

# Young massive star clusters in the era of the *Hubble Space Telescope*

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**Summary.** The *Hubble Space Telescope* (*HST*) has been instrumental in the discovery of large numbers of extragalactic young massive star clusters (YMCs), often assumed to be proto-globular clusters (GCs). As a consequence, the field of YMC formation and evolution is thriving, generating major breakthroughs as well as controversies on annual (or shorter) time-scales. Here, I review the long-term survival chances of YMCs, hallmarks of intense starburst episodes often associated with violent galaxy interactions. In the absence of significant external perturbations, the key factor determining a cluster's long-term survival chances is the shape of its stellar initial mass function (IMF). It is, however, not straightforward to assess the IMF shape in unresolved extragalactic YMCs. I also discuss the latest progress in worldwide efforts to better understand the evolution of entire cluster populations, predominantly based on *HST* observations, and conclude that there is an increasing body of evidence that GC formation appears to be continuing until today; their long-term evolution crucially depends on their environmental conditions, however.

## 1 Introduction

Young, massive star clusters (YMCs) are the hallmarks of violent star-forming episodes triggered by galaxy collisions and close encounters. This field has seen major progress and a flurry of renewed interest ever since such YMCs were first reported in the starburst galaxy NGC 1275 by Holtzman et al. (1992) using pre-COSTAR *Hubble Space Telescope* (*HST*) images. The question remains, however, whether or not at least a fraction of the compact YMCs seen in abundance in extragalactic starbursts, are potentially the progenitors of ( $\geq 10$  Gyr) old globular cluster (GC)-type objects – although of higher metallicity than the present-day GCs. If we could settle this issue convincingly, one way or the other, such a result would have far-reaching implications for a wide range of astrophysical questions, including 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 YMCs in the Local Group, however, we need to resort to either statistical arguments or to the painstaking approach of case-by-case studies of individual objects in more distant galaxies.

## 2 Individual YMC evolution

The evolution to old age of young clusters depends crucially on their stellar initial mass function (IMF). If the IMF slope is too shallow, i.e., if the clusters are significantly deficient in low-mass stars compared to, e.g., the solar neighbourhood, they will likely disperse within about a Gyr of their formation (e.g., Chernoff & Shapiro 1987; Chernoff & Weinberg 1990; Goodwin 1997b; Smith & Gallagher 2001; Mengel et al. 2002). As a case in point, Goodwin (1997b) simulated the evolution of  $\sim 10^4 - 10^5 M_\odot$  YMCs similar to those observed in the Large Magellanic Cloud (LMC), with IMF slopes  $\alpha = 2.35$  (Salpeter 1955; where the IMF is characterised as  $\phi(m_*) \propto m_*^{-\alpha}$ , as a function of stellar mass,  $m_*$ ) and  $\alpha = 1.50$ , i.e., roughly covering the range of (present-day) mass function slopes observed in LMC clusters at the time he performed his  $N$ -body simulations. Following Chernoff & Weinberg (1990), and based on a detailed comparison between the initial conditions for the LMC YMCs derived in Goodwin (1997b) and the survival chances of massive star clusters in a Milky Way-type gravitational potential (Goodwin 1997a), Goodwin (1997b) concluded that – for Galactocentric distances  $\geq 12$  kpc – some of his simulated LMC YMCs should be capable of surviving for a Hubble time if  $\alpha \geq 2$  (or even  $\geq 3$ ; Mengel et al. 2002), but not for shallower IMF slopes for any reasonable initial conditions (cf. Chernoff & Shapiro 1987; Chernoff & Weinberg 1990). More specifically, Chernoff & Weinberg (1990) and Takahashi & Portegies Zwart (2000), based on numerical cluster simulations employing the Fokker-Planck approximation, suggest that the most likely survivors to old age are, additionally, characterised by King model concentrations,  $c \geq 1.0 - 1.5$ . Mengel et al. (2002; their fig. 9) use these considerations to argue that their sample of YMCs observed in the Antennae interacting system might survive for at least a few Gyr, but see de Grijs et al. (2005a), and Bastian & Goodwin (2006) and Goodwin & Bastian (2006), for counterarguments related to environmental effects and to variations in the clusters’ star-formation efficiencies, respectively.

In addition, YMCs are subject to a variety of internal and external drivers of cluster disruption. These include internal two-body relaxation effects, the nature of the stellar velocity distribution function, the effects of stellar mass segregation, disk and bulge shocking, and tidal truncation (e.g., Chernoff & Shapiro 1987; Gnedin & Ostriker 1997). All of these act in tandem to accelerate cluster expansion, thus leading to cluster dissolution – since expansion will lead to greater vulnerability to tidally-induced mass loss.

With the ever increasing number of large-aperture ground-based telescopes equipped with state-of-the-art high-resolution spectrographs and the wealth of observational data provided by the *HST*, we may now finally be getting close to resolving the issue of potential YMC longevity conclusively. To do so, one needs to obtain (i) high-resolution spectroscopy, in order to obtain dynamical mass estimates, and (ii) high-resolution imaging to measure their sizes (and luminosities). One could then construct diagnostic diagrams

of YMC mass-to-light ( $M/L$ ) ratio versus age, and compare the YMC loci in this diagram with simple stellar population models using a variety of IMF descriptions. In de Grijs & Parmentier (2007; their fig. 2) we present an updated version of the  $M/L$  ratio versus age diagram, including all of the YMCs for which the required observables are presently available.

Despite some outstanding issues (particularly for the youngest clusters), it appears that most of the YMCs for which high-resolution spectroscopy is available are characterised by “standard” Salpeter (1955) or Kroupa (2001) IMFs. As such, a fraction of the YMCs seen today may potentially evolve to become old GCs, depending on their environmental conditions.

### 3 The evolution of star cluster systems

Following the violent relaxation induced by the supernova-driven expulsion of the left-over star-forming gas, star clusters – at least those that survive the “infant mortality” phase (i.e., roughly the first 10–30 Myr of their lives) – settle back into virial equilibrium by the time they reach an age of about 40–50 Myr (Bastian & Goodwin 2006; Goodwin & Bastian 2006). Subsequently, the initial conditions characterising these gas-free bound star clusters are modified as secular evolution proceeds. Internal (two-body relaxation) and external effects (due to interactions with the tidal field associated with the underlying galactic gravitational potential) lead to tidal stripping and the evaporation of a fraction of the low-mass cluster stars, thus resulting in the gradual dissolution of star clusters.

One of the most important diagnostics used to infer the formation history, and to follow the evolution of a star cluster population is the CMF (i.e., the number of clusters per constant logarithmic cluster mass interval,  $dN/d\log m_{cl}$ ). Of particular importance is the *initial* cluster mass function (ICMF), since this holds clues to the star and cluster formation processes. The debate regarding the shape of the ICMF, and of the CMF in general, is presently very much alive, both observationally and theoretically. This is so because it bears on the very essence of the star-forming process, as well as on the formation, assembly history and evolution of the clusters’ host galaxies over cosmic time. Yet, the observable property one has access to is the CLF (i.e., the number of objects per unit magnitude,  $dN/dM_V$ ).

In this respect, a remaining contentious issue is whether the observed CMF of YMCs will eventually evolve into that of the ubiquitous old GCs. The GCMF is a Gaussian with a mean  $\langle \log(m_{cl}[M_\odot]) \rangle \sim 5.2 - 5.3$  and a standard deviation of  $\sigma_{\log m_{cl}} \simeq 0.5 - 0.6$  dex. It seems to be almost universal, both *among* and *within* galaxies. On the other hand, many CMFs of YMCs appear to be featureless power laws with a spectral index  $\alpha \sim -2$  down to a few  $\times 10^3 M_\odot$  (e.g., de Grijs & Anders 2006; Hunter et al. 2003, for the LMC). Some cluster systems exhibit differently shaped ICMFs, however (M82 B, de Grijs et al. 2005b, but see Smith et al., in prep.; NGC 1316, Goudfrooij et

al. 2004; NGC 5253, Cresci et al. 2006). Evolving such an initial power-law CMF into the near-invariant Gaussian GCMF regardless both of the host galaxy properties and of the details of the cluster loci turns out to be most challenging and requires significant fine-tuning of the models, which is not necessarily compatible with the available observational constraints (see, e.g., Fall & Zhang 2001 vs. Vesperini et al. 2003; see also Vesperini & Zepf 2003).

In order to settle the issues of cluster evolution and ICMF shape more conclusively, major improvements are required in the near future, both observationally and theoretically. Observations reaching low-mass clusters, and with sufficiently accurate photometry, in order to derive reliable cluster ages, are required to follow the temporal evolution of the CMF. From a modeling point of view, a better treatment of the initially loosely bound clusters (i.e., the low-concentration clusters) is required, since these may account for the missing link between the Gaussian GCMF and the power laws seen for YMC systems (Vesperini & Zepf 2003). In addition, the inclusion of a time-dependent host galaxy gravitational potential will enable us to better follow the early evolution of both old GCs and YMCs formed in interacting and merging galaxies.

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