.* 2006;

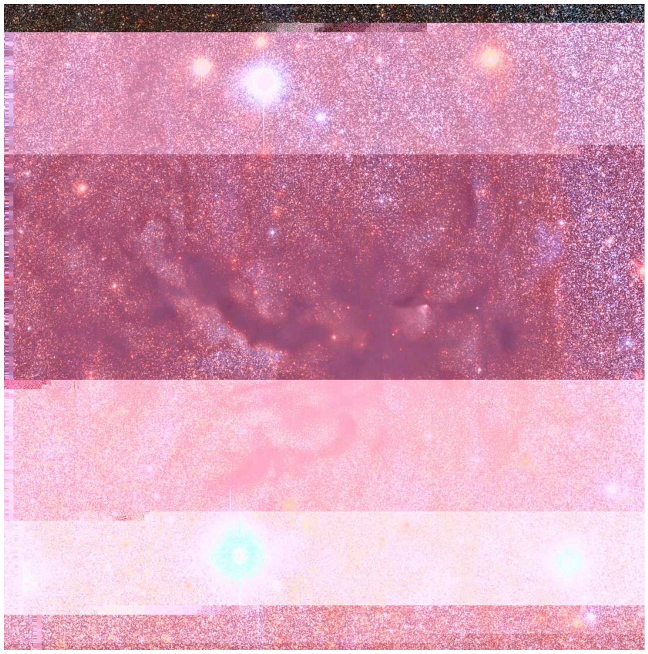

Figure 5. Optical image of B59, a compact, dense core at the apparent intersection of a number of filamentary structures and the site of the formation of a small, embedded, optically invisible cluster. (Courtesy of Alves, Vendame and Peris.)

Muench *et al.* 2007). Such observations suggest that, at birth, new stars in clusters are dynamically colder than the bulk of the gas surrounding them. Such stars are then expected to violently relax and collapse to smaller configurations. In doing so, dynamical interactions can produce segregation of the most massive stars, similar to observations (Allison *et al.* 2009). Comparison of the stellar content of embedded clusters with the mass of their surrounding cores yields star-formation efficiencies of typically between 10 and 30%. If the cluster stars were indeed initially dynamical colder than the bulk molecular gas, these measured 'final' efficiencies will be higher than the initial birth efficiencies (Lada *et al.* 1984; Goodwin & Bastian 2006). The observed low to modest final star-formation efficiencies are key to understanding the early dynamical evolution and infant mortality of such objects.

The most promising sites to investigate the formation of clusters may be found in a class of objects known as infrared dark clouds (IRDCs) (e.g., Rathborne *et al.* 2006). They are identified as high-extinction dark clouds when viewed against bright, diffuse mid-infrared (10–20μm) Galactic background emission. To be regions of high extinction in the mid-infrared requires them to have enormous column densities ($10^{23} - 10^{25}$ cm^{-2}) and correspondingly high volume densities ($> 10^5$ cm^{-3}), just the type of conditions that are ripe for star and cluster formation. The more massive of these clouds tend to be concentrated in the so-called 5 kpc ring (Simon *et al.* 2006), a large-scale Galactic structure rich in massive molecular clouds and active star formation. Millimetre-wave studies show many IRDCs to contain cores of sufficient mass (100–1000 M$_\odot$) to form modest to rich clusters. Yet, many of

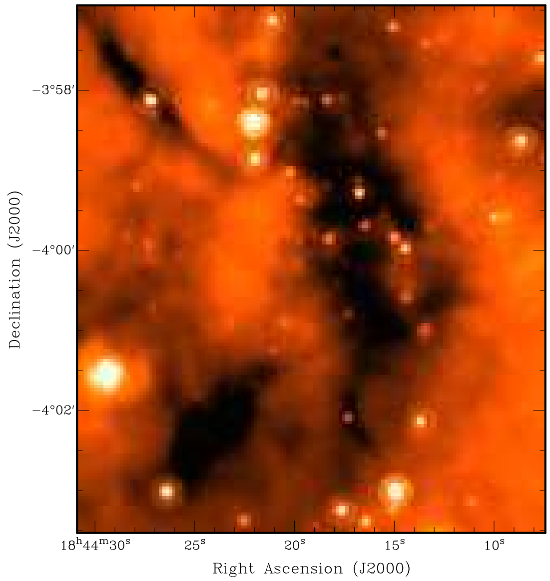

Figure 6. Image of the infrared dark cloud G028.53–00.25, obtained at 24 μm with the *Spitzer Space Telescope* (Rathborne *et al.* 2008). This cloud contains in excess of 1000 $M_\odot$ within a radius of a parsec and yet exhibits no indication of active star formation. It is possibly a future site of cluster formation.

these objects show no evidence of significant star or cluster formation. Figure 6 shows one of these IRDCs imaged with the *Spitzer Space Telescope*. This particular cloud contains more than 10^3 $M_\odot$, but exhibits no evidence for star formation. Its compact size and large mass suggest that it is gravitationally bound and very likely a site of future cluster formation. Rathborne *et al.* (2009) estimate that a 300 $M_\odot$ cluster could ultimately emerge from this cloud. Other massive IRDCs have exhibited evidence for the formation of massive stars within their boundaries. Since massive stars are rarely formed in isolation, these clouds may also be the sites of incipient cluster formation (Rathborne *et al.* 2006). Because these clouds are identified from mid-infrared observations, which can only be obtained from space, their existence has only been known for about a decade. Since the massive IRDCs tend to be relatively distant, they are challenging to observe and, as a consequence, little is known about their detailed physical properties. Unfortunately, too little is known about the detailed conditions in the clusterless IRDCs to provide any strong constraints on the problem of cluster formation. However, future observational capabilities provided by such facilities as the *Atacama Large Millimeter Array* and the *James Webb Space Telescope* hold the promise for obtaining a more detailed description of the physical conditions in these objects and for deeper insights into the cluster-formation problem.

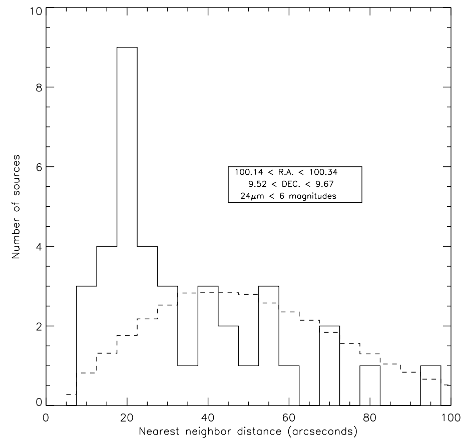

Figure 7. Distribution of the nearest-neighbour separations of protostars (solid trace) in an embedded cluster within NGC 2264, compared to the expected distribution of nearest neighbours for a random distribution of stars. The protostellar distribution is both non-random and strongly peaked. The angular scale of this peak corresponds to the expected Jeans length in the dense core containing the cluster. (From Teixeira et al. 2006.)

(*d*) *Internal structure*

Knowledge of the internal structure of an embedded cluster can provide additional clues relating to its origin and early dynamical history. For the youngest clusters, the spatial distribution of member stars may be closely related to the primordial structure of the cold, dense molecular gas from which the clusters formed. In their review of embedded-cluster properties, Lada & Lada (2003) identified two structural types of clusters, those that exhibit extended, irregular surface-density distributions, often with multiple peaks, and those that appear to be relatively more compact and have well-defined centrally condensed surface-density distributions with one dominant peak. More recently, Ferreira & Lada (2009, personal communication) used ground-based infrared imaging observations to systematically investigate the structure of approximately 40 previously catalogued embedded clusters. They found that about 60% of these objects were of the centrally condensed variety. The remainder exhibit relatively flat surface-density profiles with more irregular boundaries and more elongated shapes than the centrally condensed clusters.

Observations with the *Spitzer Space Telescope* at infrared wavelengths of 3–24 μm provide an improved census of cluster membership and thus enable better measurements of cluster shapes and sizes. These observations have shown that most embedded clusters are elongated, with a typical aspect ratio of about 2, very similar to the aspect ratios of the filamentary molecular clouds in which the clusters are born (Allen *et al.* 2007; Gutermuth *et al.* 2009). These observations imply that the structures of most embedded clusters probably reflect those of the original molecular clouds from which they formed. They also indicate that understanding the origin of such clusters is intimately tied to understanding the origin and evolution of the dense molecular material that produces them.

A potentially significant clue concerning the nature of the physical process of cluster formation is found in analysis of the distributions of spatial separations of the youngest members of some embedded clusters. Figure 7 shows the distributions of the nearest-neighbour separations of protostars in an embedded cluster in the NGC 2264 star-forming complex (Teixeira *et al.* 2006). This distribution is strongly peaked at an angular separation of 20 arcsec and clearly different from that expected for a random distribution of separations. The characteristic separation corresponds to the Jeans length for the density and temperature of the cloud core containing the cluster and suggests that Jeans fragmentation may be the physical process that governs the formation of the cluster from the massive cloud core. *Spitzer Space Telescope* studies of other clusters have found such evidence for Jeans fragmentation to be a more common property of embedded clusters than previously thought (Gutermuth *et al.* 2009).

4. Implications for understanding the origin and early evolution of embedded clusters

Because stars form in dense gas, it is the initial distribution of the dense material in a cloud that controls the degree to which a cloud forms an extended population of distributed stars and/or compact clusters. That the mass spectrum of embedded clusters resembles the shape of the mass spectrum of massive cores in GMCs appears to support this surmise (Lada & Lada 2003). Once dense gas is present, star formation likely proceeds quickly. The timescale is somewhat uncertain but the fact that numerous examples of massive, clusterless cores in IRDCs exist probably indicates a time for the onset of cluster formation on the order of a million years. On the basis of the ages of stars in embedded clusters, the time needed to construct the full cluster is likely 2–4 Myr from the onset of significant star formation. The physical mechanism that causes a massive core to fragment and form a cluster of stars is not clear. That the Jeans scale appears to describe the separations of the young stellar objects in embedded clusters suggests that a Jeans-like fragmentation process is responsible for the formation of a stellar cluster from a massive, dense core. Support for this idea also derives from measurements of the initial mass function (IMF) of stars within individual clusters. The stellar IMF has a characteristic mass of about 0.3 $M_{\odot}$, which appears invariant among clusters and even stars in the field. This suggests a mass scale for star formation that is consistent with thermal Jeans fragmentation (Larson 1992). The Jeans instability describes the situation where gravity overcomes the internal thermal pressure of a gas cloud and leads to both its fragmentation and the collapse of its individual fragments. However, it is not clear how this mechanism would operate in a very massive core where internal turbulence dominates thermal motions. Moreover, since the critical conditions of density and temperature which determine the value of the Jeans length and mass likely vary among regions, one would expect the characteristic stellar mass of clusters to likewise vary, but it does not.

Recent observations by the *Chandra* and *Spitzer Space Telescopes* have revived the idea that external triggering could represent another mode of cluster formation in the Galaxy. In the Cepheus B (Getman *et al.* 2009) and W5 (Koenig *et al.* 2009) star-forming complexes, spatiotemporal patterns of star formation have been found in the distribution of recently formed stars. Such patterns of sequential star formation have long been regarded as evidence for triggered star formation (e.g., Elmegreen & Lada 1977). Triggering produces enhanced compression of existing molecular clouds, raising their mean densities and, in doing so, increasing the fraction of cloud mass above the critical densities necessary for star formation. One way to compress a cloud is through increasing its external pressure. It is possible that conditions in merging and interacting galaxies, and in the nuclear regions of starburst galaxies, produce globally increased external pressures that significantly increase the fraction of dense material in a cloud and lead to the formation of massive dense cores and clusters. Lack of such conditions (i.e., high external pressures) may explain why very massive clusters are not presently forming in the Milky Way.

Although it is beyond the scope of this particular review to discuss the theory of cluster formation, it is useful to briefly mention the results of recent calculations since some insight into the physical process of cluster formation can be provided by numerical simulations. A more detailed discussion of the theory of cluster formation can be found in the accompanying review by Clarke (2010). Simulations of cluster formation follow the collapse and fragmentation of massive, initially turbulent clouds from some specified initial gaseous state down to the formation of stellar objects. The results of these calculations yield impressive details concerning the clusters they form but are very sensitive to the input physics. In particular, calculations starting with roughly similar initial conditions (i.e., $\sim 50 - 100$ $M_\odot$ turbulent clouds) can have drastically different outcomes, depending on whether feedback from newly formed stars is included. Models without feedback (e.g., Bate & Bonnell 2005) produce highly filamentary cloud configurations reminiscent of observed clouds. These models produce extensive (efficient) fragmentation and form rich clusters of primarily low-mass stars whose characteristic mass is directly related to the Jeans mass and thus varies with initial conditions (i.e., density). Models that include feedback (e.g., Krumholtz *et al.* 2007; Bate 2009) produce more massive cloud cores, smaller clusters, more massive stars and an invariant characteristic stellar mass, all in better agreement with observations of embedded clusters. Most importantly perhaps, the models which include feedback from the newly formed stars are also characterized by low star-formation efficiencies, again similar to observations.

Once embedded clusters are formed, the process of their subsequent dynamical evolution and emergence from molecular clouds is relatively well understood. Analytic and numerical calculations have shown that the key factor in determining the evolution of an embedded cluster is the (final) star-formation efficiency characterizing its formation (e.g., Lada *et al.* 1984; Geyer & Burkert 2001; Kroupa & Boily 2002). Observations indicate that the star-formation efficiencies for embedded clusters range between 10 and 30% (Lada & Lada 2003; Higuchi *et al.* 2009) with some indications that those with the highest efficiencies are the most evolved objects (Higuchi *et al.* 2009). Numerical simulations of cluster formation suggest that these low efficiencies are caused by the radiative feedback of the recently formed stars on their surrounding dense gas. In any case, the gravitational glue that binds the stars and gas together in an embedded cluster system is largely provided by the gas. We expect that, as more and more stars form in the cluster, the feedback from the stars due to radiation and energetic jets and outflows, generated in the early stellar-accretion process, becomes destructive and begin to disperse the dust and gas in the core. Massive stars are particularly destructive and a single O star can completely disrupt an entire cloud in a very short period of time. Because of the low efficiency of conversion of gaseous to stellar mass in these systems, they can easily be completely disrupted if the gas is removed on timescales comparable to the dynamical time of the system. Thus, low efficiency coupled with relatively rapid gas removal can explain why 90% of embedded clusters do not survive their emergence from molecular clouds as bound systems (Lada & Lada 2003).

Paradoxically, the clusters that survive emergence from molecular clouds as bound systems are likely the most massive systems at the upper end of the embedded-cluster mass function. This is despite the fact that these systems are the ones most likely to produce destructive O stars. Simulations indicate that, as clusters are disrupted by gas-removal processes, this disruption is rarely 100% complete and bound remnants containing a small fraction of the original stellar mass are often left behind (Lada *et al.* 1984; Kroupa & Boily 2002). The size of the bound remnant depends on the initial size of the cluster and on how rapidly gas removal occurs. Lada & Lada (2003) suggest that the field population of open clusters in the disc of the Milky Way was likely provided by embedded clusters with masses in excess of 500 $M_\odot$. This may also explain the relative lack of truly massive (i.e., $M > 10^4$ $M_\odot$) clusters in the Milky Way with ages in excess of 10 Myr. The few that are formed in the Milky Way do not emerge completely unscathed. Only smaller remnants of these giants survive as bound systems beyond 10 Myr.

5. Concluding remarks

More than two centuries after Herschel (1785) first considered the question, we now understand that clusters are formed in cold, dark molecular clouds. Stellar clusters begin their lives deeply buried in dense molecular gas and dust as embedded infrared protoclusters. Over the past two decades, advances in detector and telescope technology have led to steady advances in our knowledge of embedded protoclusters. These extremely young stellar systems appear to account for a significant fraction of all star formation presently taking place in the Milky Way and, thus, they are tracers of the current epoch of star formation in the Galaxy. Although considerable progress has been made towards understanding the basic physical properties of embedded clusters, a physical theory of cluster formation eludes us. In the Milky Way, the primary mode of cluster formation at the present epoch appears to be one in which relatively compact, massive dense cores in GMCs undergo a process of Jeans-like fragmentation that transforms cold, dense interstellar material into stellar form. Triggering of clouds by shocks or other mechanisms that lead to an increase in external pressure may represent an additional mode of Galactic cluster formation. Although its relative contribution to present-day cluster formation in the Milky Way is unclear, this latter mechanism may be significant in interacting galaxies and nuclear starbursts, and perhaps even in the early history of the Milky Way itself. It is now clear that to develop a predictive theory of cluster formation will require both a better understanding of the process of star formation and a comprehensive understanding of the physical mechanisms that organize the dense material of a GMC into massive, compact cores which, for a typical GMC in the Milky Way, occupy only a small fraction ($< 1\%$) of its volume and account for only a small fraction (1–10%) of its total mass.

I thank Joana Ascenso, Ken Janes, Lisa Townsley, Eric Feigelson, Elizabeth Lada and Bruno Ferreira for informative discussions, Joana Ascenso for preparing figure 3 and João

Alves for providing figure 5. I am grateful to Simon Goodwin and Richard de Grijs for constructive comments that improved this review.

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