STAR AND CLUSTER FORMATION IN EXTREME ENVIRONMENTS

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Abstract
Current empirical evidence on the star-formation processes in the extreme, high-pressure environments induced by galaxy encounters (mostly based on high-resolution Hubble Space Telescope observations) strongly suggests that star cluster formation is an important and perhaps even the dominant mode of star formation in such starburst events. The sizes, luminosities, and mass estimates of the young massive star clusters (YMCs) are entirely consistent with what is expected for young Milky Way-type globular clusters (GCs). Recent evidence lends support to the scenario that GCs, which were once thought to be the oldest building blocks of galaxies, are still forming today. Here, I present a novel empirical approach to assess the shape of the initial-to-current YMC mass functions, and hence their possible survival chances for a Hubble time.

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1. Star clusters as starburst tracers

The production of luminous, massive yet compact star clusters seems to be a hallmark of the most intense star-forming episodes in galaxies. Young massive star clusters (YMCs; with masses often significantly exceeding $M_{cl} = 10^5 M_\odot$) are generally found in intense starburst regions, often in galaxies involved in gravitational interactions of some sort (e.g., de Grijs et al. 2001, 2003a,b,c,d,e and references therein).

An increasingly large body of observational evidence suggests that a large fraction of the star formation in starbursts actually takes place in the form of such concentrated clusters, rather than in small-scale star-forming “pockets”. YMCs are therefore important as benchmarks of cluster formation and evolution. They are also important as tracers of the history of star formation of their host galaxies, their chemical evolution, the initial mass function (IMF), and other physical characteristics in starbursts.
Using optical observations of the “Mice” and “Tadpole” interacting galaxies (NGC 4676 and UGC 10214, respectively) – based on a subset of the Early Release Observations obtained with the Advanced Camera for Surveys on board the Hubble Space Telescope (HST) – and the novel technique of pixel-by-pixel analysis of their colour-colour and colour-magnitude diagrams, we deduced the systems’ star and star cluster formation histories (de Grijs et al. 2003e). In both of these interacting systems we find several dozen YMCs (or, alternatively, compact star-forming regions), which overlap spatially with regions of active star formation in the galaxies’ tidal tails and spiral arms (from a comparison with Hα observations that trace active star formation; Hibbard & van Gorkom 1996). The tidal tail of the Tadpole system is dominated by star-forming regions, which contribute \( \sim 70\% \) of the total flux in the HST F814W filter (decreasing to \( \sim 40\% \) in the F439W filter). If the encounter occurs between unevenly matched, gas-rich galaxies then, as expected, the effects of the gravitational interaction are much more pronounced in the smaller galaxy. For instance, when we compare the impact of the interaction as evidenced by star cluster formation between M82 (de Grijs et al. 2001, 2003b,c) and M81 (Chandar et al. 2001), or the star cluster formation history in M51 (Bik et al. 2003), which is currently in the process of merging with the smaller spiral galaxy NGC 5194, the evidence for enhanced cluster formation in the larger galaxy is minimal if at all detectable.

Nevertheless, we have shown that star cluster formation is a major mode of newly-induced star formation in galactic interactions, with \( \geq 35\% \) of the active star formation in encounters occurring in YMCs (de Grijs et al. 2003e).

The question remains, however, whether or not at least a fraction of the numerous compact YMCs seen in extragalactic starbursts, may be the progenitors of GC-type objects. If we could settle this issue convincingly, one way or the other, the implications of such a result would have profound and far-reaching implications for a wide range of astrophysical questions, including (but not limited to) our understanding of the process of galaxy formation and assembly, and the process and conditions required for star (cluster) formation. Because of the lack of a statistically significant sample of similar nearby objects, however, we need to resort to either statistical arguments or to the painstaking approach of one-by-one studies of individual objects in more distant galaxies.

2. **From YMC to old globular cluster?**

The present state-of-the-art teaches us that the sizes, luminosities, and – in several cases – spectroscopic mass estimates of most (young) extragalactic star cluster systems are fully consistent with the expected properties of young Milky Way-type GC progenitors.
However, the postulated evolutionary connection between the recently formed YMCs in intensely star-forming areas, and old GCs similar to those in the Galaxy is still a contentious issue. The evolution and survivability of YMCs depend crucially on the stellar IMF of their constituent stars (cf. Smith & Gallagher 2001): if the IMF is too shallow, i.e., if the clusters are significantly depleted in low-mass stars compared to (for instance) the solar neighbourhood, they will disperse within a few (galactic) orbital periods, and likely within about a billion years of their formation (e.g., Smith & Gallagher 2001, Mengel et al. 2002). Ideally, one would need to obtain (i) high-resolution spectroscopy of all clusters in a given cluster sample in order to obtain dynamical mass estimates (we will assume, for the purpose of the present discussion, that our YMCs are fully virialised) and (ii) high-resolution imaging (e.g., with the HST) to measure their luminosities and sizes. However, individual YMC spectroscopy, while feasible today with 8m-class telescopes for the nearest systems, is very time-consuming, since observations of large numbers of clusters are required to obtain statistically significant results. Instead, one of the most important and most widely used diagnostics, both to infer the star (cluster) formation history of a given galaxy, and to constrain scenarios for its expected future evolution, is the distribution of cluster luminosities, or – alternatively – their associated masses, commonly referred to as the cluster luminosity and mass functions (CLF, CMF), respectively.

Starting with the seminal work by Elson & Fall (1985) on the young cluster system in the Large Magellanic Cloud (LMC; with ages \( \leq 2 \times 10^9 \) yr), an ever increasing body of evidence, mostly obtained with the HST, seems to imply that the CLF of YMCs is well described by a power law. On the other hand, for the old GC systems in the local Universe, with ages \( \geq 10 \mathrm{Gyr} \), the CLF shape is well established to be roughly lognormal (Whitmore et al. 1993, Harris 1996, 2001, Harris et al. 1998).

This type of observational evidence has led to the popular – but thus far mostly speculative – theoretical prediction that not only a power-law, but any initial CLF (and CMF) will be rapidly transformed into a lognormal distribution (e.g., Elmegreen & Efremov 1997, Gnedin & Ostriker 1997, Ostriker & Gnedin 1997, Fall & Zhang 2001). We recently reported the first discovery of an approximately lognormal CLF (and CMF) for the star clusters in M82’s fossil starburst region “B”, formed roughly simultaneously in a pronounced burst of cluster formation (de Grijs et al. 2003b; see also Goudfrooij et al. 2004). This provides the very first sufficiently deep CLF (and CMF) for a star cluster population at intermediate age (of \( \sim 1 \mathrm{Gyr} \)), which thus serves as an important benchmark for theories of the evolution of star cluster systems.

The CLF shape and characteristic luminosity of the M82 B cluster system is nearly identical to that of the apparently universal CLFs of the old GC systems in the local Universe. This is likely to remain virtually unchanged for a Hubble
time, if the currently most popular cluster disruption models hold. With the very short characteristic cluster disruption time-scale governing M82 B (de Grijs et al. 2003c), its cluster mass distribution will evolve toward a higher characteristic mass scale than that of the Galactic GC system by the time it reaches a similar age. Thus, this evidence, combined with the similar cluster sizes (de Grijs et al. 2001), lends strong support to a scenario in which the current M82 B cluster population will eventually evolve into a significantly depleted old Milky Way-type GC system dominated by a small number of high-mass clusters (de Grijs et al. 2003b). This implies that (metal-rich) GCs, which were once thought to be the oldest building blocks of galaxies, are still forming today in galaxy interactions and mergers.

3. The $L_V - \sigma_0$ relation as a diagnostic tool

We have recently started to explore a new, empirical approach to assess the long-term survival chances of YMCs formed profusely in intense starburst environments (de Grijs, Wilkinson & Tadhunter 2005). The method hinges on the empirical relationship for old Galactic and M31 GCs, which occupy tightly constrained loci in the plane defined by their $V$-band luminosities, $L_V$ (or, equivalently, absolute magnitudes, $M_V$) and central velocity dispersions, $\sigma_0$ (Djorgovski et al. 1997, and references therein; see Fig. 1).

Encouraged by the tightness of the GC relationship, we also added the available data points for the YMCs in the local Universe, including nuclear star clusters (objects 1–5), for which velocity dispersion information was readily available. In order to be able to compare them to the ubiquitous old Local Group GCs, we evolved their luminosities to a common age of 12 Gyr, adopting the “standard” Salpeter IMF covering masses from 0.1 to 100 $M_\odot$, and assuming stellar evolution as described by the GALEV SSPs (cf. Anders & Fritze-v. Alvensleben 2003). Based on a careful assessment of the uncertainties associated with this luminosity evolution, we conclude that the most important factor affecting the robustness of our conclusions is the adopted form of the stellar IMF.

We find that if we adopt the universal solar neighbourhood IMF as the basis for the YMCs’ luminosity evolution, the large majority will evolve to loci within twice the observational scatter around the best-fitting GC relationship. In the absence of significant external disturbances, this implies that these objects may potentially survive to become old GC-type objects by the time they reach a similar age. Thus, these results provide additional support to the suggestion that the formation of proto-GCs appears to be continuing until the present. Detailed one-to-one comparisons between our results based on this new method with those obtained previously and independently based on dynamical mass estimates and mass-to-light (M/L) ratio considerations lend
strong support to the feasibility and robustness of our new method. The key characteristic and main advantage of this method compared to the more complex analysis involved in using dynamical mass estimates for this purpose is its simplicity and empirical basis. Where dynamical mass estimates require one to obtain accurate size estimates and to make assumptions regarding a system’s virialised state and M/L ratio, these complications can now be avoided.
by using the empirically determined GC relationship as reference. The only observables required are the system’s (central or line-of-sight) velocity dispersion and photometric properties.

Careful analysis of those YMCs that would overshoot the GC relationship significantly if they were to survive for a Hubble time show that their unusually high ambient density likely has already had a devastating effect on their stellar content, despite their young ages, thus altering their present-day mass function (PDMF) in a such a way that they have become unstable to survive for any significant length of time. This is, again, supported by independent analyses, thus further strengthening the robustness of our new approach. The expected loci in the $L_V - \sigma_0$ plane that these objects would evolve to over a Hubble time are well beyond any GC luminosities for a given velocity dispersion, thus leading us to conclude that they will either dissolve long before reaching GC-type ages, or that they must be characterised by a PDMF that is significantly depleted in low-mass stars (or highly mass segregated). This, therefore, allows us to place moderate limits on the functionality of their PDMFs.

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