Birth, Evolution and Death of Stellar Clusters

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Abstract

Using our recently improved understanding of star cluster physics, we are now within reach of answering a number of fundamental questions in contemporary astrophysics. Star cluster physics has immediate bearing on questions ranging from the physical basis of the stellar initial mass function – Do any O-type stars form in isolation? What is the relative importance of stochastic (random) star formation versus competitive accretion? – to the build-up of the most massive clusters – Does the cluster mass function differ in different types of galaxies? How and why do the most massive star clusters form in small dwarf galaxies and what does that imply for the build-up of larger cluster samples? What are the main observables one could (or should) use to try and distinguish among the various star- and cluster-formation scenarios? Newly emerging theoretical insights, novel high-quality observational data and the advent of the next generation of observational facilities offer significant promise to reach satisfactory and robust answers to the key outstanding questions in this field.

1 Preamble: Tertulias

When I was first approached to lead a main ‘Tertulia’ during the RIA workshop on Stellar Clusters and Associations, I was rather puzzled by the invitation, to say the least. Although this expression may be commonplace to some, it is not outside of the Spanish-speaking diaspora. Fortunately, our trusted friend Wikipedia offered answers: tertulias were originally informal, social literary or artistic get-togethers, particularly in Latin cultural contexts, often (but not always) held in public places. In relation to this conference, however, the organisers meant me to chair an open discussion on outstanding questions in contemporary star cluster-related astrophysics. In the following, I aim at setting the scene for the discussion that followed, which I attempt to summarise in general terms. The lively exchange of new (and some old) ideas that ensued led, I believe, to a general broadening of participants’ perspectives – in the true sense of the traditional tertulia.

1http://en.wikipedia.org/wiki/Tertulia
2 Outline of key emerging questions

Stars do not form in isolation, at least for stellar masses above $\sim 0.5 \, M_\odot$. In fact, 70–90% of stars may form in star clusters or associations (cf. Lada & Lada 2003). Star formation results from the fragmentation of molecular clouds, which in turn seems to preferentially lead to star cluster formation. Over time, their member stars become part of the general field stellar population. Star clusters are thus often stated as being among the basic building blocks of galaxies.

Using our improved understanding of star cluster physics, we are now within reach of answering a number of fundamental questions in contemporary astrophysics, ranging from the formation and evolution of galaxies to the details of the process of star formation itself. These two issues are the backbone of research in modern astrophysics. They lead to new questions (for a detailed discussion, see de Grijs 2010), including:

- How is star cluster formation triggered and how does it proceed?

  What is the role of ambient or internal pressure? Which other internal and/or external factors affect star cluster formation and longevity? Can we set constraints on the minimum requisite star-formation efficiency? Is star cluster formation a distinct mode of star formation or simply part of a broad spectrum of star-formation modes?

- Do star clusters really represent the basic building blocks of galaxies?

  How does the star cluster mass distribution relate to the turbulent properties of the interstellar medium (ISM)? Does initial substructure play a role? Is there a physically important difference between star formation in a ‘fractal’ ISM versus in clustered mode? Are mergers of smaller components a viable way to form more massive clusters? If so, what are the constraints implied for the relevant parameter space (e.g., velocity dispersions, half-mass radii, etc.)?

- How is the stellar mass distribution established?

  Although the stellar initial mass function (IMF) seems fairly universal, we still do not know what establishes its well-known (multiple) power-law shape. What are the roles and the formation scenario(s) of massive versus low-mass stars and the importance of feedback? How are stellar and cluster IMFs related and how are they affected by the underlying star-formation history?

- How do environmental conditions affect further cluster formation?

- How do quiescent galaxies form extremely massive clusters?

  What is the role of galaxy dynamics? Does it depend on a cluster’s position in a given galaxy or on galaxy type? How are the results affected by variations in the star-formation efficiency, or are we simply witnessing stochastic cluster formation? What triggers the formation of the most massive clusters?
These (and other) questions form the basis of much research in numerous fields in contemporary astrophysics: after all, star formation is one of the pivotal physical processes underlying most of astrophysics. Significant progress has been made in past decades, yet we still have a long way to go before all of the key questions will have been answered satisfactorily and sufficiently robustly to stand the test of time.

New advances in both theoretical and observational approaches may be required. Are the main theoretical (modelling) challenges preventing the next step change in our understanding of star and star cluster formation processes related to limitations in hardware or techniques? Are currently available instruments sufficient to reach these lofty goals, or will new facilities – including Gaia, the Atacama Large Millimetre Array (ALMA), the James Webb Space Telescope, the Large Synoptic Survey Telescope, or any flavour of extremely large telescope – be essential? Do we need higher spatial resolution than currently routinely attainable or perhaps larger fields of view, or a combination of both – and is this feasible?

3 Are star clusters indeed basic galactic building blocks?

The question as to what constitutes a characteristic scale in star formation comes down to our understanding of the way in which stars appear to form in a self-similar, hierarchical (‘fractal’) fashion. Observationally, we find a wide range in the gas distribution and star-formation properties in regions of active star formation (e.g., Bressert et al. 2010), where what we tend to call ‘clusters’ are the loci in which many stars form together in the basic, underlying hierarchical scenario. Gaia may well be instrumental in refining our understanding of the scales on which star formation occurs in the Milky Way.

Turbulent molecular clouds form clusters in the denser regions, where filaments might cross. Star formation occurs along such filaments, usually in small groups (‘knots’), which is shown beautifully by recent observations with Herschel. This is sometimes referred to as the distributed mode of star formation, but it is an integral part of the power-law distribution of structures. Clusters, or ‘spatially and temporally correlated star formation’ follow a power-law distribution of mass at a given time. One can start building galaxies from that Ansatz.

In some places, large numbers of stars are formed at roughly the same time. These loci are easily identified as star clusters. At other times, star formation proceeds in a more distributed mode, upon which the individual knots merge and also form structures we identify as star clusters. Gaia will likely find a lot of evidence of distributed star formation, where most stars never originated in clusters. The European Space Agency’s mission will, therefore, be key in distinguishing between these models.

Superficially, it appears that two somewhat different views are prevalent in the community, apparently advocating the extremes of our ideas of how stars form and the structures resulting from that process. Proponents of one viewpoint would argue that star formation occurs in a spatially confined, clustered mode, while their counterparts support the full hierarchical picture. However, as long as proponents of the tenet that star clusters are the basic building blocks from which galaxies form take their view down to the lowest-mass, often embedded clusters (which includes the distributed population of young stars), these apparent differences are merely semantic.\footnote{At the meeting, this was effectively summarised by Pavel Kroupa, who commented – in response to an
In essence, therefore, it is not important whether the star-formation process forms a dense cluster, an embedded cluster or an association. What matters is whether star formation is correlated: are star-formation events quantised? Is there any length scale that is special and unique? If so, clusters of a given size and/or mass may well be the basic building blocks of galaxies. However, if star formation is hierarchical, this implies that there is no unique timeframe or spatial scale on which star-forming clumps are absolutely correlated. In the latter case, star clusters and associations are not unique; instead, they simply represent a continuous distribution. In extragalactic environments, at least, on spatial scales in excess of 5 pc there is no specific length scale (e.g., Bastian et al. 2009, 2011).

However, there is a unique scale at bottom of the fractal distribution in both the stellar and gas distributions, i.e., that of a dense core: $\sim 0.1$ pc. This is the scale of individual stars, which we could potentially resolve with ALMA or – for nearby star-forming regions – the Plateau de Bure interferometer. This is of a similar order as the scale of subsonic turbulence. In addition, the IMF exhibits a peak at stellar masses between $\sim 0.5$ and $1 M_\odot$, which also implies a characteristic mass scale.

From this discussion, the following hypothesis naturally results. The fundamental galactic building blocks are units of star formation of a few tenths of a parsec across, distributed according to a mass spectrum that is a power law down to a few $M_\odot$. If one were to distribute this kind of structure throughout a region of a galaxy according to a model of what the ISM looks like – essentially a fractal distribution – and then let it evolve dynamically, the result would enable us to derive which fraction of stars is found in distributed versus clustered mode. The null hypothesis of a scale-free star-formation process can thus be either verified or discarded.

In a hierarchical scenario, this picture would be created by a turbulence power spectrum that is self-similar. However, even in such an ISM there is a definite scale, i.e., the scale on which the turbulence is injected into the ISM – and this differs among galaxies because of variations in the perturbing mechanism. One cannot have correlated structures on scales that are larger than the scales on which the energy is injected. In Holmberg 2, a dwarf galaxy, Dib & Burkert (2005) found that the structures are correlated on a very large scale of $\sim 6$ kpc. In the Galaxy, Dib et al. (2009) found that the orientations of molecular clouds are spatially correlated on scales of a few 100 pc. This may be related to some instability in the outer Galaxy, because it is on the order of the scales of supernova remnants which evolve in a low-pressure environment. The conclusion is, therefore, that at least on large scales there must also be a characteristic spatial scale.

From the preceding discussion, it seems that asking whether star clusters are basic galactic building blocks is a matter of semantics. More interesting, perhaps, is understanding why, when and how star formation happens. Star clusters tell us about stellar populations, the conditions in molecular clouds and the gas at the time of their formation.

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argument proposed by Simon Goodwin – that “[w]hat I said is essentially what you said, just a bit more mathematical.”
4 How is the stellar mass distribution established?

4.1 Do any O-type stars form in isolation?

Can O-type stars form in complete isolation? The answer to this question is intimately linked to our understanding of where the IMF comes from and how it fits in with the cluster mass–maximum stellar mass relation (e.g., Weidner et al. 2010, and references therein). If the (molecular cloud) core mass function is the origin of the stellar mass function, then at the top end of the core mass function a very massive core may occasionally be formed because of stochastic effects (although note that observations are affected by small-number statistics). In very rare circumstances, this core will not fragment and collapses into one single massive object. For this to happen, the core needs to be warm so that it does not fragment, although a small cluster could form at the same place as well. In this case, the term ‘isolated O stars’ does not imply that no other stars can form nearby. On the contrary, a small cluster, possibly containing an O-star binary, might form, but the IMF is simply not fully sampled: it may contain a single O star, a few G stars, and possibly one B star, for instance.

If, on the other hand, the process of competitive accretion dominates, large cores will fragment into many objects. In this case, the starting point consists of cores with masses of around $1 \, \text{M}_\odot$. These allow formation of a few objects per core, some of which may then accrete additional mass. Proponents of this scenario assume that most of the stellar mass function is set by the core mass function, and most cores do not grow very massive. All cores start small and if there is not much ambient gas, none can grow big. The only way in which a massive core can develop is if there is a lot of ambient gas present and a few objects can accrete a significant fraction of that gas. Competitive accretion naturally leads to the cluster mass–maximum stellar mass relationship.

In reality, a combination of processes is likely responsible for the final stellar mass distribution. For instance, in 30 Doradus (the largest HII region in the Local Group), competitive effects must have played a very significant role, but in associations this may be a different side of the same coin. Perhaps we should instead ask the question as to how frequently one or the other mode of star formation dominates.

In the first scenario outlined above, the core mass function sets the stellar mass function. In the latter case, however, one cannot really predict the resulting mass function, yet the observed mass functions are very similar. So, the simple question is whether we can quantify any differences: Are there measurable differences between the mass functions of cores and stars?

4.2 What sets the initial mass function?

The IMF and core mass function appear very similar in terms of their morphology (except, perhaps, at the high-mass end), but this result depends on the implicit assumption of one-to-one mapping from cores to stars. However, we definitely observe cores (e.g. B59: Covey et al. 2010) that are single, do not exhibit any substructure or fragmentation, but contain 20 stars. Therefore, the scenario in which we shift the core mass function to the stellar mass function (modulo the star-formation efficiency, usually assumed to be $\sim 30\%$) depends on some assumption as to how this efficiency acts on individual cores. We have at least one
example where the peak should shift by more than a factor of 3. This problem is difficult to solve, because once the stellar mass function can be measured, significant stellar evolution is (and has already been) proceeding, while cores represent the very early, almost unevolved stages of star formation.

In an alternative approach, one may explore differences in the mass functions at the high-mass end, where any differences will be most pronounced. Based on observations of a statistically large number of clusters, it is very difficult to show that the observed, strict relationship between the mass of the most massive star and that of its parent cluster is valid under any circumstances. However, if one were to observe the formation of a single massive star, that would represent a significant deviation from that relationship. Therefore, if a truly isolated O star were found (i.e., an exception to the rule), there would be at least one case in which competitive accretion has not worked, thus providing support for the stochastic sampling theory.

In observational terms, let us compare Taurus, a region of active star formation harbouring a mass of some $10^3 – 10^4 M_\odot$, and NGC 3603, a larger star-forming region. In essence, the random sampling scenario implies that a collection of molecular material composed of Taurus-like units equivalent to that of a large cluster would never produce a massive star. However, proponents of the idea of competitive accretion would argue that a large number of Taurus-like units do lead to the formation of massive stars. This apparent conflict may disappear if it were a simple matter of scaling up one’s star-forming regions. If one considers Orion, for instance, the morphology is always the same, exhibiting numerous filaments and clumps – just like the structure of Taurus. Scaling this kind of hierarchical structure up leads to configurations resembling Orion A. Alternatively, small sections of Orion A at high resolution look exactly like Taurus or the Pipe Nebula.

An alternative approach to the conundrum of massive-star formation may be found in considering the ratio between the number of massive to low-mass stars in different regions. If we first consider Orion and count the total number of low-mass stars as well as the number of massive stars, and we find that the number of massive stars is underrepresented in the entire Orion area, what do we deduce from this? Similarly, if we explore this ratio in dwarf galaxies, i.e., we count the number of massive stars in a dwarf galaxy with a low star-formation rate and we find that there are too few massive stars compared to what we expect from the shape of the ‘canonical’ IMF, what do we conclude from this, since it is all driven by purely stochastic (random) sampling? The underlying idea of stochastic sampling is that if we add many Taurus-Auriga-like structures to form an Orion-like configuration, we should find an IMF that is more dominated by low-mass stars than expected for a canonical IMF. We can thus either exclude or verify random sampling as a viable star-formation scenario.

However, these scenarios may be too simplistic. First, if massive clusters form from hierarchical mergers of subclusters before gas expulsion, then the prestellar clumps in these subclusters do not know \textit{a priori} where they will end up. Why then is there a clear correlation between the maximum stellar mass in a cluster and the total cluster mass? Second, one may wonder whether there are any clumps that collapse in which the star formation has completely stopped. Instead, star formation is likely ongoing while the clumps collapse and during the early dynamical evolution of the resulting systems. This early collapse occurs on essentially the free-fall timescale, at least in Orion-like clusters (e.g., Allison et al. 2009, 1010; Yu et al. 2011). This is corroborated by arguments based on structural parameters:
at longer wavelengths (e.g., as seen with the Spitzer Space Telescope), star-forming regions are rather filamentary. However, when we consider nearly ‘complete’ clusters, they are quite spherical but not extremely substructured: collisions of these clumps seem, therefore, quite fast. Perhaps some of these clumps first merge before forming a massive star (e.g., to release angular momentum). One should keep in mind that the entire picture is extremely dynamical; one certainly cannot assume that young star-forming clumps evolve in isolation.

Finally, one should be cautious in linking the stellar mass distribution directly to the star-formation process. Although we have assumed in this discussion that the IMF is somehow the result of star formation, it is perhaps better to state that at the end of the star-formation process, a near-invariant IMF results. A similar IMF is also observed at the start of the process of star formation. However, one should keep in mind that the start of the fragmentation process may be driven by different physics than that underlying that of star formation itself (i.e., the reasons for the onset of the collapse). As a consequence, depending on how one defines one scale, the resulting clusters and cluster masses may differ, so that the IMF does not carry much or any information about the star-formation process.

4.3 Binarity

What is the role of multiplicity in high-mass stars? There are numerous examples of significant multiplicity fractions in young (star-forming) environments, e.g. the Orion Nebula’s Trapezium system or the young Large Magellanic Cloud (LMC) cluster NGC 1818 (Hu et al. 2010). Each of the massive Trapezium stars is at least a binary, and there are many more examples. Even based on interferometric submillimetre observations, some Class 0 objects have been found to be multiple.

Let us assume that the power-law stellar mass distribution goes down to very low masses. For stellar masses below $\sim 100 \, M_\odot$, the population of these objects will not be dynamically processed; it will simply disperse. Given that the IMF is quite invariant, it then follows quite reasonably that the binary populations may also be initially invariant (assuming universal binary properties). One can now calculate the binary population expected for a galactic field or an entire galaxy, if we understand star formation to the extent we believe we do in the Milky Way, i.e., where the IMF and binary populations are both universal and stars form in power-law structures. One can show that the galactic-field binary population is derived beautifully, because the more massive objects break up the binaries, while the lower-mass objects do not. This leads to an invariant IMF and binary population. One can then predict that dwarf galaxies should have high and starburst galaxies low binary fractions. This could potentially be checked observationally, at least if we could resolve nearby galaxies into individual stars.

5 What are the conditions for massive-cluster formation?

On larger scales, how do globular clusters (GCs) form? The answer to this question is linked to how environmental conditions affect further cluster formation. Large numbers of massive proto-GCs formed in the past, but why do we not see similar numbers at the present time in the Milky Way? The massive young cluster Westerlund 1 may be a recent example, although it is also possible that it may turn into an open cluster or dissolve into the Galactic field because
of its rather extreme environmental conditions. In fact, we have to be careful in making a clear distinction between open and globular clusters. We see young GCs in massive galaxy mergers, and even in spiral disks. Instead of advocating distinct formation mechanisms, we are most likely observing the remnants of a much more varied original population – which may have formed following a variety of mechanisms – of which many members have disappeared because of dynamical evolution. The main physical driver underlying the mass build-up of young star clusters is the star-formation-rate density: higher densities allow a cluster to assemble more mass before star formation ceases.

At least some of the massive globular-like clusters in galaxies like the Milky Way originated in smaller dwarf galaxy companions (including, most likely, ω Centauri), which later merged with the main galaxy dominating the local gravitational potential. This leads to the question as to why we do not observe many of such massive proto-GCs in dwarf galaxies like the Magellanic Clouds. The LMC contains the most significant H II region in the Local Group, 30 Doradus, but it is small by comparison of the structures required to form true GCs. Other nearby dwarf galaxies, including NGC 1569 and NGC 1705, do contain the type of object that may evolve into genuine GCs, however.

How can such small dwarf galaxies host several globular or young massive clusters that contain some 10% of the total mass of these galaxies? Molecular clouds can be larger in dwarf galaxies because of the lower shear and tidal forces in these systems compared to large spiral galaxies. In the Milky Way, molecular cloud masses are of order $10^5 - 10^6 M_\odot$, while in the LMC they are approximately $10^7 M_\odot$, for instance. Molecular clouds in galaxies with lower shear can grow larger by agglomeration.

Two other, complementary effects (both related to metallicity) might make clumps and/or giant molecular clouds more massive in galaxies like the Large and Small Magellanic Clouds. In lower-metallicity galaxies, the gas-to-dust coupling occurs at a different density compared to that in higher-metallicity environments. The probability density function is broader and extends to higher densities, because a cloud has to accumulate more mass to shield itself (e.g., Glover & Clark 2011). Second, lower-metallicity feedback is less effective and allows for more star formation, potentially also resulting in more massive clusters and associations.

The natural question to ask in this context is whether the cloud (and cluster) mass function in dwarf galaxies is different from that in $L^*$ galaxies. Current thinking implies that complete universality is no longer fully supported by the data, but one has to look carefully at where the differences arise. There are no significant differences between the Magellanic Clouds and the Milky Way. On the other hand, despite the small-number statistics affecting these arguments, it is curious that dwarf galaxies like NGC 1569 and NGC 1705 host very massive ($> 10^5 M_\odot$) clusters, which are truly outstanding in their respective cluster mass functions.

Ongoing research aimed at addressing the question of the origin of the most massive young and globular clusters has not yet produced a satisfactory answer. The most massive clusters in extragalactic environments are found in merging systems. Observations and theory support many mergers in the young Universe. However, mergers are not necessarily the evolutionary end point of a galaxy: disks can reform within a Gyr, potentially allowing the formation of new populations of GCs at that stage.
Perhaps the most promising approach to addressing the GC formation scenario resides in the use of concrete, observable indicators that can help distinguish the various formation scenarios proposed. Massive ellipticals contain the largest populations of GCs, the most massive GCs and the highest metallicities. Dwarf galaxies have very low metallicities, so that it appears unfeasible to merge large numbers of dwarf galaxies to form ellipticals. To understand GC formation, much better metallicity measurements are required. Similarly, better determinations of ages and age spreads are advisable, although they are much harder to obtain. Metallicities – both integrated and of individual stars in resolved, nearby clusters – are the most basic, clearest and most important indicator of how GCs may have formed.

Despite a significant body of recent work in this field, there is no single observation of a subclustered massive proto-GC. Most of our theoretical understanding of the details of massive cluster formation hinge on scenarios involving scaled-up versions of smaller open cluster-like configurations, where we do see clear substructure at early stages. Nevertheless, tantalising objects that might indeed provide clues as to the morphology of forming proto-GCs on small scales include Sagittarius B2 (e.g., Bally 2010) – observed as part of the Bolocam Galactic Plane Survey – and the embedded massive young clusters in NGC 5253. Further Galactic Plane surveys (e.g., Lucas et al. 2008; Minniti et al. 2010) will be instrumental in constraining the early evolutionary properties of such objects.

Although at the present time we do not know of any proto-GCs in the Milky Way, with the possible exception of Westerlund 1, our observational sample is very incomplete: to date, only 14 massive young stellar clusters have been discovered on the near side of the Galaxy, all with masses around $10^4 \, M_\odot$. In addition, Davies et al. (2011) recently discovered a 1 Gyr-old, $10^5 \, M_\odot$ cluster in the Galactic disk at a distance of only $\sim 2$–3 kpc. Indeed, very massive clusters do form occasionally in galactic disks (e.g., Larsen et al. 2001).

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