A revolution in star cluster research:
setting the scene

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Star clusters and their stellar populations play a significant role in the context of galaxy evolution, across space (from local to high redshift) and time (from currently forming to fossil remnants). We are now within reach of answering a number of fundamental questions that will have a significant impact on our understanding of key open issues in contemporary astrophysics, ranging from the formation, assembly and evolution of galaxies to the details of the star-formation process. Our improved understanding of the physics driving star cluster formation and evolution has led to the emergence of crucial new open questions that will most likely be tackled in a systematic way in the next decade.

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1. Our improved understanding of star cluster physics

It is now widely accepted that 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 a clustered mode (cf. Lada & Lada 2003). Star formation results from the fragmentation of molecular clouds, which in turn preferentially leads to star cluster formation. Over time, clusters dissolve or are destroyed by interactions with molecular clouds or tidal stripping by the gravitational field of their host galaxy. Their member stars become part of the general field stellar population. Star clusters are thus among the basic building blocks of galaxies. Star cluster populations, from young associations and open clusters to old globular clusters, are therefore powerful tracers of the formation, assembly and evolutionary history of their host 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 related to the make-up of the cluster and field stellar populations in a variety of galaxies and galaxy types, their relative formation timescales (and what this implies for overall and resolved galactic star-formation histories) and the relationships between local and high-\( z \) stellar and cluster populations.
The refereed contributions in this issue of Phil. Trans. R. Soc. A cover a wide range of topics in contemporary astrophysics related to star cluster formation, evolution, destruction and environmental impact, particularly in the context of star formation on galactic scales. Lada (2010) and Clarke (2010) discuss the formation of star clusters from, respectively, an observer’s and a simulator’s point of view. Kalirai & Richer (2010) and van Loon (2010) then take detailed looks at stellar and chemical evolution of star clusters and their constituent stars, while Goodwin (2010) and Vesperini (2010) focus specifically on aspects related to the binary stellar populations affecting star cluster evolution and the makeup of the general field, and cluster dynamics, respectively. Larsen (2010) and Harris (2010) take wide-angle views of entire cluster populations, roughly split between young (Larsen 2010) and old (Harris 2010) samples, while Bruzual (2010) discusses their integrated evolution and issues relevant to the assumptions usually adopted for modelling these systems as ‘simple stellar populations’ (SSPs).

While the review articles in this volume focus in detail on the wide-ranging fields touched by state-of-the-art star cluster research, here I address—non-exhaustively and roughly as a function of cluster age—some of the higher-level challenges limiting sustained progress, which will most likely be tackled by the research community in the next decade.

2. Early evolution

One of the critical remaining issues pivotal to our understanding of the early evolution of star clusters is the question as to precisely how and when stars form. Although I will focus on the issues pertinent to star cluster research, solving this issue will clearly have profound consequences for a much wider range of fields in astrophysics. Simplistically, the problem can be divided into two subquestions: (i) How is star formation triggered and how does it proceed, and (ii) How do the star-formation mode, efficiency and pressure of the interstellar medium (ISM) lead to the resulting stellar mass distribution (i.e., the initial mass function, IMF) and in particular what is the role of the massive stars compared to that of their lower-mass counterparts? The latter links the early evolution of star clusters unequivocally to their environmental impact, which I will address in §3a.

(a) The low-mass stellar initial mass function

Although the shape of the stellar IMF in the solar neighbourhood, and particularly for stellar masses > 1 M⊙, has essentially been unchallenged since Salpeter’s (1955) seminal study, its origin remains hotly debated (e.g., Bonnell et al. 2007; Goodwin & Kouwenhoven 2009). Constraining the physical origin of the IMF will have a major impact on, e.g., our understanding of the conditions prevailing in a wide range of starburst events, and the formation of the first stars and clusters in the early universe, at z ≥ 5—although, for a full understanding, we would need to follow the radiative cooling processes from primordial gas and the subsequently formed metallic elements in full detail!

Significant uncertainties in shape remain at both the low- and high-mass extremes of the IMF, however. At the low-mass end, the prevailing models agree that the solar-neighbourhood IMF flattens. This can be modelled by either multi-
ple power-law or lognormal mass distributions (cf. Kroupa 2001; Chabrier 2003). While the former provides a mathematically simple and observationally useful scaling law, the latter is supported by realistic numerical simulations (Hennebelle & Chabrier 2008). These take into account dynamical depletion of the lowest-mass stars and replace the idea of a single Jeans mass for all newly formed stars in a given molecular cloud by a distribution of local Jeans masses which are representative of the lognormal density distribution of the turbulent, fragmenting gas. As statistically significant samples of roughly coeval stars, rich young star clusters play a major role in constraining the low-mass IMF. Open questions remaining in this field relate to whether there is any metallicity dependence of the IMF shape for stellar masses $< 1 \, M_\odot$, the initial structure of newly formed clusters, and whether the ubiquitous mass segregation observed in clusters of any age is dynamical or perhaps primordial (i.e., related to the process of star formation).

Preliminary clues as to the shape of the low-mass IMF (down to $\sim 0.15$–$0.30 \, M_\odot$) in the low-metallicity ($Z \sim 0.4 \, Z_\odot$) environment of young ($\sim 4$–$45$ Myr) Large Magellanic Cloud (LMC) clusters have recently been uncovered on the basis of deep Hubble Space Telescope (HST) imaging observations (e.g., Da Rio et al. 2009; Liu et al. 2009a,b). These studies imply that the IMFs of these young clusters are essentially the same as that in the solar neighbourhood, although the characteristic stellar masses are somewhat higher. One would ideally want to probe younger star-forming regions to reach firmer conclusions, but these are inevitably obscured by large amounts of dust, hence requiring deep and often wide-field infrared (IR), (sub)millimetre, radio and X-ray surveys (and pointed observations) that are now coming online (e.g., the Spitzer Space Telescope’s GLIMPSE survey or the UKIRT IR deep-sky survey, UKIDSS; e.g., Benjamin et al. 2003; Lucas et al. 2008) and which probe the low-mass stellar mass distribution in particular (see, e.g., Rathborne et al. 2009).

Simulations of star cluster evolution almost always assume that the stars are initially smoothly distributed and in dynamical equilibrium. However, both observations and the theory of star formation tell us that this is not how clusters form. Goodwin & Whitworth (2004) and, more recently, Allison et al. (2009) investigated the effects of substructure and initial clumpiness on the early evolution of clusters. Comparisons with observations will allow us to constrain how much initial substructure can be present. The most massive stars in young star clusters are almost always observed to be in the inner regions of those clusters (e.g., Hillenbrand & Hartmann 1998; de Grijs et al. 2002a,b,c; Gouliermis et al. 2004). A crucial question triggered by this observation relates to the origin of this observed mass segregation. Do massive stars form in the centres of clusters, or do they migrate there over time due to gravitational interactions with other cluster members? In smooth, relaxed clusters it seems that the most massive stars must form in the cores, which is therefore often referred to as primordial mass segregation (but see Ascenso et al. 2009). But does substructure play a role?

Both observational evidence (e.g., Larson 1995; Testi et al. 2000; Elmegreen 2000; Lada & Lada 2003; Gutermuth et al. 2005; Allen et al. 2007) and theoretical considerations suggest that young star clusters tend to form with a significant
amount of substructure. Their progenitor molecular clouds are observed to have significant levels of substructure in both density and kinematics (e.g., Carpenter & Hodapp 2008), which is likely induced by the supersonic turbulence thought to dominate molecular cloud structure (e.g., Mac Low & Klessen 2004; Ballesteros–Paredes et al. 2007). Observations also imply that young clusters lose their substructure on timescales of < 2 Myr (e.g., Cartwright & Whitworth 2004; Schmeja et al. 2008). Simulations suggest that the only way in which this could happen is if clusters are born dynamically cool (Goodwin et al. 2004; Allison et al. 2009; Lada 2010). On the basis of these arguments, Allison et al. (2009) recently performed an ensemble of N-body simulations aimed at exploring the earliest phases of cluster evolution. They find that cool, substructured clusters appear to mass segregate dynamically for stellar masses down to a few M⊙ on timescales of a few Myr. This is reminiscent of the observational status of the Orion Nebula Cluster (e.g., Bonnell & Davies 1998; Allison et al. 2009; Moeckel & Bonnell 2009). More work is required to systematically address the most likely initial conditions for cluster formation leading to the observed configurations.

(c) Initial binarity

Simulations of star clusters also often tend to neglect the presence of binary stars. Observations of local star-forming regions lead us to suspect that all, or nearly all, stars form in binary or triple systems (Goodwin & Kroupa 2005; Duchêne et al. 2007; Goodwin et al. 2007). Such systems significantly affect the dynamical evolution of the cluster, yet the initial binary fractions in dense star clusters are poorly known. Almost all studies of binarity have been limited to nearby solar-metallicity populations (see Duchêne 1999 and Duchêne et al. 2007 for reviews). However, it might be expected that metallicity (e.g., through its effects on cooling and hence on the opacity limit for fragmentation) will play a role in the fragmentation of cores to produce binary systems (Bate 2005; Goodwin et al. 2007).

The binary fractions in more distant, massive clusters have not yet been studied thoroughly, because of observational limitations—although statistical colour–magnitude analysis based on artificial-star tests offer a promising alternative (e.g., Romani & Weinberg 1991; Rubenstein & Bailyn 1997; Bellazzini et al. 2002; Cool & Bolton 2002; Zhao & Bailyn 2005; Davis et al. 2008). However, all clusters thus far studied in this way are old stellar systems, in which dynamical evolution is expected to have altered the initial binary population significantly. Efforts have begun to address this issue for the much more distant young populous clusters in the LMC (e.g., Elson et al. 1998). Hu et al. (2009) estimate that the binary fraction in NGC 1818 in the mass range between 1.3 and 1.6 M⊙ is ∼ 0.35 for systems with an approximately flat mass-ratio distribution, q, for q > 0.4. This is consistent with a total binary fraction of F stars of 0.6 to unity. Do high binary fractions affect mass segregation at early times or the relaxation of substructure? Do they leave observational signatures? NGC 1818 is several crossing times old, so that the binary population should have been modified by dynamical interactions. In particular, soft (i.e., wide) binaries are expected to have been destroyed by this age. Therefore, the high binary fraction found for F stars suggests that these binaries are relatively ‘hard’ and able to survive dynamical encounters.
(d) The high-mass end of the stellar IMF

Understanding the origin of mass segregation may also help distinguish models of massive star formation. In particular, are the masses of the most massive stars set by the mass of the core from which they form (e.g., Krumholz et al. 2007), or by competitively accreting mass due to being located at a favourable position in the cluster (e.g., Bonnell et al. 1998; see also Krumholz et al. 2005, and Bonnell & Bate 2006)? Allison et al.'s (2009) result showing that dynamical mass segregation can occur on a few crossing timescales suggests that massive stars could form in relative isolation in large cores and mass segregate later, possibly avoiding the need for competitive accretion as dominant process to form the most massive stars in the centre of a cluster.

The formation of the most massive stars in a given stellar population is thus riddled with uncertainties. Claims (as well as counterclaims) abound in the literature of top-heavy IMFs (i.e., containing too few low-mass stars compared to the solar-neighbourhood IMF) among resolved star clusters, both in and beyond the Local Group of galaxies (e.g., Smith & Gallagher 2001 versus Bastian et al. 2008; Kim et al. 2006 versus Klessen et al. 2007 versus Espinoza et al. 2009; Harayama et al. 2008; McKee & Tan 2002; Dabringhausen et al. 2009). The relevant open questions that require firmer answers address why there are so few massive stars in most 'normal' stellar populations (is this simply a matter of small-number statistics and hence stochasticity?) and, consequently, how they form (cf. Zinnecker & Yorke 2007) and what their impact is on the cluster environment. The physical conditions in clusters containing significant numbers of massive OB stars are of prime interest for planetary scientists: although planet formation may be qualitatively different in dense clusters compared to the more quiescent field, is the formation of planetary systems from protoplanetary discs and subsequent planet growth inhibited or promoted near OB stars (e.g., Hollenbach et al. 2000; Throop & Bally 2005)? Clearly, this question also applies to further star formation near such massive stars.

(e) Timescales and triggering of star and cluster formation

Following on from our rather rudimental understanding of the role of massive stars during cluster formation, the latter is still far from well understood. The two main competing scenarios require either a rapid collapse in a single crossing time (e.g., Elmegreen 2000, 2007; Heitsch & Hartmann 2008) or slow formation over many dynamical times (e.g., Tan et al. 2006). Proponents of the former scenario suggest that this can be facilitated by flow-driven cloud formation of atomic gas aided by gravitational compression, with supersonic turbulence (or internal feedback) and star/protostar interactions playing only minor roles. Arguments offered in favour of a slower formation timescale include observational details such as age spreads in star-forming clusters (for recent new insights, including multiple main sequences in individual clusters, see the review by Piotto 2009) and the momentum flux of molecular outflows, where turbulence does play an important role. Kine-matical studies based on precision astrometry and radial velocities will hopefully soon enable us to refine theoretical models of turbulent cloud collapse and draw firmer conclusions on the timescales of star formation in a clustered mode and their subsequent evolution.

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This leads us to the question as to how exactly star formation in clusters and associations is triggered, and how much of the molecular gas is converted into stars (i.e., the star-formation efficiency, SFE). On the smallest scales, the effects of the first generations of massive stars in a particular star-forming region, in the form of expanding HII regions and pre-supernova shocked and ionized OB winds, trigger ongoing star formation by destroying their natal molecular clouds (e.g., Joung & Mac Low 2006; Elmegreen & Palouš 2007). On galaxy-wide scales, both gravitational and feedback processes seem important for the formation of the most massive clusters. However, this may simply be the result of the hierarchical star-formation process, where the densest regions have the highest SFEs. If this were the full scenario, how then do quiescent spiral galaxies characterized by low SFEs manage to form extremely massive clusters that may eventually become counterparts to the ubiquitous old globular clusters (see for a review de Grijs & Parmentier 2007)? Are there environments today that are conducive to the formation of massive clusters that may eventually become old globular cluster counterparts, or did the oldest star clusters in our Milky Way form in an entirely different star-formation mode? Alternatively, how do dwarf galaxies form extremely massive star clusters without external triggers?

\[ (f) \text{ The star-formation efficiency} \]

Does the formation of the highest-mass star clusters need an external trigger, and hence does their age distribution fully reflect the underlying galactic interaction history? How does the inferred SFE compare to equivalent values elsewhere in the same or other galaxies undergoing more quiescent star formation? Alternatively, do the highest-mass clusters (with masses of, say, \( > 10^6 \) M\(_\odot\)) form differently from their lower-mass counterparts, for instance through large-scale mergers of cluster complexes (e.g., Bastian et al. 2006; Fellhauer et al. 2009) and how does this differ from the formation of tidal dwarf galaxies (e.g., Bournaud et al. 2008)? On the other hand, is their formation simply a consequence of the hierarchy of star formation? If these young massive clusters are not very rare exceptions, where then are the descendants of all those massive star clusters that presumably formed earlier on in their host galaxies?

Hydrodynamical cluster-formation modelling shows that SFEs on the order of 30% or higher are required to form a massive cluster that is long-term stable (e.g., Brown et al. 1995; Elmegreen & Efremov 1997; Bastian & Goodwin 2006). This is at least an order of magnitude higher than the SFEs in normal spiral and irregular galaxies, or in dwarf galaxy starbursts (see, for a review, Anders et al. 2007). SFEs as high as 30% or more, however, are observed in global and nuclear starbursts triggered by massive gas-rich mergers, such as NGC 7252, and ultra-luminous IR galaxies (Fritze–v. Alvensleben & Gerhard 1994; Gao & Solomon 2004).

In addition, observations of a gap in cluster ages but not in that of the field stellar population in the LMC suggest that cluster formation there took place in stages of enhanced star formation only, possibly related to close encounters of the LMC with the Milky Way and/or the Small Magellanic Cloud (SMC). Similarly, star cluster formation in both M51 and M82 is found to have been significantly enhanced during their last close encounters with their neighbouring galaxies (e.g., de Grijs et al. 2001; Bastian et al. 2005; Smith et al. 2007), once again, precisely
when the overall star formation and the SFE are expected to be enhanced. In interacting galaxies, the frequency of molecular cloud collisions is expected to increase strongly. This will considerably enhance star formation. Moreover, molecular clouds get shock-compressed by external pressure, grow denser and more massive, and this can drive up the SFE very efficiently (e.g., Jog & Solomon 1992; Barnes 2004). Jog & Das (1992, 1996) showed that a relatively small increase in the external ambient pressure to values 3–4 times the internal pressure within the molecular clouds in an undisturbed galaxy can drive SFEs up to 70–90%. Does this mean that the molecular cloud structure in galaxies characterized by enhanced SFEs is somehow different from that in more quiescent galaxies? We probably need to wait until the Atacama Large Millimeter/submillimeter Array (ALMA) comes online before we can even begin to address this question in more distant interacting galaxies. It probably implies, however, that star formation is more fundamentally governed by the content of high density gas, not the overall gas content (Solomon et al. 1992; Gao & Solomon 2004). Hydrodynamical modelling of galaxies and galaxy mergers will thus need to account for a multi-phase ISM and include a careful description of phase transitions, star formation and feedback processes.

Despite significant recent theoretical and observational progress, the quantitative importance of triggering and the effects of varying SFEs in cluster formation remain major challenges.

3. Environmental impact

(a) Feedback and star cluster survival

Star clusters, and particularly their most massive member stars, ionize their natal H\textsuperscript{II} regions, inflate wind-blown bubbles and outflows, and eventually explode as supernovae. The latter, in turn, chemically enrich the ISM, drive turbulence, and may trigger secondary star and cluster formation and power superbubbles (e.g., Silich et al. 2007, 2009; Wünsch et al. 2008) and ‘superwinds’ (e.g., Westmoquette et al. 2007, 2008, 2009; Law et al. 2009 for the Milky Way) into the haloes of their host galaxies. Star cluster feedback processes are therefore of fundamental importance for our understanding of the overall energetics and evolution of galactic-disc stellar populations.

Young massive star clusters are of particular interest in this context, as they contain some of the most massive main-sequence, supergiant, hypergiant and Wolf–Rayet stars, which are associated with strong winds and supernova remnants that profoundly affect the surrounding ISM. Assessing the relationship of the most massive clusters to the local ISM is critical to validate formation scenarios of massive star clusters, and in particular whether IMF variations might be expected as a function of ISM pressure differences (e.g., McKee & Tan 2002). Recently, wide-field survey products in hitherto inaccessible spectral domains (e.g., GLIMPSE in the mid-IR) have revealed a significant population of previously unknown ionized bubbles and supernova remnants, likely produced by thus far hidden star clusters. Efforts are underway to better characterize the star-forming landscape in the Galactic plane using these and other surveys (e.g., Lucas et al. 2008; Minniti et al. 2009).
Cluster winds are as yet poorly understood because it is not possible to treat directed outflows self-consistently (while full 3D radiative transport computations are still beyond reach), but their importance for chemical enrichment of the ISM is profound. The amount of radiative cooling present within the cluster volume seems important for a fuller understanding of their impact. It may be possible, under the right conditions, for the wind to cool sufficiently within the cluster to generate a second stellar generation. Could this perhaps explain the secondary main sequences (or self-enrichment) observed in some globular clusters (e.g., Bedin et al. 2004; Piotto 2009)? What exactly is the interplay between cluster winds and the ISM and how does this depend on the ISM pressure (cf. Westmoquette et al. 2007, 2008)? Can cluster outflows be inhibited if the ISM pressure is sufficiently high?

New key questions are emerging rapidly: What are the survival chances of young, embedded star clusters beyond the first $\sim 10$ Myr, in view of the disruptive effects of these large-scale outflows (see also §4a)? What is the initial distribution of gravitationally bound cluster masses (see for a review de Grijs & Parmentier 2007)? This is, of course, linked to the conditions (e.g., the interstellar pressure and density) under which bound objects form, which traces back to the issue of whether star clusters form the top of the hierarchy of star formation. What is the SFE, and in particular the cluster-formation efficiency, in regions of intersecting and colliding (super)winds?

Finally, and more speculatively, do these feedback processes have any bearing on the difference in dark matter content between compact star clusters (no need for dark matter), the population of faint dwarf spheroidal galaxies in the Local Group (dark-matter dominated; e.g., Swaters et al. 2003), the newly discovered extended clusters in M31 (Huxor et al. 2005), and the population of ultracompact dwarf galaxies (e.g., Gregg et al. 2009)? In the diagnostic diagram showing absolute $V$-band magnitude as a function of half-mass radius (e.g., Huxor et al. 2005), the region between the dark-matter dominated objects and that occupied by ‘normal’ clusters is increasingly being filled in, particularly by the extended star cluster population in M31 (A. M. N. Ferguson 2009, personal communication). Is there a regime between these objects where there is a sudden step change in dark matter content, or is this change more gradual? Ongoing and planned projects, such as the Pan-Andromeda Archaeological Survey (PAndAS; McConnachie 2009), may soon shed light on these questions. Their answers will have far-reaching implications for our understanding of the cosmological evolution of dark matter haloes and their star-forming cores (e.g., Bullock & Johnston 2005; Johnston et al. 2008).

(b) Products of binary evolution

Many exotic objects observed in star clusters, such as blue stragglers (BSs), cataclysmic variables and X-ray sources, as well as the putative intermediate-mass black holes, are believed to be related to binary systems. Cluster environments are particularly interesting in the context of binary systems: they can be created, altered and destroyed by interactions with their many nearby neighbours. Naively, one would expect that the gravitational interactions of stars in clusters will ultimately lead to a core collapse to an infinite mass in a finite time. Indeed, post-core-collapse (PCC) clusters do exist, but their cores have not collapsed in such a dramatic manner. Something must therefore eventually stop this process, most likely the
formation of binaries in the cluster cores during the late collapse stages. In fact, the formation of a few hard binaries could entirely halt this core collapse, even in the most massive clusters.

X-ray observations, in particular, have provided circumstantial evidence for significant binary populations in star clusters. A much higher fraction of X-ray-bright sources in our Milky Way is associated with globular clusters than would be expected from the field stellar population. These are believed to be short-period binaries in which mass is transferred from a main-sequence onto a neutron star (cf. Phinney & Kulkarni 1994). These low-mass X-ray binaries form preferentially in globular clusters, perhaps as the result of core collapse. However, many PCC clusters do not contain X-ray binaries, so other types of binaries must exist there to halt their collapse.

Perhaps the most common binary collision products in clusters include the ubiquitous BSs. Although BSs are relatively rare in number compared to the regular member stars in a given cluster, these luminous stars have a non-negligible effect on the cluster’s integrated-light properties. Nevertheless, their contributions to the most commonly used SSP models are routinely neglected. Preliminary results show that the integrated spectral properties of a sample of Galactic open and rich Magellanic Cloud clusters are dramatically modified by their BS components (Xin & Deng 2005; Xin et al. 2007; Y. Xin 2009, personal communication). Using either spectra or broad-band colours, the resulting ages and/or metallicities will be underestimated significantly. Conservatively, the underestimates to both cluster ages and metallicities are $\sim 50\%$. Given the ubiquity of BSs in a great variety of environments, this seems an issue that needs to be addressed rather urgently.

4. Death throes

Star clusters are subject to a variety of internal and external mechanisms that, under the appropriate conditions, will gravitationally unbind and subsequently disrupt them. These effects include (see de Grijs & Parmentier 2007), approximately as a function of increasing timescale, (i) formation in a marginally bound state (see also the review by Mac Low & Klessen 2004), (ii) rapid removal of the intracluster gas due to adiabatic or explosive expansion driven by stellar winds or supernova activity, typically on timescales much shorter than the proto-cluster dynamical crossing time, (iii) mass loss due to normal stellar evolution (including the effects of stellar winds and supernova explosions), (iv) internal two-body relaxation effects, leading to dynamical mass segregation and the preferential ejection of lower-mass stars, (v) release of energy stored in a significant fraction of primordial hard binary systems, and (vi) tidal and gravitational effects due to interactions with other significant mass components, spiral arms, bulge or disc shocking and dynamical friction.

(a) Cluster infant mortality

Observations of increasing numbers of interacting and starburst galaxies show a significantly larger number of young ($\lesssim 10$–$30$ Myr) star clusters than expected from a simple extrapolation of the cluster numbers at older ages, taking into account the observational completeness limits and the effects of sample binning, and under the additional, simplifying assumption that the star cluster formation rate has
been roughly constant over the host galaxy’s history (see for reviews de Grijs & Parmentier 2007; Whitmore et al. 2007).

These observations have prompted a flurry of activity in the area of cluster disruption processes. This has led to suggestions that cluster systems appear to be affected by a disruption mechanism that acts on very short timescales ($\lesssim 10–30$ Myr) and which may be mass-independent, at least for masses $\gtrsim 10^4 M_\odot$ (e.g., Fall et al. 2005; Bastian et al. 2005; Fall 2006). This fast disruption mechanism, which is thought to effectively remove up to 50–90% of the youngest clusters from a given cluster population (e.g., Lada & Lada 1991; Whitmore 2004; Bastian et al. 2005; Mengel et al. 2005; Goodwin & Bastian 2006; Whitmore et al. 2007), is in essence caused by the rapid removal of the intracluster gas on timescales of $\lesssim 30$ Myr. The observational effect resulting from this rapid gas removal has been coined cluster ‘infant mortality’ (Lada & Lada 2003); it was originally reported in the context of the number of very young embedded clusters in the Milky Way, compared to their older, largely gas-free counterparts.

The general consensus emerging from recent studies into these effects is that rapid gas removal from young star clusters, which could leave them severely out of virial equilibrium, would be conducive to subsequent cluster disruption (Vesperini & Zepf 2003; Bastian et al. 2005; Fall et al. 2005). The efficiency of this process will be enhanced if a cluster’s SFE is less than about 30%, independent of the mass of the cluster (see de Grijs & Parmentier 2007 for a review). Goodwin & Bastian (2006) show that this type of cluster destruction occurs in 10–30 Myr (see also Kroupa & Boily 2002; Lada & Lada 2003; Lamers & Gieles 2008). The consequence of this is that clusters will expand rapidly to attain a new virial equilibrium, and hence disappear below the observational detection limit on a similar timescale. Depending on their SFE, a fraction of the more tightly bound clusters will, by the time they reach an age of $\sim 30–40$ Myr, subsequently contract again (Goodwin & Bastian 2006), hence increasing their mean surface brightness and thus their chances of being detected in magnitude-limited photometric surveys.

The early evolution of the star cluster population in the SMC has been the subject of considerable recent interest and debate (e.g., Rafelski & Zaritsky 2005; Chandar et al. 2006; Chiosi et al. 2006; Gieles, Lamers & Portegies Zwart 2007; de Grijs & Goodwin 2008). Chandar et al. (2006) argued that the galaxy has been losing up to 90% of its star clusters per decade of age, at least for ages from $\sim 10^7$ up to $\sim 10^9$ yr, while Gieles et al. (2007) concluded that there is no such evidence for a rapid decline in the cluster population, and that the decreasing number of clusters with increasing age is simply caused by evolutionary fading of their stellar populations in a magnitude-limited cluster sample. de Grijs & Goodwin (2008) set out to shed light on this controversy (see also Lamers 2008). On the basis of an independent data set, they placed a limit on the extent of infant mortality between the age ranges $\sim 3–10$ Myr to $\sim 40–120$ Myr of $\lesssim 30\%$ (1σ). They ruled out a $\sim 90\%$ mortality rate per decade of age at a $>6\sigma$ level. In addition, a first glance at the LMC cluster population’s age distribution (de Grijs & Goodwin 2009) indicates that the number of clusters populating the first $\sim 100$ Myr can likely also be fully explained by simple evolutionary fading of a magnitude-limited cluster sample, without the need to invoke infant mortality for cluster masses $\gtrsim 10^3 M_\odot$.

These results raise a number of important questions. In particular, could the apparent absence of infant mortality be hidden by assumptions of a constant clus-
ter formation rate? Alternatively (or additionally), could mass-dependent infant mortality be at work in the Magellanic Clouds? Or does the apparent difference between the Magellanic Clouds on the one hand and the Antennae system, M51 and the Milky Way on the other suggest a completely different underlying physical process which may be density dependent? Finally, do the effects of gas expulsion differ if we properly include realistic initial conditions for star cluster formation in a combined hydrodynamical/N-body modelling approach (cf. Fellhauer et al. 2009)?

(b) Dynamical dissolution

Those clusters that survive the infant mortality phase will be subject to the processes driving longer-term star cluster dissolution (see de Grijs & Parmentier 2007 for a review). The longer-term dynamical evolution of star clusters is determined by a combination of internal and external timescales. The free-fall and two-body relaxation timescales, which depend explicitly on the initial cluster mass density (e.g., Spitzer 1958; Chernoff & Weinberg 1990; de la Fuente Marcos 1997; Portegies Zwart et al. 2001), affect the cluster-internal processes of star formation and mass redistribution through energy equipartition, leading to mass segregation and, eventually, core collapse. Internal relaxation will, over time, eject both high-mass stars from the core (e.g., due to interactions with hard binaries (Can we detect high-proper-motion escapers and predict their orbits and observational properties, possibly using numerical approaches?) and lose lower-mass stars from its halo through diffusion. However, the external processes of tidal disruption, disc and bulge shocking, and stripping by the surrounding galactic field (see, e.g., De Marchi et al. 2006) are in general more important for the discussion of this disruption phase. Tidal disruption is enhanced by stellar evolution, leading to mass loss through winds and/or supernova explosions, which will further reduce the stellar density in a cluster, and thus make it more sensitive to external tidal forces.

The remaining key open questions related to star cluster disruption beyond the infant mortality phase appear mostly observational. However, the more fundamental issues that might affect our understanding of star cluster disruption relate to the accuracy of the age determinations of the individual clusters, on which statistical disruption analyses are based. Although contemporary studies take account of the so-called ‘chimneys’ in age space around 10 and 100 Myr (see, e.g., Bastian et al. 2005; de Grijs & Goodwin 2008), caused by the onset of, respectively, red supergiants and asymptotic giant-branch stars in normal stellar populations (neither of which are as yet robustly implemented in any of the suites of SSP models commonly used to convert multi-passband spectral energy distributions into robust age estimates), the more fundamental question to ask is what the realistic uncertainties are in the derived age distributions.

In addition to the uncertain contributions of BSs (see §3b), which may artificially bias age estimates for intermediate-age and older unresolved clusters, at younger ages ($\lesssim 30$ Myr) the key uncertainty relates to the discrepancy of approximately a factor of two between the pre-main-sequence contraction and nuclear main-sequences age scales for resolved clusters. Naylor (2009) suggests that by accounting for this discrepancy, the well-known lack of clusters with ages in the range from 5 to 30 Myr (Jeffries et al. 2007) may disappear. In addition, and perhaps more speculatively, he implies that this may also alleviate the problem that the
planetary disc-clearing timescale of $\sim 3$ Myr for young stars, as measured from IR observations (e.g., Briceño et al. 2007) does not match the $\sim 9$ Myr timescale required for planetary formation through classical core accretion (cf. Pollack et al. 1996).

5. Concluding thoughts

Although the importance of understanding star cluster physics (e.g., in mapping out the Milky Way or as SSP probes) had been recognized for decades, major progress has only become possible in recent years, both for Galactic and extragalactic cluster populations. We have seen a major recent investment in time and effort, largely thanks to significant new resources in theory, simulations and observations. These include breakthroughs in computational power (such as the recent embrace of graphics processing units by the computational astrophysics community), the maturing of HST-driven science (and the new generation of instruments as well as upgrades and refurbishment of the older facility instruments), deep and more precise (photometric, spectroscopic and astrometric) data for large numbers of Galactic clusters spanning a significant age range (including adaptive-optics-assisted imaging opportunities with the largest ground-based telescopes, and wide-field developments associated with intermediate-size apertures), and an explosion of astrometric data.

In addition, rapid progress has been facilitated by the coming online of observing facilities enabling access to hitherto unavailable spectral regions, both on the ground and in space. The latter include, among others, the Spitzer Space Telescope and the Japanese AKARI satellite at IR wavelengths, the GALaxy Evolution eXplorer (GALEX) in the ultraviolet, the Japanese Suzaku and the European X-ray Multi-Mirror mission (XMM–Newton), and the Chandra X-ray Observatory at shorter wavelengths. These facilities will soon be complemented by the Herschel Space Observatory once commissioning has been completed, and in the intermediate and long term by the James Webb Space Telescope and Gaia, respectively. Ground-based precursors to the ALMA and upgrades of and extensions to existing (sub)millimetre and radio facilities worldwide are starting to enable access to the full submillimetre to metre-wave spectral range, with new facilities like the Square Kilometer Array due to come online in the next decade. Recent advances in instrumentation are driving a renaissance in the study of Galactic clusters (e.g., addressing the relationships among open, globular and young massive clusters, and narrowing down the systematic uncertainties hampering determinations of absolute cluster ages in the Milky Way), while extragalactic cluster studies are significantly aided by the development of new instrumentation supporting ever wider fields of view.

Putting these results and new developments into the broader context of galaxy evolution is the next logical step, which requires the combined efforts of theorists, observers and modellers working on a large variety of spatial scales, and spanning a very wide range of expertise. I am confident that the next decade will see a continued high level of research activity related to the physics driving star cluster formation and evolution, with perhaps an enhanced focus on their impact on the physics of their host galaxies. Given the exciting new observational facilities due to come online in the next few years, combined with major progress on computational and theoretical fronts, a bright future no doubt awaits this field!
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