INVITED REVIEWS

The Long-term Survival Chances of Young Massive Star Clusters

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Abstract We review the long-term survival chances of young massive star clusters (YMCs), hallmarks of intense starburst episodes often associated with violent galaxy interactions. We address the key question as to whether at least some of these YMCs can be considered proto-globular clusters (GCs), in which case these would be expected to evolve into counterparts of the ubiquitous old GCs believed to be among the oldest galactic building blocks. 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. We discuss in detail the promise of using high-resolution spectroscopy to make progress towards this goal, as well as the numerous pitfalls associated with this approach. We also discuss the latest progress in worldwide efforts to better understand the evolution of entire cluster systems, the disruption processes they are affected by, and whether we can use recently gained insights to determine the nature of at least some of the YMCs observed in extragalactic starbursts as proto-GCs. We 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.

Key words: stellar dynamics — globular clusters: general — galaxies: interactions – Magellanic Clouds — galaxies: starburst — galaxies: star clusters

1 INTRODUCTION

Young, massive star clusters (YMCs) are the hallmarks of violent star-forming episodes triggered by galaxy collisions and close encounters. Their contribution to the total luminosity induced by such extreme conditions completely dominates the overall energy output due to the gravitationally-induced star formation (e.g., Holtzman et al. 1992; Whitmore et al. 1993; O'Connell, Gallagher & Hunter 1994; Conti, Leitherer & Vacca 1996; Watson et al. 1996; Carlson et al. 1998; de Grijs et al. 2001, 2003a, b, c, d, e).

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 ($\gtrsim 10\,\mathrm{Gyr}$) 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

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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.

A variety of methods have been employed to address the issue of the long-term survival of massive star clusters. The most promising and most popular approach aimed at establishing whether a significant fraction of an entire *population* of YMCs (as opposed to individual objects) might survive for any significant length of time (say, in excess of a few $\times 10^9$ yr) uses the "cluster luminosity function", or its equivalent mass function (CLF, CMF), as a diagnostic tool. In essence, the long-term survival of dense YMCs depends sensitively on the low-mass section (below a few $M_\odot$) of their stellar initial mass function (IMF). Clearly, assessing the shape of the stellar IMF in unresolved extragalactic star clusters is difficult, potentially ambiguous and riddled with pitfalls. Nevertheless, and despite these difficulties, an ever increasing body of observational evidence lends support to the scenario that GCs, which were once thought to be the oldest building blocks of galaxies, are still forming today.

In this review, we discuss the chances for YMCs to survive a Hubble time of evolution and disruptive internal and external effects, and thus to become equivalent objects to the old GCs seen in abundance in the large spiral and elliptical galaxies in the local Universe. This is a very topical area of research in the star cluster community. Here, we will review the variety of view points expressed in the community and address both the well-established cluster evolution scenarios and the more controversial issues that regularly appear in the literature. We start, in Section 2, by focusing on the process of "cluster infant mortality", which in essence causes the almost instantaneous disruption of some 90 per cent of a young cluster population in the first ~ 30 Myr of their lifetime. We then discuss the effects and observational signatures of star cluster disruption on longer time-scales (Sect. 3). In Section 4 we address the survival chances of individual massive star clusters, for which we have access to the most up-to-date and detailed observations. Whereas we discuss the internal dynamics of individual star clusters to some extent, for more details we refer the interested reader to the excellent review on this topic by Meylan & Heggie (1997). We continue, in Section 5, by scrutinising the evolution of entire cluster populations, in essence by looking at their CLFs and CMFs. Here, we focus predominantly on the evolution of *young* cluster systems; for an in-depth overview of the properties, evolution and context of old GC systems we refer to the recent review by Brodie & Strader (2006). In Section 6 we provide a summary of our main conclusions and an outlook to future developments in this very vibrant field.

2 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, under the assumption of a roughly constant star cluster formation rate over the host galaxy's history, and taking into account the observational completeness limits as well as the effects of sample binning. Notable examples of galaxies in which this effect is clearly seen include the Antennae interacting system, NGC 4038/9 (Whitmore 2004; Fall, Chandar & Whitmore 2005; Mengel et al. 2005; see also Whitmore, Chandar & Fall 2006 for a presentation of earlier results), M51 (Bastian et al. 2005), and NGC 6745 (de Grijs et al. 2003c). This significant overdensity remains, even in view of the presence of a recent burst of star cluster formation in many of these galaxies. In addition, there has been a recent surge of interest in the star cluster populations in the Magellanic Clouds (Rafelski & Zaritsky 2005; Chandar, Fall & Whitmore 2006; Gieles, Lamers & Portegies Zwart 2007; de Grijs et al. 2007), which we can probe in much more detail and to much fainter flux limits than the extragalactic starburst cluster populations.

2.1 Cluster Disruption on Short Time-Scales

The current consensus is that there are most likely two types of cluster disruption scenarios, which can account for these observations on their own specific time-scales. These include an initial fast ($\lesssim 10 - 30$ Myr) disruption mechanism that may be mass-independent – at least for masses in excess of $\sim 10^4 M_\odot$ (e.g., Bastian et al. 2005; Fall et al. 2005; Fall 2006) – and a subsequent secondary (secular) disruption mechanism.

The proposed fast disruption mechanism, which is thought to effectively remove up to 50 (Wielen 1971, 1988; Rafelski & Zaritsky 2005; Goodwin & Bastian 2006), 70 (Bastian et al. 2005; Mengel et al. 2005; de Grijs et al. 2007) or even 90 per cent (Lada & Lada 1991; Whitmore 2004; Whitmore et al. 2006; see

also Lamers & Gieles 2007) of the youngest, short-lived clusters from a given cluster population, has been coined cluster "infant mortality" (Whitmore 2004). The observational effects and their consequences had, however, already been discussed in detail much earlier, both in Galactic (e.g., Wielen 1971, 1988; Lada & Lada 1991, 2003) and in extragalactic environments (Tremonti et al. 2001).

In particular, based on ultraviolet *Hubble Space Telescope (HST)*/STIS spectroscopy of the YMCs and diffuse background light in the dwarf starburst galaxy NGC 5253, the latter study suggested that star clusters may have been forming continuously in this galaxy, and then dissolve on $\sim$ 10–20 Myr time-scales (based on arguments related to tidal effects worked out in detail in Kim, Morris & Lee 1999), dispersing their stars into the field star population. The main observational evidence lending support to this suggestion comes from the composite spectrum of eight YMCs versus that of the diffuse "inter-cluster" field star population covered by their long-slit spectra. While the former exhibits so-called P Cygni features in their Nv, Siv and Civ lines, characteristic of stellar winds generated by massive young O-type stars, the latter spectrum lacks these stellar wind features.

Tremonti et al. (2001) conclude from the difference between the composite cluster and field-star spectra that the NGC 5253 field star population contains stars at a more advanced evolutionary stage than the clusters they sampled; they suggest that a straightforward interpretation of this result is that stars tend to form in star clusters, while a fraction of them populate the field after the clusters have dissolved on 10–20 Myr time-scales. They point out that a similar scenario seems feasible for NGC 1569 as well, based on the *HST*/WFPC2 photometry of Greggio et al. (1998). These latter authors find that the stellar population of NGC 1569 is composed of recently formed YMCs and resolved field stars with ages in excess of 10 Myr (see also Harris et al. 2001 for a similar conclusion based on the resolved diffuse stellar population in M83). In a follow-up paper, Chandar et al. (2005) compare the *HST*/STIS ultraviolet spectral signatures of both the star clusters and the diffuse intercluster light originating in the galactic disks of 12 local starburst galaxies. They show that in 11 of their 12 sample galaxies the "field" spectra lack the O-star signatures observed in the (young) star cluster spectra; the "field" spectra are, instead, dominated by B-type stellar features (the only exception to this rule is Henize 2–10, which exhibits the youngest field star population among their sample galaxies, including O-star signatures). Thus, Chandar et al. (2005) conclude that, under the assumption that the field star population is composed of dissolved clusters, cluster dissolution needs to happen on time-scales of 7–10 Myr. If, instead, the field is composed of unresolved young clusters, these need to be less massive than a few $\times 10^2 M_\odot$, in order to lack O stars at the youngest ages.

Similarly, Pellerin et al. (2006) conclude, based on resolved colour-magnitude diagrams obtained with *HST*/Advanced Camera for Surveys (ACS) that the background field stars in the nearby galaxy NGC 1313 are young, massive ($m_* \gtrsim 7 M_\odot$) B-type stars. Since such stars tend to be born in clusters and have lifetimes of 5 to 25 Myr, they conclude that this implies that significant cluster "infant mortality" must be at work in this environment. They also suggest that this is a plausible scenario to explain the presence of a B-type stellar population exciting the diffuse ionised gas of normal galaxies (Hoopes et al. 2001), and for the bright diffuse UV emission observed to account for some 80 per cent of the UV emission in starburst galaxies (Meurer et al. 1995).

The rationale for the cluster "infant mortality" interpretation for the Antennae galaxies, rather than a recent large-scale, intense burst of star cluster formation (which might mimic the observations as well), was provided in detail by Whitmore (2004), and repeated by Fall et al. (2005) and Whitmore et al. (2006). It consists of two interlinked arguments: (i) the Antennae galaxies have been interacting for much longer than the median cluster age (the time-scales involved are a few $\times 10^8$ versus $\sim 10^7$ yr, respectively), and (ii) the cluster age distribution is similar across different areas of the galaxies, irrespective of the intensity of the interaction, and on spatial scales much larger than those traveled by the sound speed on time-scales on the order of the median cluster age.

2.2 Disruption Mechanisms

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 Mengel et al. 2005), approximately as a function of increasing time-scale, (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 time-scales 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, hence altering the cluster's stellar mass function, (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.

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 star-formation efficiency (SFE) is less than about 30 per cent, independent of the mass of the cluster (see e.g. Lada, Margulis & Dearborn 1984; Goodwin 1997a, b; Adams 2000; Geyer & Burkert 2001; Kroupa & Boily 2002; Boily & Kroupa 2003a, b; Fellhauer & Kroupa 2005; Bastian & Goodwin 2006; Parmentier & Gilmore 2007, their fig. 1). Goodwin & Bastian (2006) show that this type of cluster destruction occurs in 10–30 Myr (see also Kroupa & Boily 2002; Lada & Lada 2003; and the discussion in Lamers & Gieles 2007). The consequence of this is that clusters will expand rapidly, in order to attain a new virial equilibrium, and hence disappear below the observational detection limit on a similar time-scale (see also Bastian et al. 2005; Fall et al. 2005). This might be the reason for Mengel et al.'s (2005) conclusion that the average cluster size in the Antennae system decreases with age, for ages up to ~ 10 Myr. However, they also note that the most extended clusters might be more sensitive to dissolution due to tidal effects, and to mass loss as a result of stellar winds (see also Vesperini & Zepf 2003), and hence the observed sample may maintain an apparently small average size. Gieles et al. (2005) also noticed that, among their M51 cluster sample, there are no old clusters with large radii. Although this would suggest that large clusters are more easily disrupted over time, and thus that tidal shocks may be dominating cluster disruption, their result is hardly conclusive, given the observational uncertainties. On the other hand, in the Large Magellanic Cloud (LMC) it is well known that both the upper envelope to the size distribution of the star cluster population and its spread increases with increasing age (e.g., Elson, Freeman & Lauer 1989; Elson 1991, 1992; de Grijs et al. 2002c; Mackey & Gilmore 2003). The difference in this sense between the LMC and the Antennae star cluster system might lie, apart from the obvious difference in the observational detection limit, in the significantly higher-density disk of the Antennae system compared to that of the LMC, so that one might expect external effects due to disk shocking to be more important in the Antennae galaxies.

The above scenario is, in essence, the key argument proposed by Hills (1980) to explain the expansion of the Galactic OB associations, where the energy and momentum output of massive stars causes an association to expand, and ultimately dissolve. However, the problem is likely more complex than outlined here. Boily & Kroupa (2003a) suggest that in order to form bound clusters with a low average SFE, the SFE must peak in the cluster core, thus naturally leading to a concentration of stars (see also Tenorio-Tagle et al. 1986; Adams 2000).

For completeness, we should point out that many of the youngest star clusters observed in environments like those of the Antennae galaxies might simply be unbound associations. Mac Low & Klessen (2004, and references therein) reviewed a star-formation scenario in which the driving force is provided by supersonic turbulent convergence flows in the interstellar medium, which might lead to high-intensity star formation in *unbound* associations (see also Mengel et al. 2005).

2.3 Cluster Mass (in) Dependence?

Bastian et al. (2005) attempted a first observational assessment of the dependence of the cluster infant mortality on cluster mass in M51. Their results seem to indicate that the effect of infant mortality is largely independent of mass, although close inspection of their figure 14 shows that this may not be as strongly supported for the lower masses ($m_{cl} \lesssim 10^4 M_\odot$) as for the higher-mass clusters (see also de Grijs et al. 2007). However, in view of the large uncertainties, we cannot easily quantify the importance of a possible mass dependence in M51. Fall et al. (2005; see also Fall 2006), in a more carefully worded statement, conclude that the shape of the age distribution of the YMCs in the Antennae galaxies is nearly independent of mass, at least for $m_{cl} > 3 \times 10^4 M_\odot$. This is equivalent to the statement that the effects of cluster infant mortality are largely mass independent above this mass limit.
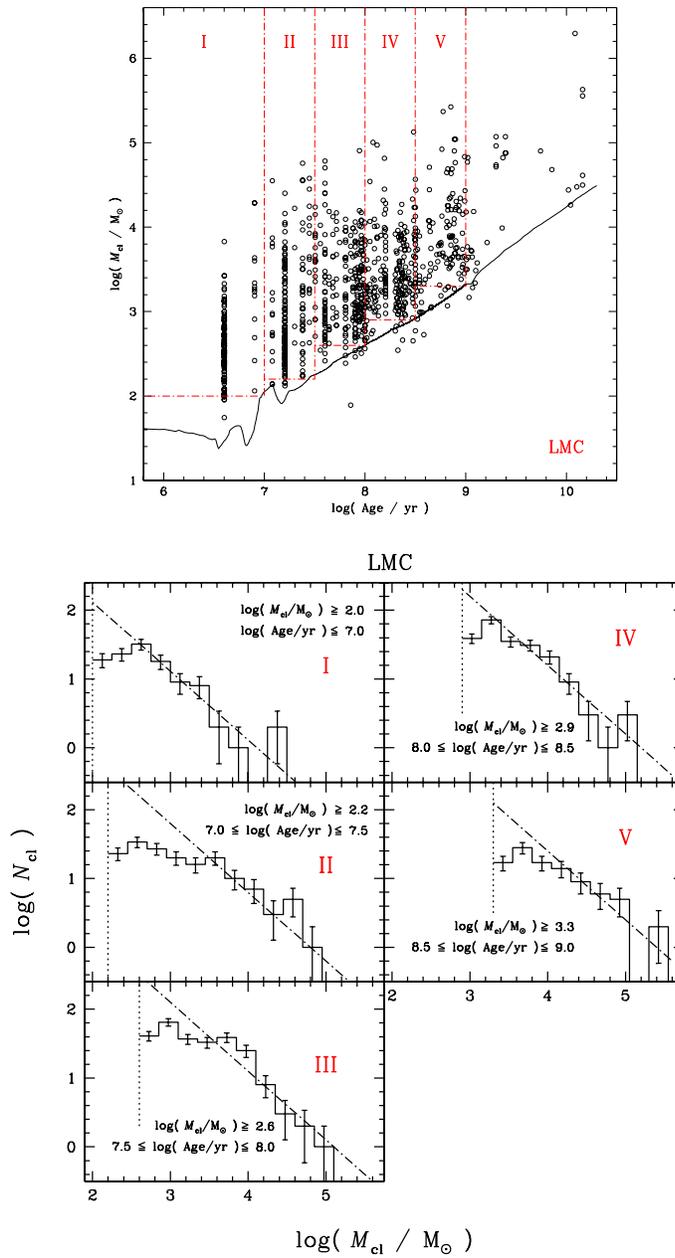
Fig. 1 *Upper:* Distribution of the LMC cluster sample of de Grijs et al. (2007) in the (age versus mass) plane. Overplotted is the expected detection limit based on stellar population synthesis for a 50 per cent completeness limit of $M_V = -3.5$ mag, assuming no extinction. For a nominal extinction of $A_V = 0.1$ mag, the detection limit will shift to higher masses by $\Delta \log(m_{cl}[M_\odot]) = 0.04$. The features around 10 Myr are caused by the appearance of red supergiants in the models. The age limits used to generate the different panels in the right-hand panels are shown as the vertical dash-dotted lines; the various subsets are also cross-linked between the figures using roman numerals. The horizontal dash-dotted lines indicate the 50 per cent completeness limits in mass for each of the age-selected subsamples. *Lower:* CMFs for statistically complete LMC cluster subsamples. Age and mass ranges are indicated in the panel legends; the vertical dotted lines indicate the lower mass (50 per cent completeness) limits adopted. Error bars represent simple Poissonian errors, while the dash-dotted lines represent CMFs with spectral index $\alpha = 2$, shifted vertically to match the observational data.

Such a result would be expected if, on average, the SFE of YMCs is mass-independent. Goodwin & Bastian (2006; also S. P. Goodwin, priv. comm.) determined approximate SFEs for their sample of high-mass clusters, and compared these to photometric mass estimates. They mention in passing that the SFEs they determine for their sample clusters are to first order mass-independent. The physical importance of such a result, if this can be confirmed more robustly, implies that the turbulent structure of the molecular cloud YMC progenitors is scale-independent (e.g., Elmegreen 2002) and thus that the higher-mass clusters are simply scaled-up versions of their lower-mass counterparts.

We recently re-analysed the LMC cluster population in detail (de Grijs et al. 2007; see Fig. 1), thereby focusing on the effects of infant mortality, and concluded that there appears to be a mass-dependent infant mortality rate, at least for masses below a few $\times 10^3 M_\odot$. In view of the arguments presented above in favour of a mass-independent YMC SFE, this observation seems to imply that clusters below this mass limit might not simply be scaled-down versions of the higher-mass YMCs, but that the effective cluster SFE does in fact depend on mass, thus establishing a clearer distinction between gravitationally bound and unbound objects at the low-mass extreme (see also Weidner et al. 2007 for a theoretical perspective).

In the right-hand panels of Figure 1 we show the CMFs for statistically complete subsamples of LMC clusters (taken from de Grijs & Anders 2006; de Grijs et al. 2007), as indicated in the left-hand panel. We draw the reader's attention to the significant change in the CMF slope between the youngest two age bins, which cannot be explained satisfactorily by the difference in our mass sampling and the completeness fractions only (de Grijs et al. 2007; based on extensive Monte Carlo simulations of the observations). Instead, this is clear observational evidence of mass-dependent cluster infant mortality from clusters younger than 10 Myr in the first age bin to clusters in the age range between 10–30 Myr in the second.

3 CLUSTER DISRUPTION BEYOND THE INFANT MORTALITY PHASE

3.1 General Framework

Those clusters that survive the infant mortality phase will be subject to the processes driving longer-term star cluster dissolution. The longer-term dynamical evolution of star clusters is determined by a combination of internal and external time-scales. The free-fall and two-body relaxation time-scales, 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. While the internal relaxation process will, over time, eject both high-mass stars from the core (e.g., due to interactions with hard binaries; see Brandl et al. 2001; de Grijs et al. 2002a) and lose lower-mass stars from its halo through diffusion (e.g., due to Roche-lobe overflow), the external processes of tidal disruption, disk and bulge shocking, and stripping by the surrounding galactic field (see, e.g., De Marchi, Pulone, & Paresce 2006 for a detailed recent observational study in this area) are in general more important for the discussion of this disruption phase of star clusters. Tidal disruption is enhanced by stellar evolution, leading to mass loss by 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.

From the bimodal age distribution of (young) open and (old) globular clusters in the Milky Way, Oort (1957) concluded that disruption of Galactic star clusters must occur on time-scales of $\sim 5 \times 10^8$ yr (see also Wielen 1971, 1988; Battinelli & Capuzzo-Dolcetta 1991; Lamers et al. 2005b; Lamers & Gieles 2006, 2007; Piskunov et al. 2006). Roughly simultaneously, Spitzer (1958) derived an expression for the disruption time-scale as a function of a cluster's mean density, ρ_c ($M_\odot$ pc^{-3}): $t_{\rm dis} = 1.9 \times 10^8 \rho_c$ yr, for $2.2 < \rho_c < 22\ M_\odot$ pc^{-3}. More advanced recent studies, based on N-body modeling, have shown that the cluster disruption time-scale is sensitive to the cluster mass, the fraction of binary (or multiple) stars, the ambient density (and hence the cluster's galactocentric distance), its orbital velocity, and the IMF adopted (e.g., Aguilar 1988; Chernoff & Weinberg 1990; de la Fuente Marcos 1997; Meylan & Heggie 1997; Baumgardt & Makino 2003; Lamers, Gieles & Portegies Zwart 2005a; Gieles et al. 2005). However, Gieles et al. (2005) showed, for the M51 cluster system (see also Sect. 3.2), that the mass dependence of the cluster disruption time-scale, within a given galaxy, is the dominant effect, with the other effects being of second-order importance; the ambient density appears to be a major driver of the variation of the characteristic cluster disruption time-scale among galaxies (Portegies Zwart, Hut & Makino 1998; Portegies Zwart et al. 2002; Baumgardt & Makino 2003; Lamers et al. 2005a).

Boutloukos & Lamers (2003) derived an empirical relation between the disruption time and a cluster's initial mass from observations of a small but diverse sample of galaxies containing rich cluster systems: the Milky Way (i.e., the solar neighbourhood), the Small Magellanic Cloud (SMC), M33 and the inner spiral arms of M51. Similar analyses have since been published for M82's fossil starburst region "B" (de Grijs et al. 2003a, 2005b), NGC 3310 and NGC 6745 (de Grijs et al. 2003c), NGC 5461, NGC 5462 and NGC 5471 (Chen, Chu & Johnson 2005), and in more detail for the solar neighbourhood (Lamers et al. 2005b; Lamers & Gieles 2006; see also Piskunov et al. 2006), M51 (Gieles et al. 2005), the SMC (Chiosi et al. 2006), and the LMC (de Grijs & Anders 2006). Boutloukos & Lamers (2003) showed, based on an analysis of the mass and age distributions of magnitude-limited samples of clusters, that the empirical disruption time of clusters depends on their initial mass[1], M_i, as

$$t_{dis} = t_4^{dis}\Big(\frac{M_i}{10^4 M_\odot}\Big)^\gamma \quad , \tag{1}$$

where t_4^{dis} is the disruption time of a cluster of initial mass $M_i = 10^4 M_\odot$. The value of γ is approximately the same in these four galaxies, $\gamma = 0.62 \pm 0.06$ (see also Gieles et al. 2005; Lamers et al. 2005b; Rafelski & Zaritsky 2005; Elmegreen et al. 2006; Lamers & Gieles 2006, 2007). However, the characteristic disruption time-scale, t_4^{dis}, varies widely in the different galaxies. The disruption time-scale is shortest[2] in M82 B, $\log(t_4^{dis}\,yr^{-1}) \simeq 7.5$ (de Grijs et al. 2003a); it is longest in the LMC, $\log(t_4^{dis}yr^{-1}) = 9.9 \pm 0.1$ (Boutloukos & Lamers 2002; de Grijs & Anders 2006), and SMC, $\log(t_4^{dis}\,yr^{-1}) = 9.9 \pm 0.2$ (de la Fuente Marcos 1997; Boutloukos & Lamers 2003). This is not unexpected, considering the low-density environment of the Magellanic Clouds – and their relative paucity of giant molecular clouds compared to the Milky Way – in which these clusters are found (van den Bergh & McClure 1980; Elson & Fall 1985, 1988; Hodge 1987, 1988; Lamers et al. 2005a; see also Krienke & Hodge 2004, for the NGC 6822 cluster system).

Even with recent improvements (e.g., Gieles et al. 2005) to the simple model of Boutloukos & Lamers (2003), the characteristic cluster destruction time-scales resulting from a more sophisticated, non-instantaneous destruction process are very similar to those based on the simple method; see Lamers et al. (2005a) for a detailed comparison, in particular their table 1.

3.2 Environmental Impact

While there seems to be a very strong mass dependence of the characteristic star cluster disruption time-scale in a given galaxy, when comparing cluster systems from different galaxies the ambient density becomes an important secondary effect (Portegies Zwart et al. 1998, 2002; Baumgardt & Makino 2003; Lamers et al. 2005a). Baumgardt & Makino (2003) and Portegies Zwart et al. (1998, 2002), based on N-body simulations in the Galactic halo tidal field (represented as a logarithmic gravitational potential), and Lamers et al. (2005a), based on an empirical approach, showed that the characteristic disruption time-scale in a given galaxy depends on the initial mass and the ambient density, ρ_{amb}, as

$$t_4^{dis}\ (yr) \propto M_i^\gamma\ (M_\odot)\ \rho_{amb}^{-0.5}\ (M_\odot pc^{-3}). \tag{2}$$

Lamers et al. (2005a, their fig. 4) confront the theoretical N-body predictions with their empirically derived disruption time-scales, and show that both approaches are in reasonable agreement, at least for the star cluster systems in the solar neighbourhood, the SMC and M33. However, the N-body simulations overpredict the cluster disruption time-scale significantly both for the clusters in M51 ($\log(t_4^{dis}\,yr^{-1}) = 7.85 \pm 0.22$; Lamers et al. 2005a; see also Boutloukos & Lamers 2003), and also for the YMCs in M82 B (de Grijs et al. 2005b). In both cases, the N-body simulations overpredict the empirically derived characteristic cluster disruption time-scales by a factor of ~ 10–15.

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[1] It is well-established, however, that the disruption time-scale does not only depend on mass, but also on the initial cluster density and internal velocity dispersion. Following Boutloukos & Lamers (2003), however, we point out that if clusters are approximately in pressure equilibrium with their environment, we can expect the density of all clusters in a limited volume of a galaxy to be roughly similar, so that their disruption time-scale will predominantly depend on their (initial) mass, with the exception of clusters on highly-eccentric orbits.

[2] Note that this time-scale was based on the assumption of an underlying mass function of the form $N(m_{cl}) \propto m_{cl}^{-\alpha}$, with $\alpha = 2$ (cf. Boutloukos & Lamers 2003). However, this assumption is unlikely to be correct for the M82 B cluster system, thus casting doubt on the very short characteristic cluster disruption time-scale – the shortest known of any galactic disk region – thus derived (de Grijs et al. 2005b; see also Sects. 3.2 and 5).

Gieles et al. (2005) explored whether the empirical result could have underestimated the actual time-scale because of the assumption adopted by Boutloukos & Lamers (2003) and Lamers et al. (2005a) of a constant cluster formation rate, despite the fact that M51 is clearly interacting with its smaller companion galaxy, NGC 5195. This would naturally lead to periods of enhanced cluster formation around the time of closest approach between both galaxies, and thus render the assumption of a constant cluster formation rate rather questionable. In addition, Gieles et al. (2005) also take into account the effects of cluster infant mortality (see Sect. 2), in essence by disregarding all clusters younger than $\sim 10^7$ yr in their sample; if they were to include these YMCs, this would artificially shorten the disruption time-scale. Due to the lack of a reliable method to distinguish between bound and unbound clusters at these young ages, this is a reasonable approach. The latter correction appears of the greatest importance for the M51 system; their new estimates for the characteristic disruption time-scale, based on the clusters older than 10^7 yr, is $t_4^{\mathrm{dis}} = 1.0^{+0.6}_{-0.5} \times 10^8$ yr for a constant cluster formation rate, and $t_4^{\mathrm{dis}} \simeq 2.0 \times 10^8$ yr for both a cluster formation rate that has been increasing linearly for the past Gyr (assuming a few different models for the shape of the cluster formation rate during this period), and a cluster formation rate undergoing exponentially decaying bursts around the times of closest approach between the two galaxies. These values are still a factor of ~ 5 below the theoretically predicted time-scales. We note that Lamers et al. (2005b) found a similar discrepancy for the Galactic open clusters in the solar neighbourhood. In a very recent contribution, Lamers & Gieles (2007) show that if one takes the combined effects of stellar evolution, the underlying galactic tidal field, and perturbations by spiral arms and giant molecular clouds properly into account, this discrepancy can be understood. They show that by including the significant impact of cluster disruption by giant molecular clouds (shown to be an order of magnitude more important than that of the spiral arms, and just as important as the other effects combined), the theoretically predicted cluster disruption time-scales shorten dramatically, and the discrepancy between the theoretically and empirically derived time-scales disappears.

For M82 B (de Grijs et al. 2003a), we did not have to correct for the effects of infant mortality because of the greater average age of the cluster system (and the much smaller number of very young clusters in this region). In addition, we treated the periods before, during and after the burst of cluster formation (which occurred $\sim 10^9$ yr ago) separately, by assuming constant cluster formation rates during each of these epochs. We note that the most crucial assumption underpinning our disruption time-scale estimate is that of the initial cluster mass distribution. For the M82 B time-scale – following Lamers et al. (2005a) – we used an initial power-law CMF, with spectral index $\alpha = -2$. However, we noted in de Grijs et al. (2003d; see also Sect. 5) that the observed CMF of the approximately coeval cluster population in M82 B resembles Vesperini's (1998) (quasi-)equilibrium log-normal CMF relatively closely, for cluster masses down to $\log(m_{\mathrm{cl}}[M_\odot]) \simeq 4.4$ (i.e., at our 100 per cent observational completeness limit). The implication of our assumption of "instantaneous disruption" only constrains t_4^{dis} to $t_4^{\mathrm{dis}} \lesssim 10^9$ yr, i.e., less than the present age of the clusters formed simultaneously in the burst of cluster formation. Therefore, if the initial CMF of the *bound* clusters comprising the observed M82 B CMF at its current age is more similar to a log-normal distribution than to a power law (Sect. 5; see also de Grijs et al. 2005b), we cannot constrain the characteristic disruption time-scale to better than $t_4^{\mathrm{dis}} \lesssim 10^9$ yr.

Based on the M51 cluster age and mass determinations of Bastian et al. (2005; N. Bastian & R. Scheepmaker, priv. comm.) we constructed statistically complete CMFs covering intervals of 0.5 dex in $\log(\mathrm{Age\, yr}^{-1})$. The M51 cluster subsamples in the age ranges $\log(\mathrm{Age\, yr}^{-1}) \leq 7.0$, $7.0 < \log(\mathrm{Age\, yr}^{-1}) \leq 7.5$, and $7.5 < \log(\mathrm{Age\, yr}^{-1}) \leq 8.0$ are all consistent with power laws down to the 50 per cent observational completeness limits, at $\log(m_{\mathrm{cl}}[M_\odot]) \simeq 3.3, 3.8$ and 4.1, respectively. It is clear, therefore, that a similar explanation as for M82 B for the short characteristic disruption time-scale cannot feasibly be invoked for the M51 clusters. Instead, Gieles et al. (2005) suggest that this may be due to (i) variations, in particular a low-mass cut-off, in the stellar IMF, (ii) significant external perturbations, (iii) YMC formation in non-virial equilibrium conditions, or to (iv) variations in the clusters' central concentration (see also Lamers et al. 2005b in the context of the Galactic open clusters in the solar neighbourhood).

As we will discuss in detail in Section 4, it is unlikely that an entire YMC population is affected by a low-mass cut-off to its IMF, although this may speed up cluster dissolution in individual cases. The N-body models of Portegies Zwart et al. (1998, 2002) and Baumgardt & Makino (2003) assume a smooth underlying gravitational potential; the introduction of additional external perturbations by, e.g., giant molecular clouds

or spiral-arm passages will shorten the typical disruption time-scale (e.g., Ostriker, Spitzer & Chevalier 1972; Terlevich 1987; Theuns 1991; Gieles et al. 2006a, b; Lamers & Gieles 2006, 2007; Gieles 2007; see also Lamers et al. 2005b). Similarly, after the initial fast infant mortality phase, the surviving clusters will have lost the gas comprising their interstellar medium, and will expand in an attempt to regain virial equilibrium as a consequence (see Sect. 4.2 for a detailed discussion). It is at this stage that they are most vulnerable to additional tidal disruption, which will thus also speed up their dissolution (e.g., Bastian & Goodwin 2006; Goodwin & Bastian 2006; and references therein). The efficiency of this process will be enhanced if the YMCs are initially more extended than assumed in the *N*-body models, which generally adopt cluster concentrations similar to those of the Galactic GCs.

While all of these effects may operate in any galactic environment, the M51 clusters discussed by Gieles et al. (2005), as well as the massive clusters in M82 B (de Grijs et al. 2005b; and references therein) and the Galactic open clusters in the solar neighbourhood (Lamers et al. 2005b), are located in the dense inner regions of their host galaxies, where one would expect any additional perturbing effects to be most efficient. It may therefore simply be the case that the *disk* regions of M51, M82 B and the solar neighbourhood provide unsuitable conditions for proto-GCs to survive for a Hubble time, while YMCs formed in the lower-density halo regions stand a better chance of long-term survival.

4 THE LONG-TERM EVOLUTION OF INDIVIDUAL STAR CLUSTERS

The crucial question remains, however, whether or not at least *some* of the YMCs observed in extragalactic starbursts might survive to become (possibly somewhat more metal-rich) counterparts of the Galactic GCs when they reach a similar age. If we could resolve this issue convincingly, one way or the other, the implications would be far-reaching for a wide range of astrophysical questions. On galactic scales, on the one hand, this would improve – or confirm – our understanding of how galaxy formation, assembly and evolution proceeds, and what the process and necessary conditions are for star (cluster) formation. On the other hand, on the scales of the individual cluster stars, and possibly as a function of the environment in which the clusters formed, star cluster survival for a Hubble time sets tight constraints on the slope and possible low-mass cut-off of the stellar IMF, as we will discuss in more detail below.

The evolution to old age of young clusters depends crucially on their stellar 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; Kouwenhoven, de Grijs & Goodwin, in preparation). 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 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 (see also de Grijs et al. 2002b, c). The stellar mass range covered ranged from 0.15 to $15 M_\odot$; his *N*-body runs spanned at most a few 100 Myr. 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; see also Takahashi & Portegies Zwart 2000, their fig. 8) concluded that – for Galactocentric distances $\gtrsim 12\,\mathrm{kpc}$ – some of his simulated LMC YMCs should be capable of surviving for a Hubble time if $\alpha \geq 2$ (or even $\gtrsim 3$; 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, $c \gtrsim 1.0 - 1.5$. 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), Bastian & Goodwin (2006) and Goodwin & Bastian (2006), for counterarguments related to environmental effects and to variations in the clusters' SFEs, respectively.

In addition, YMCs are subject to a variety of additional 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.

4.1 Survival Diagnostics: the Mass-to-Light Ratio versus Age Diagram

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). As a simple first approach, 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 (SSP) models using a variety of IMF descriptions (cf. Smith & Gallagher 2001; Mengel et al. 2002; Bastian et al. 2006; Goodwin & Bastian 2006). In Figure 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. However, such an approach, while instructive, has serious shortcomings. The viability of this approach depends, in essence[3], on the validity of the virial equation to convert line-of-sight velocity dispersions, σ_{los}^2, to dynamical mass estimates, M_{dyn}, via (Spitzer 1987):

$$M_{\mathrm{dyn}} = \frac{\eta \sigma_{\mathrm{los}}^2 r_{\mathrm{h}}}{G} \quad , \tag{3}$$

where $r_{\mathrm{h}} = 1.3 \, R_{\mathrm{eff}}$ are the half-mass and effective (or half-light) radii of the cluster, respectively, and $\eta = 3a$; $a \approx 2.5$ is the factor required to convert the half-mass to the gravitational radius, r_{g}. More specifically, following Fleck et al. (2006), we write

$$r_{\mathrm{g}} = \frac{5}{2} \times \frac{4}{3} r_{\mathrm{h}} \quad , \tag{4}$$

where the factor 5/2 provides an approximate conversion for a large range of clusters characterised by King (1966) mass profiles; the second numerical factor in Equation (4) results from projection on the sky, assuming that light traces mass throughout the cluster. The use of both Equation (3) and the M/L ratio versus age diagram rely on a number of assumptions and degeneracies, however, which we will discuss in detail below.

4.1.1 IMF Degeneracies

In the simplest approach, in which one compares the YMC loci in the M/L ratio versus age diagram with SSP models, the data can be described by *both* variations in the IMF slope *and* variations in a possible low-mass cut-off (e.g., Sternberg 1998; Smith & Gallagher 2001; Mengel et al. 2002); the models are fundamentally degenerate for these parameters. For instance, based on K-band observations, Mengel et al. (2002) find that their sample of high-mass YMCs in the Antennae system contains a subgroup of clusters with either a relatively shallow IMF slope down to the hydrogen-burning limit, $m_* \sim 0.1 M_\odot$ (the exact value depending on metallicity), or perhaps with a slightly steeper slope but a truncated IMF at higher stellar masses, $m_* \sim 1 M_\odot$. They note that these alternatives are less apparent in the V band.

Similarly, Sternberg (1998) derived for the YMC NGC 1705-I that it must either have a flat mass function ($\alpha < 2$) or a low-mass truncation between 1 and $3 M_\odot$ (see also Smith & Gallagher 2001); in both cases, it is unlikely that this cluster may be capable of surviving for a Hubble time. In addition, Smith & Gallagher (2001), using a similar approach, found that the unusual YMC M82-F may also be characterised by a low-mass cut-off of its mass function at $\sim 2 - 3 M_\odot$, or perhaps by a shallow slope, $\alpha \sim 2$ for a mass function that is well sampled down to the hydrogen-burning limit (but see Sect. 4.3 for a more in-depth discussion on this object).

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[3] To a small extent, this also depends on our assumptions of spherical symmetry and the fact that the clusters are gravitationally bound. While the effect of slight non-sphericity will lead to underestimates of σ_{los}, this effect is almost negligible compared to the other effects described here, except for M82-F (see Sect. 4.3). As long as we consider compact ($r_{\mathrm{h}} \lesssim$ a few pc) clusters older than a few Myr, the assumption that they are gravitationally bound is reasonable, since typical crossing times are $t = r_{\mathrm{h}} \sigma_{\mathrm{los}}^{-1} \sim 1 \, \mathrm{Myr}$ (e.g., Larsen 1999, his table 4.4).
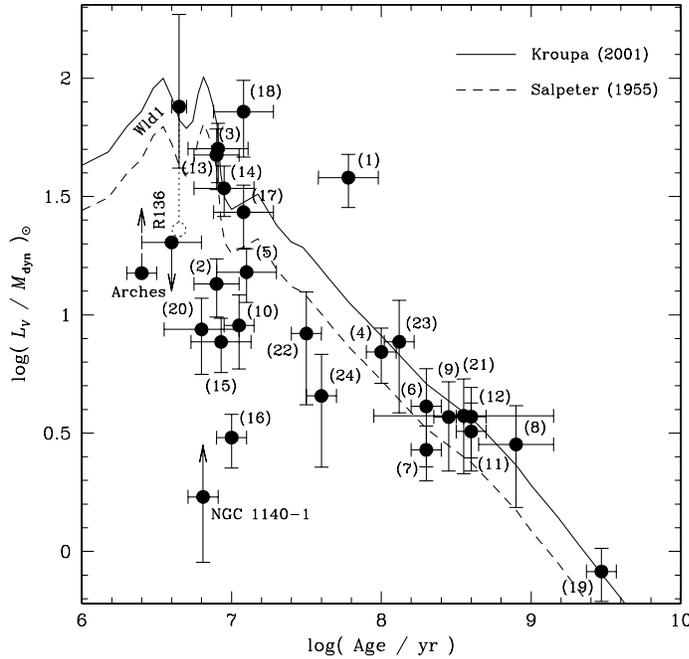
Fig. 2 Updated version of the YMC M/L ratio versus age diagnostic diagram. The numbered data points were taken from Bastian et al. (2006; and references therein); overplotted are the SSP predictions for a Salpeter (1955) and a Kroupa (2001) stellar IMF. We have included four new YMCs, NGC 1140–1 (Moll et al. 2006) the Galactic Centre Arches cluster (see Sect. 4.4), R136 in 30 Doradus (Goodwin & Bastian 2006) and Westerlund 1 (denoted 'Wld 1'; Sect. 4.4). Regarding the latter, the vertical error bars are entirely due to the uncertainty in the dynamical mass estimate of Mengel & Tacconi-Garman (2007); the uncertainty introduced by the various foreground extinction estimates is shown by the dotted line (see text).
YMC identifications – (1): M82-F; (2): M82 MGG-9; (3): M82 MGG-11; (4): NGC 5236–502; (5): NGC 5236–805; (6): NGC 4214–10; (7): NGC 4214–13; (8): NGC 4449–27; (9): NGC 4449–47; (10): NGC 6946–1447; (11): NGC 7252 W3; (12): NGC 7252 W30; (13): (Antennae) W99–1; (14): W99–2; (15): W99–15; (16): W99–16; (17): NGC 1569 A1; (18): NGC 1705-I; (19): NGC 1316 G114; (20): ESO 338-IG04 #23; (21): ESO 338-IG04 #34; (22): NGC 1850; (23): NGC 1866; (24): NGC 2157.

However, the conclusion that the IMFs of these clusters may be unusual must be regarded with caution. As Smith & Gallagher (2001) point out, previous claims for highly abnormal (initial) mass functions have often proven incorrect. If anything, the shape of the mass function may vary on the size scales of the individual clusters, but once one considers their birth environments on larger scales the present-day mass function appears to be remarkably robust (e.g., Scalo 1998, Kroupa 2001), with the possible exception of the resolved starburst clusters in the Milky Way (e.g., Stolte et al. 2005, 2006), NGC 3603 and – in particular – the Galactic Centre Arches cluster (see Sect. 4.4).

Despite this controversy (particularly for some of 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 (e.g., Larsen et al. 2001; McCrady, Gilbert & Graham 2003; Maraston et al. 2004; Larsen, Brodie & Hunter 2004; Larsen & Richtler 2004; Bastian et al. 2006; see also de Grijs et al. 2005a for a comparison of dynamical and photometric masses, the latter based on "standard" IMF representations). In addition, significant recent progress has been made in our understanding of the properties of the YMCs characterised by apparently non-standard IMFs, which we will discuss in detail in Section 4.2.

4.1.2 Mass Segregation

While the assumption that these objects are *approximately* in virial equilibrium is probably justified at ages greater than a few $\times 10^7$ yr and for realistic SFEs $\gtrsim 30$ per cent (at least for the stars dominating the light; see, e.g., Goodwin & Bastian 2006), the *central* velocity dispersion (as derived from luminosity-weighted high-resolution spectroscopy) does not necessarily represent a YMC's total mass. It is now well-established that almost every YMC exhibits significant mass segregation from very young ages onwards, so that the effects of mass segregation must be taken into account when converting central velocity dispersions into dynamical mass estimates (see also Lamers et al. 2006; Fleck et al. 2006; Moll et al. 2006; S. L. Moll et al. in prep.).

By ignoring the effects of mass segregation, as is in essence done if one simply applies Equation (3), the underlying assumption is then that of an isotropic stellar velocity distribution, i.e., $\sigma_{\rm total}^2 = 3\sigma_{\rm los}^2$, where $\sigma_{\rm total}^2$ is the cluster's mean three-dimensional velocity dispersion. In the presence of (significant) mass segregation in a cluster, the central velocity dispersion will be dominated by the higher-mass stars populating the cluster core. If we focus on dynamical evolution as the dominant cause of mass segregation in clusters (as opposed to the possible preferential formation of the higher-mass stars close to the cluster core, also known as "primordial" mass segregation; e.g., Bonnell & Davies 1998; de Grijs et al. 2002b), it follows that for the high-mass stars to migrate to the cluster core, i.e., to the bottom of the gravitational potential, they must have exchanged some of their kinetic energy with their lower-mass counterparts on more extended orbits. As a consequence, the velocity dispersion dominating the observed high-resolution spectra will be *lower* than expected for a non-mass-segregated cluster of the same mass. In addition, measurements of $r_{\rm h}$ will also be biased to smaller values, and not to the values associated with the cluster as a whole. Mass segregation will thus lead to an *under*estimate of the true cluster mass.

We also note that the assumption of virial equilibrium only holds to a limited extent, even in old GCs, because cluster-wide relaxation time-scales of massive GC-type objects are of order 10^9 yr or longer (Djorgovski 1993). In fact, full global, or even local, energy equipartition among stars covering a range of masses is never reached in a realistic star cluster, not even among the most massive species (e.g., Inagaki & Saslaw 1985; Hunter et al. 1995). As the dynamical evolution of a cluster progresses, low-mass stars will, on average, attain larger orbits than the cluster's higher-mass stars, and the low-mass stars will thus spend most of their time in the cluster's outer regions, at the extremes of their orbits. For this reason alone, we would not expect to achieve global energy equipartition in a cluster.

The time-scale for the onset of significant dynamical mass segregation is comparable to the cluster's dynamical relaxation time (Spitzer & Shull 1975; Inagaki & Saslaw 1985; Bonnell & Davies 1998; Elson et al. 1998). A cluster's characteristic time-scale may be taken to be its half-mass (or median) relaxation time, i.e., the relaxation time at the mean density for the inner half of the cluster mass for cluster stars with stellar velocity dispersions characteristic for the cluster as a whole (Spitzer & Hart 1971; Lightman & Shapiro 1978; Meylan 1987; Malumuth & Heap 1994).

Although the half-mass relaxation time characterises the dynamical evolution of a cluster as a whole, significant differences are expected locally within the cluster. The relaxation time-scale will be shorter for higher-mass stars than for their lower-mass companions; numerical simulations of realistic clusters confirm this picture (e.g., Aarseth & Heggie 1998; Kim et al. 2000; Portegies Zwart et al. 2002). From this argument it follows that dynamical mass segregation will also be most rapid where the local relaxation time is shortest, i.e., near the cluster centre (cf. Fischer et al. 1998, Hillenbrand & Hartmann 1998). Thus, significant mass segregation among the most massive stars in the cluster core occurs on the local, central relaxation time-scale (comparable to just a few crossing times; cf. Bonnell & Davies 1998).

The combination of these effects will lead to an increase of the dimensionless parameter η in Equation (3) with time, if the characteristic two-body relaxation time of a given (massive) stellar species is short (Boily et al. 2005; Fleck et al. 2006), and thus to an *under*estimate of the true cluster mass. However, we note that Goodwin & Bastian (2006) point out that a large fraction of the youngest clusters in the M/L ratio versus age diagram appear to have dynamical masses well in excess of their photometric masses, and that, therefore, the result of Boily et al. (2005) and Fleck et al. (2006) does not seem applicable to these YMCs.

4.1.3 Stellar Masses

Estimating dynamical masses via Equation (3) assumes, in essence, that all stars in the cluster are of equal mass. This is clearly a gross oversimplification, which has serious consequences for the resulting mass estimates. The straightforward application of the virial theorem tends to *under*estimate a system's dynamical mass by a factor of ~ 2 compared to more realistic multi-mass models (e.g., Mandushev et al. 1991; based on an analysis of the observational uncertainties). Specifically, Mandushev et al. (1991) find that the mass-luminosity relation for GCs with mass determinations based on multi-component King-Michie models (obtained from the literature) lies parallel to that for single-mass King models, but offset by $\Delta \log(m_{cl}[M_\odot]) \simeq 0.3$ towards higher masses. Farouki & Salpeter (1982) already pointed out that cluster relaxation and its tendency towards stellar energy equipartition is accelerated as the stellar mass spectrum is widened; mass segregation will then take place on shorter time-scales than for single-component (equal mass) clusters, and thus this will once again lead to an *under*estimate of the true cluster mass (see also Goodwin 1997a; Boily et al. 2005; Fleck et al. 2006 for multi-mass *N*-body approaches).

We also point out that if the cluster contains a significant fraction of primordial binary and multiple systems, these will act to effectively broaden the mass range and thus also speed up the dynamical evolution of the cluster (e.g., Fleck et al. 2006).

4.1.4 Can We Reduce the Number of Assumptions?

Motivated by a desire to reduce the number of assumptions involved in these dynamical mass estimates, in de Grijs et al. (2005a) we explored whether we could constrain the evolution of individual YMCs based on their loci in the plane defined by their luminosities (or absolute V-band magnitudes, M_V) and central velocity dispersions, σ_0. The method hinges on the empirical relationship for old GCs in the Local Group, which occupy a tightly constrained locus in this plane (Djorgovski et al. 1997; McLaughlin 2000; and references therein). We concluded that the tightness of the relationship for a sample drawn from environments as diverse as those found in the Local Group, ranging from high to very low ambient densities, implies that its origin must be sought in intrinsic properties of the GC formation process itself, rather than in external factors.

Encouraged by the tightness of the GC relationship, we also added the available data points for the YMCs in the local Universe for which velocity dispersion information was readily available. In order to compare them to the old Local Group GCs, we evolved their luminosities to a common age of 12 Gyr, adopting the "standard" Kroupa (2001) IMF (for stellar masses from 0.1 to $100 M_\odot$). We found that the ($\sim \frac{2}{3}$) majority of our sample YMCs end up scattering closely about the Local Group GC relationship. In the absence of significant external disturbances, this would imply that these objects may potentially survive to become old GC-type objects by the time they reach a similar age. In order to investigate whether dynamical evolution would have a dramatic impact on the evolution of clusters in the $M_V - \sigma_0$ plane, we analysed the results of a number of *N*-body simulations. We showed that the evolution of the observed σ_0 is relatively small for clusters that survive to old age, and in the sense that the central velocity dispersion decreases with time.

Thus, these results provide additional support to the suggestion that the formation of proto-GCs appears to be continuing until the present. Detailed case by case comparisons between our results in de Grijs et al. (2005a) with those obtained previously and independently based on dynamical mass estimates and M/L ratio considerations lend significant support to the feasibility and robustness of this novel method (see de Grijs et al. 2005a for a detailed discussion). The main advantage of this method compared to the more complex analysis involved in using dynamical mass estimates is its simplicity and empirical basis. The only observables required are the system's line-of-sight velocity dispersion and photometric properties.

4.2 Gas Expulsion

It may appear that a fair fraction of the ~ 10 Myr-old YMCs that have been analysed thus far might be characterised by unusual IMFs, since their loci in the diagnostic diagram are far removed from any of the "standard" SSP models (see, e.g., Smith & Gallagher 2001; Bastian et al. 2006; Goodwin & Bastian 2006; Moll et al. 2006; S. L. Moll et al. in prep.). However, Bastian & Goodwin (2006) and Goodwin & Bastian (2006) recently showed that this is most likely an effect of the fact that the velocity dispersions of these young objects do not adequately trace their masses. Using a combination of high-resolution *HST* observa-

tions of the YMCs M82-F, NGC 1569-A and NGC 1705-I combined with *N*-body simulations of clusters that have recently undergone the rapid removal of a significant fraction of their mass due to gas expulsion (e.g., caused by supernova activity and massive stellar winds), Bastian & Goodwin (2006) suggest that these clusters are undergoing violent relaxation and are also subject to *stellar* mass loss. As a result, the observed velocity dispersions of these YMCs will include the non-gravitational motions of the escaping stars, and thus lead to artificially enhanced dynamical mass estimates. More specifically, Bastian & Goodwin (2006) derive that such dynamical mass estimates may be wrong by a factor of up to 3 for 10–20 Myr after gas expulsion, for SFEs $\gtrsim 40$ per cent, as for YMCs of similar age as NGC 1569-A and NGC 1705-I, as well as for many young LMC clusters.

Although this discrepancy between the dynamical and the true stellar mass will disappear quickly (i.e., within 10–15 Myr) for clusters with SFEs $\gtrsim 50$ per cent, clusters with lower SFEs are more significantly affected. Bastian & Goodwin (2006) show that for YMCs with SFE ~ 40 per cent, the apparent dynamical mass will be much greater than the true stellar mass for YMCs at an age of ~ 10 Myr, and virial equilibrium is not achieved until an age of ~ 50 Myr. The observed stellar velocity dispersions of such clusters may even *under*estimate the true stellar mass by up to 30 per cent, as the cluster has overexpanded in its attempt to reach a new virial equilibrium.

Thus, claims of abnormal stellar (initial) mass functions based on such erroneous dynamical mass estimates, which would clearly affect the clusters' loci in the M/L ratio versus age diagram, should be treated with extreme caution (cf. de Grijs et al. 2005a; Bastian et al. 2006; Bastian & Goodwin 2006; Goodwin & Bastian 2006). In this respect, it is encouraging to see that the older clusters (i.e., older than a few $\times 10^7 - 10^8$ yr) seem to conform to "normal" IMFs; by those ages, the clusters' velocity dispersions seem to represent the underlying gravitational potential much more closely; see Goodwin & Bastian (2006; see also Fig. 2) for the most recently updated M/L ratio versus age diagram. Goodwin & Bastian (2006) show indeed that, depending on the cluster's SFE, an equilibrium state is reached after ~ 30 Myr, when the effects of gas expulsion are no longer easily detectable in the cluster's stellar velocity dispersion (at least for SFEs $\gtrsim 40$ per cent; lower-SFE clusters most likely disperse into the background field star population well before that age). In fact, Goodwin & Bastian (2006) show conclusively that the scatter in the YMC loci for the youngest ages ($\sim 10^7$ yr) in this diagnostic diagram can be fully understood if we vary the effective SFE to allow for SFEs as low as about 10 per cent. This then implies that those YMCs that lie well below the diagnostic line based on the "standard" IMF evolution will disperse; these objects include, among others, many of the YMCs in the Antennae galaxies (Mengel et al. 2002; see also de Grijs et al. 2005a for a discussion of these YMCs), some of the young LMC clusters (McLaughlin & van der Marel 2005), including R136 in 30 Doradus (see Goodwin & Bastian 2006), NGC 1569-A and NGC 1705-I (e.g., Smith & Gallagher 2001), NGC 6946–1447 (Larsen et al. 2006; corrected for extinction in Goodwin & Bastian 2006), YMC number 23 in ESO 338-IG04 (Östlin, Cumming & Bergvall 2007), and NGC 1140–1 (Moll et al. 2006). Of all these discrepant YMCs, NGC 1140–1 appears to have the largest velocity dispersion (and hence dynamical mass estimate). This is most likely due to its environmental effects; the YMC is situated in a vigorously star-forming region of its host galaxy, and is possibly interacting with a neighbouring YMC (de Grijs et al. 2004; S. L. Moll et al. in prep.). In addition, the ground-based high-resolution spectra likely include flux from the nearest neighbouring clusters as well, which might enhance the observed velocity dispersion of the region covered. As such, one should treat this data point with due caution.

4.3 The Enigmatic Cluster M82-F

Thanks to the recent studies of Bastian & Goodwin (2006) and Goodwin & Bastian (2006), we are now confident that we understand why some of the YMCs deviate significantly from the expected evolution – for a "standard" IMF – of the stellar M/L ratio at ages of $\sim 10^7$ yr, as discussed in the previous section. However, the location of the massive cluster F in M82 remains to be understood, despite having been the subject of a considerable number of recent studies (e.g., O'Connell et al. 1995; Gallagher & Smith 1999; Smith & Gallagher 2001; McCrady et al. 2003, 2005; Bastian & Goodwin 2006; Bastian et al. 2007).

Smith & Gallagher (2001) concluded that, assuming that their age (60 ± 20 Myr), mass ($1.2 \pm 0.1 \times 10^6 M_\odot$) and luminosity ($M_V = -14.5 \pm 0.3$ mag; $L_V/M_{\rm dyn} = 45 \pm 13 \, L_{V,\odot}/M_\odot$) measurements for the object were correct, it must either have a low-mass cut-off of its mass function at $\sim 2 - 3 M_\odot$, or a shallow mass function slope, $\alpha \sim 2$ for a mass function including stellar masses down to $0.1 M_\odot$. McCrady et al.

(2003) suggested, based on near-infrared population synthesis modeling, that Smith & Gallagher (2001) had overestimated their ages as well as the half-mass radius of the cluster; they derived the latter more accurately based on higher-resolution (*HST*/ACS) imaging than available to Smith & Gallagher (2001). However, in a recent contribution, Bastian et al. (2007) used optical spectroscopy, in essence confirming the YMC's age to be in the range from 50–70 Myr. However, contrary to the earlier studies, Bastian et al. (2007) conclude that M82-F is subject to a large amount of differential extinction, thus rendering earlier luminosity estimates based on foreground-screen extinction very uncertain. They conclusively show that the apparently large degree of mass segregation in the cluster, derived by McCrady et al. (2005) based on the variation of $r_{\rm h}$ as a function of wavelength, is in fact caused by this differential extinction. Applying their spatially resolved extinction corrections to the *HST*/ACS data, Bastian et al. (2007) also confirm the size estimate of Smith & Gallagher (2001). Thus, Bastian et al. (2007) have firmly placed the M82-F data point close to its original location well away from the prediction for the evolution of an SSP characterised by a "standard" IMF in the diagnostic M/L ratio versus age diagram.

Smith & Gallagher (2001), Bastian et al. (2006) and Bastian & Goodwin (2006) have all suggested that the discrepancy between the observations of M82-F and the evolution of an SSP with a "standard" IMF could be resolved if the YMC were as young as ~ 15 Myr. However, while the cluster's structure reveals evidence for non-virial equilibrium at large radii (Bastian & Goodwin 2006), non-sphericity (Smith & Gallagher 2001; McCrady et al. 2005), clumpy substructure (e.g., Bastian et al. 2007) and multiple stellar populations (see Bastian et al. 2007 for details), none of these properties seem capable of resolving the age issue; the current best age estimate for M82-F remains close to 60 Myr (Bastian et al. 2007). In fact, based on its location in the diagnostic diagram, the object appears to be subvirial instead of supervirial as expected if the effects of gas expulsion were significant. In addition, any subvirial phase would be expected to occur shortly after the main gas expulsion phase, when the cluster is attempting to regain virial equilibrium; the current best YMC age estimate is too old for this to be a likely evolutionary state for M82-F, however. Secondly, the young age solution seems to be ruled out by the spectroscopic data of Bastian et al. (2007); we note that the cluster is projected onto a background H II region (e.g., Smith & Gallagher 2001), which might affect the integrated photometry.

Thus, we conclude that the YMC M82-F remains an enigma. Based on the simplest assumptions it appears that its present-day mass function may be deficient in low-mass stars, although its complicated substructure might imply that there are unknown factors at work here (such as tidal disruption in the intense tidal field in the M82 disk). If the cluster's mass function is indeed "top heavy", it is unlikely to survive for more than 1–2 Gyr (Smith & Gallagher 2001; McCrady et al. 2005).

4.4 Galactic Starburst Clusters

Thus far, the best evidence yet for an unusual present-day mass function in a compact, massive young star cluster relates to the ~ 2 Myr-old Arches cluster near the Galactic Centre. Stolte et al. (2005) present direct evidence for a low-mass depleted mass function, based on a turn-over of the cluster's mass function around 6–$7 M_{\odot}$, i.e., well above their observational detection limit in the cluster core, at $\sim 4 M_{\odot}$, decreasing to $\sim 2 M_{\odot}$ at large radii. They hypothesize that the significant overdensity of high-mass stars and the depletion of low and intermediate-mass stars in the cluster core could be caused by either rapid dynamical mass segregation or the preferential formation of high-mass stars with respect to their lower-mass counterparts (i.e., primordial mass segregation; see also Figer et al. 1999), while at larger radii they suggest that either tidal stripping of lower-mass stars ($m_* \lesssim 6 M_{\odot}$) by the Galactic Centre's tidal field (based on the rapid dissolution time-scales suggested by *N*-body simulations; Kim et al. 2000; Portegies Zwart et al. 2002), or a physically truncated *initial* mass function might be responsible. In the latter case, this might imply that a low-mass truncated and possibly (Figer et al. 1999; Stolte et al. 2002, 2005) also a somewhat flattened IMF may be more appropriate for starburst YMCs[4]. If so, this will have significant consequences for stellar population synthesis modeling of extragalactic starburst environments and the derivation of integrated properties. An apparent flattening of the IMF was also observed in NGC 3603 (Stolte et al. 2006; but see

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[4] A similar flattening of the IMF slope has been found for the young starburst cluster R136 in 30 Doradus in the LMC (Sirianni et al. 2000), where the slope flattens below $m_* \simeq 2 M_{\odot}$, and in the embedded young Galactic (starburst) cluster NGC 2024, which shows a flattening of the IMF slope below $m_* \sim 1 M_{\odot}$ (Comeron, Rieke & Rieke 1996).

Eisenhauer et al. 1998) although this YMC's mass function does not appear to be truncated at low masses (Eisenhauer et al. 1998; Sung & Bessell 2004; Stolte et al. 2006).

For completeness, we have added the appropriate data point for the Arches cluster to the diagnostic M/L ratio versus age diagram of Figure 2. Figer et al. (2002) derive an age of 2.5 ± 0.5 Myr, and an upper limit to the mass of the Arches cluster of $m_{\rm cl} < 7 \times 10^4 M_\odot$ within a radius of 0.23 pc, which they claim to be "about 5 times greater than what would be expected from the mass function" in Figer et al. (1999). The latter, photometric, mass estimate of $10800\,M_\odot$ is based on extrapolating the YMC's (significantly flattened) IMF to a lower mass limit of $1 M_\odot$, although adopting a lower mass limit of $0.1 M_\odot$ results in a total mass that is merely a factor of ≈ 1.1 greater. Thus, the Arches data point in Figure 2 is located at a ~ 5 times smaller light-to-mass ratio than expected for a Kroupa-type IMF (which we deem to be a more appropriate IMF for the purpose of this comparison than the single power-law Salpeter IMF). Although the YMC's location in Figure 2 suggests that its SFE may be as low as 30 per cent (cf. fig. 5 in Goodwin & Bastian 2006), we point out that (i) our value is in fact a lower limit, and (ii) its location near the Galactic Centre implies that it is subject to significant external pressures, which are likely to inject additional energy into the system, thus artificially increasing its velocity dispersion. Nevertheless, whether because of the internal dynamics, or because of external tidal effects, given its current mass function the Arches cluster is unlikely to survive for a Hubble time.

Possibly the best local example of a YMC in the Galaxy is Westerlund 1 ($m_{\rm cl} \sim 10^5 M_\odot$, with an absolute lower limit of $m_{\rm cl,low} \simeq 1.5 \times 10^3 M_\odot$; Clark et al. 2005; see also Mengel & Tacconi-Garman 2007, who recently determined $m_{\rm cl} = 6.3^{+5.3}_{-3.7} \times 10^4 M_\odot$, based on its near-infrared velocity dispersion and assuming the object to be in virial equilibrium), at an age of 4–5 Myr (Crowther et al. 2006). Due to the large extinction[5] towards the cluster, $A_V \sim 12.9$ mag (Piatti et al. 1998), its stellar mass function below $m_* \sim 1.5 M_\odot$ is essentially unconstrained by direct observations (e.g., Clark et al. 2007; and references therein). Clark et al.'s (2005) mass estimate of $m_{\rm cl} \sim 10^5 M_\odot$ was based on the assumption of a Kroupa (2001) stellar IMF. By comparison of the X-ray fluxes of the Orion Nebula Cluster (ONC) and Westerlund 1, Clark et al. (2007) speculate that the 45 X-ray bright pre-main sequence (pre-MS) candidate stars in Westerlund 1 form the high-luminosity tail of $\geq 36,000$ lower-luminosity (and hence lower-mass, $m_* < 1.5 M_\odot$) pre-MS stars.

On the other hand, Muno et al. (2006) argue that the non-thermal spectrum of the diffuse X-ray emission from Westerlund 1 and the ONC are markedly (physically) different, in the sense that the stellar metallicities are much lower (around solar) in Westerlund 1 than in the ONC. This implies (Muno et al. 2006) that the low-mass stars ($0.3 M_\odot < m_* < 2 M_\odot$) contribute $\lesssim 30$ per cent of the diffuse X-ray flux from Westerlund 1, corresponding to $\lesssim 40,000$ low-mass stars in this mass range. If the YMC's stellar IMF were of the Kroupa (2001) type, one would expect $\gtrsim 100,000$ stars in this mass range. This result seems to imply, therefore, that either the stellar IMF in Westerlund 1 is flat ($\alpha \lesssim 2.1$), or that it is truncated at $m_* < 0.6 M_\odot$ (Muno et al. 2006). In the latter case, the total mass of the cluster would not change significantly under the assumption of a Kroupa (2001) IMF; in the former case, the total mass of the cluster would only be $m_{\rm cl} \sim 40,000 - 70,000 M_\odot$. In either case, it is unlikely that Westerlund 1 will survive for a Hubble time. However, while the Muno et al. (2006) and the Clark et al. (2007) estimates seem to constrain the number of low-mass stars in the cluster quite well, we note that the arguments presented here are based on observations of the massive stars only, and hence on assumed extrapolations of the mass function to lower masses. These results must therefore be treated with due caution.

4.5 A "Super" Star Cluster Grown Old?

We recently reported the discovery of an extremely massive, but old (12.4 ± 3.2 Gyr) GC in M31, 037-B327, that has all the characteristics of having been an exemplary YMC at earlier times, based on an extrapolation of its present-day extinction-corrected V-band luminosity back to an age of 10 Myr (Ma et al. 2006b; see also Cohen 2006). To have survived for a Hubble time, we conclude that its stellar IMF cannot have been

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[5] Clark et al. (2005) derive an updated value of $A_V = 11.6$ mag. We include Westerlund 1 in Figure 2, adopting the recent dynamical mass estimate of Mengel & Tacconi-Garman (2007), the integrated V-band luminosity out to a radius $R \simeq 1.4$ pc derived from figure 8 of Piatti et al. (1998; corrected for a current best distance estimate of $D = 5.5$ kpc; Clark et al. 2005), and the current best age estimate of Crowther et al. (2006). We also show the object's location in this diagram if we had assumed Clark et al.'s (2005) extinction estimate (dotted line).

top-heavy. Using this constraint, and a variety of SSP models, we determined a *photometric* mass for 037-B327 of $M_{\mathrm{GC}} = (3.0 \pm 0.5) \times 10^7 M_{\odot}$, somewhat depending on the SSP models used, the metallicity and age adopted and the IMF representation. In view of the large number of free parameters, the uncertainty in our photometric mass estimate is surprisingly small (although this was recently challenged by Cohen 2006). This mass, and its relatively small uncertainties, make this object potentially one of the most massive star clusters of any age in the Local Group. As a surviving "super" star cluster, this object is of prime importance for theories aimed at describing massive star cluster evolution.

Cohen (2006) obtained an optical velocity dispersion for the cluster using the Keck/HIRES spectrograph, and showed that it is comparable to that of M31 G1. Depending on the wavelength range used, they find $\sigma_{\mathrm{los}} = 19.2 \pm 3.5 \mathrm{\,km\,s}^{-1}$ ($5150 - 5190$ Å) and $\sigma_{\mathrm{los}} = 19.9 \pm 3.4 \mathrm{\,km\,s}^{-1}$ ($6545 - 6600$ Å), compared to $\sigma_{\mathrm{los}} \sim 22 \mathrm{\,km\,s}^{-1}$ for M31 G1. The cluster's half-light radius, $r_{\mathrm{h}} \simeq 2.5 \pm 0.2 \mathrm{\,pc}$ (Ma et al. 2006b). For M31 G1, we recently redetermined $r_{\mathrm{h}} = 6.5 \pm 0.3 \mathrm{\,pc}$ (Ma et al. 2007). Thus, based on these most recent results, it appears that 037-B327 may be a factor of $\sim 2 - 3$ less massive than M31 G1, assuming that both GCs have the same stellar IMF. Nevertheless, this still confirms the nature of 037-B327 as one of the most massive star clusters in the Local Group.

Cohen (2006) suggests that the high mass estimate of Ma et al. (2006b) may have been affected by a non-uniform extinction distribution across the face of the cluster (see also Ma et al. 2006a for a more detailed discussion). She obtains, from new K-band imaging and different assumptions on the extinction affecting the K-band light, that M_K of 037-B327 may be some 0.16 mag brighter than that of M31 G1, or about twice as luminous. Despite these corrections provided by Cohen (2006), the basic conclusion from Ma et al. (2006b), i.e., that at the young age of 10 Myr cluster M31 037-B327 must have been a benchmark example of a "super" star cluster, and that its IMF must thus have contained a significant fraction of low-mass stars, still stands firmly.

In this context, it is interesting to note that we recently also determined photometric masses for the YMCs in the interacting system NGC 6745, the "Bird's Head Galaxy" (de Grijs et al. 2003c). NGC 6745 contains a significant population of luminous (and therefore presumably massive) "super" star clusters. Using the stellar population synthesis method developed in Anders et al. (2003; see also de Grijs et al. 2003b), with which we obtained robust, independent estimates of the star cluster ages, metallicities and extinction from the shape of their broad-band spectral energy distributions (SEDs), and masses from a simple scaling of our model SEDs to the observations, we concluded that a number of the most massive star clusters in this galaxy are characterised by masses in the range $6.5 < \log(m_{\mathrm{cl}}[M_{\odot}]) < 8.3$.

These surprisingly high masses are much larger than those of the most massive GCs in the Milky Way or other galaxies in the Local Group. However, the mass determination via population synthesis models is affected by uncertainties in the age and metallicity derivation.

For the two highest-mass clusters in NGC 6745, we derive a combined photometric mass of $M_{\mathrm{phot}} \sim 6 \times 10^8 M_{\odot}$. We should keep in mind, of course, that this high mass estimate is a strong function of the (low) metallicity assumed; if we had assumed solar metallicity for these objects, the derived age would have been significantly smaller ($\sim 10 - 20$ Myr versus ~ 1 Gyr), and the mass could be smaller by a factor of ~ 10. Even so, if we can verify (S. L. Moll et al. in preparation) our photometric mass estimates of the two most massive NGC 6745 clusters via spectral linewidth analysis, these clusters would be the most massive star clusters known to date, exceeding even the mass of the 300 Myr-old cluster W3 in the merger remnant galaxy NGC 7252, $M_{\mathrm{dyn}} = (8 \pm 2) \times 10^7 M_{\odot}$ (e.g., Schweizer & Seitzer 1998; Maraston et al. 2001, 2004). The latter mass is in excellent agreement with their photometric mass determination ($M_{\mathrm{phot}} \sim 7.2 \times 10^7 M_{\odot}$; Maraston et al. 2001), assuming a Salpeter stellar IMF. Thus, in the absence of significant external perturbations, W3 has the potential to survive for a Hubble time, by virtue of its large complement of low-mass stars.

The immediate implication of a similar result for the NGC 6745 clusters would be that galaxy interactions indeed produce extremely massive star clusters, as also suggested by Maraston et al. (2004) based on their analysis of NGC 7252-W3; see also Pasquali, de Grijs & Gallagher (2003) and Pollack, Max & Schneider (2007) for tentative indications that the more massive clusters in the galaxy merger NGC 6240 tend to form closer to the most intense interaction regions near the galaxy's double nucleus. This gives important insights into the still largely unknown star and star cluster formation processes in extreme environments.

5 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 – 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 (Meylan & Heggie 1997; Vesperini & Heggie 1997; Portegies Zwart et al. 1998; Baumgardt & Makino 2003; see also Odenkirchen et al. 2001 and Dehnen et al. 2004 for a study of the currently dissolving Galactic GC Pal 5).

   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, $\mathrm{d}N/\mathrm{d}\log m_{\mathrm{cl}}$).[6] 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 processes, 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, $\mathrm{d}N/\mathrm{d}M_V$). While the ubiquitous old GCs show a well-established Gaussian CLF, an ever increasing amount of data suggests that the CLF of YMCs formed in starbursts and mergering galaxies is best represented by a power-law function.

5.1 The CLF of Massive Star Clusters

5.1.1 Old Globular Clusters

Associated with the vast majority of large galaxies, as well as with the most luminous dwarf galaxies, old GCs are ubiquitous in the local Universe (e.g., Brodie & Strader 2006). With ages comparable to that of the Universe ($\simeq 13$ Gyr), they are regarded as the present end point of massive compact star cluster evolution. The postulated evolutionary connection between the old GCs and the massive star clusters recently formed in interacting and merging galaxies remains a contentious issue, however. Specifically, the key issue of relevance here is whether the power-law CLF of YMC populations will evolve into a bell shape similar to that of the CLF of old GCs.

   Typical parameters for the Gaussian shape of the GC luminosity function (GCLF) in the V band are a peak (or "turn-over") at a magnitude of $M_V \simeq -7.4$ mag, and a standard deviation σ_M of $1.2 - 1.4$ mag (e.g., Harris 1991, 2001; Harris, Harris & McLaughlin 1998; Barmby, Huchra & Brodie 2001; Richtler 2003). Intriguingly, this shape and parameters seem to be almost universal among galaxies as they show only a weak dependence on the size, the morphological type, the metallicity and the environment of the host galaxy (Ashman, Conti & Zepf 1995; Kavelaars & Hanes 1997; Ashman & Zepf 1998; Harris 1999; Whitmore et al. 2002). The relative robustness of the cluster luminosity at the turn-over magnitude has prompted its use as a distance indicator (Harris 2001; Richtler 2003; but see Fritze–v. Alvensleben 2004 for a critical assessment), although its use in dwarf galaxies remains a matter of debate (see Brodie & Strader 2006; and references therein). Limited, albeit systematic, differences in the detailed shape of the GCLF from one galaxy to another do exist, however (Harris 2001; Brodie & Strader 2006), such as, for instance, variations in the extension of the high-luminosity wing (McLaughlin & Pudritz 1996; Burkert & Smith 2000; Jordan et al. 2006; see also section 3.2 in Parmentier & Gilmore 2007).

   The GCLF constitutes a faithful mirror of the underlying GCMF only if cluster-to-cluster variations of the integrated cluster M/L ratios are small. This is true for any cluster system characterised by a stellar IMF that is invariant, and if the cluster age range is a limited fraction of the mean age of the cluster population. As regards the old GCs in the Galactic halo, the range spanned by their visual M/L ratio is limited (i.e., $1 \lesssim M/L_V \lesssim 4$, with a mean $\langle M/L_V \rangle \sim 2$; Pryor & Meylan 1993; see also Parmentier & Gilmore 2001,

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[6] We adopt the nomenclature of McLaughlin & Pudritz (1996). We refer to the number of objects per *linear* mass interval $\mathrm{d}N/\mathrm{d}m_{\mathrm{cl}}$ as the mass *spectrum*. Where we refer to the mass *function*, this describes the number of objects per *logarithmic* mass interval, $\mathrm{d}N/\mathrm{d}\log m_{\mathrm{cl}}$.

their fig. 1), and the scatter partly reflects variations in the dynamical evolution of individual GCs. It is widely, and probably safely, assumed that the GCLF is a good proxy of the GCMF for (old) extragalactic GC systems as well. Assuming a near-invariant M/L ratio, $M/L_V \sim 2$, that *universal* GCMF is well-represented by a Gaussian distribution with a mean $\langle \log(m_{\rm cl}[M_\odot]) \rangle \sim 5.2$–5.3 and a standard deviation $\sigma_{\log m_{\rm cl}} \sim 0.5$–0.6 dex. The origin of this universality among galaxies remains an outstanding issue in modern astrophysics. The peaked shape of the GCMF has sometimes been interpreted as evidence that GC masses bracket one characteristic value of $m_{\rm GC} \sim 2 \times 10^5 M_\odot$ (e.g., Peebles & Dicke 1968). This is, however, mainly an artefact produced by the logarithmic binning of the data. The underlying mass spectrum is well described by a two-index power-law, with exponents $\alpha \sim -2$ and $\alpha \sim -0.2$ above and below $m_{\rm GC} \sim 2 \times 10^5 M_\odot$, respectively (Surdin 1979; McLaughlin 1994). Such a monotonic behaviour highlights the absence of any GC mass scale.

5.1.2 *Young Massive Star Clusters*

The advent of the *HST* and the subsequent discovery (in particular in interacting and merging galaxies) of star clusters with the high luminosities and the compact sizes expected for GCs at young ages has prompted renewed interest in the evolution of the CLF (and CMF) of massive star clusters, both observationally and theoretically. Starting with the seminal work by Elson & Fall (1985) on the young LMC cluster system (with ages $\lesssim 2 \times 10^9$ yr), an ever increasing body of evidence, mostly obtained with the *HST*, seems to imply that the CLF of these YMCs is well described by a power law of the form $\mathrm{d}N \propto L^{1+\alpha} \mathrm{d} \log L$, equivalent to a cluster luminosity spectrum $\mathrm{d}N \propto L^\alpha \mathrm{d}L$, with a spectral index $-2 \lesssim \alpha \lesssim -1.5$ (e.g., Elson & Fall 1985; Whitmore & Schweizer 1995; Elmegreen & Efremov 1997; Miller et al. 1997; Whitmore et al. 1999; Whitmore et al. 2002; Bik et al. 2003; de Grijs et al. 2003c; Hunter et al. 2003; Lee & Lee 2005; see also Elmegreen 2002). Since the spectral index, α, of the observed CLFs is reminiscent of the slope of the high-mass regime of the old GC mass spectrum ($\alpha \sim -2$; McLaughlin 1994), 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 Gaussian distribution because of (i) stellar evolutionary fading of the lowest-luminosity (and therefore lowest-mass) objects to below the detection limit; and (ii) disruption of the low-mass clusters due both to interactions with the gravitational field of the host galaxy, and to internal two-body relaxation effects leading to enhanced cluster evaporation (e.g., Elmegreen & Efremov 1997; Gnedin & Ostriker 1997; Ostriker & Gnedin 1997; Fall & Zhang 2001; Prieto & Gnedin 2007).

   This approach has two drawbacks, however. Observationally, it has been pointed out by various authors that for YMCs exhibiting an age range, one must first correct their CLF to a common age before a realistic assessment of their *initial* CLF (or CMF) can be achieved (e.g., Meurer 1995; Fritze–v. Alvensleben 1998, 1999; de Grijs et al. 2001, 2003a,d). Whether the observed power laws of the CLF for YMC systems are intrinsic to the cluster populations or artefacts caused by the presence of a cluster age spread – which might mask a differently shaped underlying mass distribution – is therefore a matter of ongoing debate (see, e.g., Meurer 1995; Fritze–v. Alvensleben 1998, 1999; Carlson et al. 1998; Zhang & Fall 1999; Vesperini 2000, 2001; Anders et al. 2007). From a theoretical point of view, while the preferential removal of the more vulnerable low-mass clusters indeed results in an initial power-law CMF being turned into an approximately Gaussian CMF (e.g., Okazaki & Tosa 1995; Baumgardt 1998; Vesperini 1998; Fall & Zhang 2001; Prieto & Gnedin 2007), recovering the *present-day* GCMF after a Hubble time of evolution requires considerable fine-tuning of the models, which is hardly compatible with the near-invariance of the GCMF among large galaxies. We review each of these aspects in Section 5.2.

5.2 Recovering the Initial GC Mass Function via Modeling

Since individual GCs and GC systems have evolved over a Hubble time in their galactic environment, the recovery of the initial GCMF is model dependent. At present, this model dependence is believed to be through one of two competing hypotheses. The initial GCMF may have been a featureless power law, with a spectral index $\alpha \sim -2$ (i.e., equivalent to $\mathrm{d}N \propto m_{\rm cl}^{-2} \mathrm{d}m_{\rm cl}$), or a Gaussian distribution similar to that seen today. Regardless of the actual shape of the initial GCMF, it is worth bearing in mind that this exercise includes the *bound* star clusters only, as these are the only ones "recovered" by the modeling of the secular dynamical evolution of entire star cluster systems. In other words, proto-clusters that are disrupted by the

time their member stars reach an age of 10–30 Myr as a result of gas removal combined with a $\lesssim 30$ per cent SFE are not relevant to the present discussion.

5.2.1 Is the Initial GCMF Similar to the CLF of YMCs ...

In the framework of the initial power-law hypothesis, the Gaussian distribution characteristic of old GC populations results from evolutionary effects, predominantly the preferential removal of the more vulnerable low-mass clusters (Fall & Zhang 2001). The cluster mass at the turn-over of the present-day mass function then depends on the age of the cluster system, and on the cluster disruption time-scale (see Eqs. (1) and (2)), in the sense that the older the cluster system and/or the shorter the disruption time-scale, the higher the expected turn-over mass of the cluster system will be. The evolutionary rate of the GCMF turn-over is thus a function of the initial spatial distribution of the GCs in their host galaxy (Parmentier & Gilmore 2005), of their initial velocity distribution or, equivalently, of the clusters' orbital distribution (Murali & Weinberg 1997b; Baumgardt 1998; Baumgardt & Makino 2003; Fall & Zhang 2001), as well as of the circular (rotation) velocity of the host galaxy (Baumgardt & Makino 2003, their eq. 10; see also Gieles et al. 2006 and Lamers & Gieles 2007 for the shortening of the cluster disruption time-scale due to close encounters with giant molecular clouds). Thus, the near-invariance of the GCMF in very different types of galaxies is neither easily understood, nor straightforwardly reproduced (Vesperini 2001). Additionally, the predicted cluster mass at the turn-over of model GCMFs is often significantly lower than observed (Baumgardt 1998; Vesperini 2001). Based on a subsample of host galaxies with effective masses and radii equal to those determined using observational data for a number of giant, normal, and dwarf elliptical galaxies, Vesperini's (2001) figure 6a shows that the predicted logarithmic GC masses at the turn-over, at an age of 13 Gyr, are in the range $4.2 \lesssim \langle \log(m_{cl}[M_\odot]) \rangle \lesssim 5$, i.e. significantly lower than the observed value, $\langle \log(m_{cl}[M_\odot]) \rangle \sim 5.3$. Similar results are obtained for the Galactic GC system, with a predicted $\langle \log(m_{cl}[M_\odot]) \rangle \sim 4.3$ (Vesperini 1998, his fig. 8). These results were obtained for circular orbits; we discuss the case of GCs on elliptical orbits below.

Not only is the observed GC mass at the Gaussian peak universal *among* galaxies, it is also universal *within* galaxies, i.e. the turn-over location of the GCMF is constant over a large range of galactocentric distances (e.g. Harris, Harris & McLaughlin 1998 and Kundu et al. 1999 for M87; Kavelaars & Hanes 1997 and Parmentier & Gilmore 2005 for the Galactic halo; Kavelaars & Hanes 1997 for M31; Larsen 2006 and Spitler et al. 2006 for the Sombrero galaxy; but see also Gnedin 1997 for a discussion of the possible role of the statistical methodology used in the determination of the difference between the GCLF parameters of the inner and outer clusters). Equivalently, the shapes of the radial number density profile (the number of clusters per unit volume in space as a function of galactocentric distance) and of the radial mass density profile (the spatial distribution of the cluster system mass around the galactic centre) of the GC system are similar.

Yet, due to the higher environmental density (see Eq. (2)) in the inner region of any GC system, evolutionary processes proceed at a faster rate there. Therefore, evolutionary models building on the power-law hypothesis, and assuming an isotropic cluster velocity distribution, predict a radial gradient of the mean logarithmic cluster mass (i.e., $\langle \log(m_{cl}[M_\odot]) \rangle$ is higher in the inner than in the outer regions of a given galaxy). The resulting gradient appears too large to be consistent with the observations (Vesperini 2001). Addressing the coherent and well-defined group of Galactic Old Halo GCs, Parmentier & Gilmore (2005) demonstrate that, at an age of 13 Gyr, the theoretically predicted radial number density profile of the GC system is significantly shallower than the radial mass density profile, contrary to observations (see the bottom panels of their figs. 2 and 3). This behaviour results from the fact that, for a power-law initial GCMF with a spectral index, $\alpha \sim -2$, low-mass clusters dominate the total cluster population in terms of number, but not in terms of mass. Hence, while the radial mass density profile remains well-preserved throughout their evolution – in spite of their preferential disruption – the radial number density profile becomes significantly shallower.

Starting from a power-law CMF with a slope similar to that characterising the CLF of YMC systems in starbursts thus seems to fail to reproduce fundamental properties of the present-day GCMF. In fact, the theoretically predicted scatter in the turn-over mass among and even within galaxies is significantly greater than observed. Nevertheless, the initial power-law hypothesis cannot be completely ruled out, although it requires very specific conditions; careful consideration of the consistency of these conditions with obser-

vational data is required, however. The initial power-law assumption can account for both the present-day turn-over GC mass and its near-invariance with galactocentric distance, provided that the initial GC velocity distribution is characterised by a strong radial anisotropy that increases as a function of increasing radius, in the sense that the farther from the galactic centre a given cluster is located, the higher its orbital eccentricity will be (Fall & Zhang 2001). The net result of this assumption is that, in these models, *all* GCs have similar perigalactic distances. Because the mass-loss rate of a GC on an eccentric orbit is significantly more sensitive to its perigalactic than to its apogalactic distance (Baumgardt 1998, his fig. 2), the relatively narrow distribution of pericentres causes a nearly invariant GCMF turn-over over the entire radial extent of the GC system, regardless of the clusters' loci at any given point in time. In addition, the small anisotropy radius ($\sim 2\,\mathrm{kpc}$) of the velocity distribution (or, equivalently, the mean perigalactic distance) implies that GC evolutionary processes, and hence the shift of the GCMF towards higher cluster masses, proceed at a faster rate than in the case of an isotropic velocity distribution. As a consequence, the cluster mass at the peak of the GCMF at an age of 13 Gyr matches the observations, both in the inner and outer galactic regions (Fall & Zhang 2001).

Vesperini et al. (2003) tested this model against data of the M87 GC system. Owing to the preferential disruption of GCs on highly eccentric orbits, the initial amount of radial anisotropy in the velocity distribution decreases during the evolution of the cluster population. Yet, the initial radial anisotropy required to reproduce the near-constancy of the GCMF turn-over mass is so strong that, in spite of its steady decrease with time, at an age of 13 Gyr, it will still be significantly stronger than what is inferred from the observed projected velocity dispersion profile of the M87 GC system (Côté et al. 2001). In other words, the lack of any significant radial gradient in the mean logarithmic GC mass, and the observed kinematics of the M87 GC system, cannot be reproduced simultaneously. The former requires a small initial anisotropy radius ($\lesssim 3\,\mathrm{kpc}$), while the latter requires an anisotropy radius greater by at least an order of magnitude.

In an additional attempt to reconcile the Gaussian mass function of old GCs with the power-law CLF of YMCs, Vesperini & Zepf (2003) built on the observed trend between the mass of Galactic GCs and their concentration (i.e., the more massive the cluster, the higher its concentration; van den Bergh 1994; see also Larsen 2006, his fig. 4). Since this rough correlation is likely of primordial origin (Bellazini et al. 1996), they investigated how the dissolution of low-mass, low-concentration clusters induced by early stellar mass loss affects the temporal evolution of the CMF. Their results suggest that it may be possible to reproduce, at an age of 13 Gyr, a Gaussian CMF with a turn-over occurring at about the observed mass, even if starting from an initial power-law, $\mathrm{d}N \propto m_{\mathrm{cl}}^{-2}\mathrm{d}m_{\mathrm{cl}}$. Moreover, the dissolution of the low-mass clusters is mostly caused by their low initial concentration; it depends weakly only on environmental conditions such as the structure of the host galaxy and the cluster orbit. Consequently, their model reproduces the lack of significant radial variations in the mean logarithmic GC mass across the Galactic GC system, even for an isotropic initial velocity distribution. Dissolution of low-concentration clusters may therefore provide the missing link between the power-law CLF observed for YMCs in violently star-forming environments and the Gaussian CMF characteristic of old GC populations, although a detailed study of this effect remains to be done. In addition, accounting for the near-universality of the GCMF turn-over mass requires the existence, in other large galaxies containing significant cluster population, of a similar cluster mass-concentration relationship. This is, as yet, unknown.

5.2.2 ... or Is It Similar to the Present-Day GCMF?

The large amount of fine-tuning required to reconcile the initial power-law hypothesis to the observations stimulated the search for an alternative, more robust, initial GCMF. Building on the *N*-body simulations of Vesperini & Heggie (1997), Vesperini (1998, 2000) performed detailed simulations of star cluster systems evolving in time-independent Milky Way and elliptical galaxy-type gravitational potentials. He demonstrated the existence of a dynamical equilibrium Gaussian GCMF. That particular CMF maintains its mean and standard deviation ($\langle\log(m_{\mathrm{cl}}[M_\odot])\rangle \sim 5$ and $\sigma_{\log m_{\mathrm{cl}}} \sim 0.6\,\mathrm{dex}$) during the entire evolution through a subtle balance between disruption of clusters on the one hand and evolution of the masses of the surviving clusters on the other, even though a significant fraction of the clusters is destroyed. In addition, owing to the combined effects of tidal disruption and dynamical friction (which preferentially affect low-mass and high-mass clusters, respectively), *any* Gaussian ICMF eventually evolves into that equilibrium CMF (Vesperini

1998, his fig. 13). The speed at which this evolution proceeds is determined by the initial deviation of the system from the equilibrium CMF.

The shape of the equilibrium CMF is very close to that of the GCMF observed in the outer regions of elliptical galaxies, where the initial conditions are likely retained because of the low efficiency of cluster disruption processes expected at large galactocentric distances (Vesperini 2000; see also McLaughlin, Harris & Hanes 1994). Therefore, these GCMFs may be significantly better proxies to the initial CMF than the featureless power-law (Murali & Weinberg 1997a, b). As a dynamical equilibrium CMF, its shape is practically independent of both the age of the cluster system and the cluster disruption time-scale. Its temporal evolution therefore differs substantially from that of the initial power-law CMF, as the turn-over mass of the latter depends heavily on initial and environmental properties. In contrast, the equilibrium GCMF maintains its initial shape during its evolution, regardless of either the underlying initial cluster position-velocity distribution, or the rotation velocity of the host galaxy. As a result, the near universality of the GCMF turn-over mass and the small radial dependences observed in GC systems with sufficient radial sampling (see Sect. 5.2.1, and references therein) are retrieved naturally. Only the fraction of surviving clusters and the ratio of the final to initial total mass in clusters vary among and within galaxies, as a result of cluster disruption time-scale variations.

Generally speaking, the evolution of other bell-shaped GCMFs with similar turn-over masses (e.g., a Student t-distribution; Secker 1992) is not markedly different from that of the equilibrium Gaussian GCMF (Vesperini 2002; see also Parmentier & Gilmore 2007). The bell-shaped initial GCMF generated by the gas-removal model of Parmentier & Gilmore (2007) shows, once corrected for stellar evolutionary mass losses, a mean logarithmic cluster mass at about a factor of 2 higher than that of Vesperini's (1998, 2000) equilibrium Gaussian CMF (i.e., $\langle \log(m_{cl}[M_\odot]) \rangle \sim 5.3$), as well as a more prominent low-mass wing than expected for a Gaussian CMF. In spite of these differences, once evolved to an age of 13 Gyr using the results of the N-body simulations performed by Baumgardt & Makino (2003), this initial GCMF also appears to be an almost perfect dynamical equilibrium GCMF (Parmentier & Gilmore 2007, their fig. 11).

Although considerable work has been done on this topic, the shape of the initial GCMF still remains a model-dependent and contentious issue. We note that, while the initial power-law cannot be firmly ruled out (Vesperini & Zepf 2003), a Gaussian initial GCMF similar to the universal present-day GCMF represents a safer solution by virtue of its robustness to model inputs.

5.2.3 The 1-Gyr Old Fossil Starburst Site M82 B

Based on deep *HST* optical and near-infrared imaging, de Grijs et al. (2003a,d) reported the first discovery of an approximately Gaussian CLF (and CMF) for the roughly coeval, ~ 1 Gyr-old star clusters in the fossil starburst region "B" of M82. With a turn-over mass at $\log(m_{cl}[M_\odot]) = 5.1 \pm 0.1$ (which occurs some 2 mag brighter than the 100 per cent observational completeness; this corresponds to $\log(m_{cl}[M_\odot]) \simeq 4.4$), this CMF very closely matches the universal GCMF of old GC systems (de Grijs et al. 2003d, their fig. 1c). The fact that they considered an approximately coeval subset of the M82 B cluster population, combined with the use of the 100 per cent completeness limit as their base line ensures the robustness of the CMF peak detection (see de Grijs et al. 2005b for a detailed discussion). This provided the first deep CLF (CMF) for a star cluster population at intermediate age, which thus serves as an important benchmark for theories of the evolution of star cluster systems. In this respect, the M82 B cluster population represents an ideal sample to test these evolutionary scenarios since, for such a roughly coeval intermediate-age population in a spatially confined region, (i) the observational selection effects are very well understood (de Grijs et al. 2003a,d), and (ii) the dynamical cluster disruption effects are very similar for the entire cluster population.

If the ICMF is a power-law with a spectral index, $\alpha \sim -2$, a cluster mass at a 1-Gyr old turn-over similar to that observed for 13-Gyr old GC populations implies that, in the M82 B region, cluster evolution has *necessarily* proceeded at a much faster rate than in, e.g., the Galactic halo. This is required in order to deplete the star cluster system at an accelerated rate, and evolve the presumed initial power law to the observed distribution on a time-scale of ~ 1 Gyr. In fact, using the Boutloukos & Lamers (2003) framework, de Grijs et al. (2003a) deduce that in order to produce a Gaussian present-day CMF in M82 B as is observed, the time-scale on which a typical $\sim 10^4 M_\odot$ cluster is expected to disrupt must be $t_4^{dis} \simeq 30$ Myr. This is the shortest disruption time-scale known in any (disk region of a) galaxy. In addition, de Grijs et al. (2005b) noticed that such a short disruption time-scale implies a correspondingly low cluster survival rate, implying

that the initial number of clusters, $\sim 80,000$ with an average mass of order $m_{\rm cl} \sim 10^4 M_\odot$, would be unphysically high for the relatively small ($\lesssim 1\,{\rm kpc}^3$) M82 B region. Observations of the present-day M82 B CMF are thus inconsistent with a scenario in which the 1 Gyr-old cluster population originated from an initial power-law mass distribution. [7] Alternatively, considering the close coincidence in shape of the observed CMF to that of Vesperini's (1998) (quasi-) equilibrium CMF, they demonstrate that the M82 B ICMF may have been a Gaussian similar to that of old GCs, irrespective of the exact cluster disruption time-scale. The analysis of the M82 B cluster sample, and the conclusions drawn from these observations, have proven to be contentious. With the recent release of the M82 *HST*/ACS Treasury data set of imaging observations in the F435W, F555W and F814W broad-band filters as well as in the F658N Hα filter, supplemented by targeted ACS/High-Resolution Channel (HRC) observations (GO-10853; PI L. J. Smith) of M82 B in particular in the F330W filter (equivalent to the Johnson U band) should shed further light on the robustness of the CMF peak in this region. Initial results (L. J. Smith, priv. comm.) suggest that the peak of the age distribution inferred from the U-band selected YMCs in M82 B is shifted to systematically somewhat lower ages than those obtained by de Grijs et al. (2001, 2003a) without access to these short wavelengths.

5.2.4 The Merger Remnant NGC 1316

Recently, Goudfrooij et al. (2004) added a second important data point to constrain cluster evolution theories, based on the $\sim 3\,{\rm Gyr}$-old metal-rich ($Z \sim Z_\odot$) cluster population in NGC 1316, a merger remnant, based on *HST*/ACS observations. The CLF of the intermediate-age population of massive star clusters in NGC 1316 appears to be a power-law with a spectral index, $\alpha \simeq -1.75$, down to the observational 50 per cent completeness limit. They divide their cluster sample into two equal-sized subsamples sorted by projected galactocentric distance. Whereas they detect a clear turn-over at $M_V \sim -6.2\,{\rm mag}$ in the "inner" cluster population ($R_{\rm proj} \leq 9.4\,{\rm kpc}$), the CLF of the "outer" population continues to rise all the way down to the detection limit. If the ICMF in this galaxy were a power-law similar to that of the "outer" population, this illustrates the greater efficiency of evolutionary processes at closer distance from the galactic centre, as well as the absence of any strong radially dependent velocity distribution anisotropy. To compare the observed CLFs with the CMFs predicted by Fall & Zhang (2001), Goudfrooij et al. (2004) convert the latter into CLFs on the basis of Maraston et al.'s (2001) stellar population synthesis models. They note that the turn-over magnitude of the "inner" CLF matches Fall & Zhang's (2001) predictions rather well at an age of 3 Gyr (see their fig. 3f, although the observed width of the CLF is significantly narrower than predicted). They deduce that the "inner" CLF (and CMF) will eventually evolve into that characteristic of old GCs by the time the NGC 1316 "inner" clusters reach an age of 13 Gyr. Clearly, this conclusion does not apply to the "outer" clusters. The power-law CLF of the latter subsample illustrates that these clusters have thus far experienced little, if any, preferential depletion of low-mass clusters, and hence dynamical evolution (at least above the observational completeness limit).

However, de Grijs et al. (2005b) note that based on the published CLFs and the discussion in Goudfrooij et al. (2004), and assuming a Salpeter-like IMF with masses $m_* \geq 0.1\ {\rm M}_\odot$, the GALEV simple stellar population models (Schulz et al. 2002; Anders & Fritze–v. Alvensleben 2003) indicate a mean cluster mass of $\log(m_{\rm cl}/M_\odot) \sim 4.0$, with a FWHM of $\sim 0.9\,{\rm dex}$. These are significantly smaller masses (and a smaller width) than expected for GC progenitors. At an age of 13 Gyr, the cluster mass at the "outer" CMF turn-over will thus be markedly lower than the universal turn-over GC mass of $2 \times 10^5 M_\odot$. The difference in shape between the CLFs of the "inner" and "outer" samples also demonstrates that the solar-abundance intermediate-age massive clusters of NGC 1316 fail to reproduce the near-invariance of the mean logarithmic cluster mass with galactocentric distance that is observed for the ubiquitous old GC systems. Therefore, while at least a fraction of the observed clusters will likely survive until an age of 13 Gyr,

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[7] We caution that the M82 B cluster mass estimates derived by de Grijs et al. (2003a) are based on a Salpeter (1955)-type stellar IMF. Recent determinations of realistic stellar IMFs deviate significantly from that representation at low masses, in the sense that they appear to be significantly flatter than the Salpeter slope. The implication of this is, therefore, that we may have *overestimated* the individual cluster masses. A more modern IMF, such as that of Kroupa, Tout & Gilmore (1993) implies overestimated cluster masses by factors of 1.7 to 3.5 for an IMF containing stellar masses in the range $0.1 \leq m_*/M_\odot \leq 100$, the exact value depending on the slope adopted for the lowest stellar mass range, $0.08 < m_*/M_\odot \leq 0.5$. This corresponds to a correction of -0.23 to -0.54 to the peak of the CMF, so that a more realistic estimate for the peak of the M82 B CMF would be $\langle \log(m_{\rm cl}[M_\odot]) \rangle = 4.7 \pm 0.2$. However, once again, the observed cluster population would be the remains of an unphysically high initial census of $\sim 20,000$ clusters if starting from an initial power-law mass distribution.

particularly in the outer regions, they do not represent proto-GCs in the sense that their CMF does *not* show the properties characteristic of the universal GCMF.

5.3 The CMF of Young Massive Clusters and the (Many) Associated Caveats

5.3.1 Caveats beyond the Local Group

Observational evidence of YMC systems in many star cluster-forming interacting and starburst galaxies appears to indicate that they are well represented by power-law cluster *luminosity* functions with a spectral index in the range from -1.8 to -2 (see Sect. 5.1 and references therein; de Grijs et al. 2003c for a comprehensive review; but see also Anders et al. 2007). Yet, rapid changes to the properties of young stellar populations, combined with a possible age range within a given cluster system (possibly on the order of its median age) may conspire to give rise to a power-law-like CLF, even if the true underlying cluster *mass* function is not a power-law (Meurer 1995; Fritze–v. Alvensleben 1998, 1999; de Grijs et al. 2001, 2003a,d; Hunter et al. 2003). In addition, because of the fading with time of the cluster luminosity, high-mass clusters can be observed over a wide range of ages, while low-mass clusters are detectable at young ages only, for a flux limited sample selection. This results in the underrepresentation of the latter in the age-integrated CMF. Therefore, it is obviously very important to age-date the individual clusters, before interpreting the cluster luminosities in terms of the corresponding mass distribution.

Beyond addressing the issue of the shape of the CMF in violently star-forming environments, and because the old GCMF itself appears to be universal, it is worth considering whether the ICMF of present-day forming massive star clusters is near-invariant as well. However, the CMF of young massive star clusters (which we take as a good proxy to the ICMF in the absence of any significant secular dynamical evolution) has been probed to sufficient depth in only a limited number of galaxies.

In most cases, the reported CMF is consistent with a power-law of which the spectral index has the canonical $\alpha \sim -2$ value. The depth of the cluster mass range probed by the observations varies among galaxies, however. Bik et al. (2003) infer a power-law CMF down to $10^3 M_\odot$ for the cluster population in the inner spiral arms of the interacting galaxy M51 (see also the discussion in Sect. 3.2). Similar results are obtained by Zhang & Fall (1999) for the YMCs of the Antennae system for cluster age ranges $2.5 < t < 6.3$ Myr and $25 < t < 160$ Myr, down to the observational completeness limits, at $\simeq 8 \times 10^3 M_\odot$ and $\simeq 25 \times 10^3 M_\odot$, respectively. In contrast to Zhang & Fall (1999), however, Fritze–v. Alvensleben (1998, 1999) favours a Gaussian mass distribution at young age, similar to the present-day GCMF. Fritze–v. Alvensleben (2004) notes that both approaches have their drawbacks. Zhang & Fall (1999) exclude a significant number of clusters from the ambiguous age range in the reddening-free $Q_1 - Q_2$ index diagram they use, while Fritze–v. Alvensleben (1998, 1999) assumes a uniform average reddening in the *HST* / WF/PC1 *UVI* data. A recent re-analysis of *HST*/WFPC2 data of the Antennae galaxies (Anders et al. 2007) may help clarify this complex situation (see below). If one accepts the hypothesis that the ICMF of old GCs is a Gaussian similar to what is observed today, these results suggest that the ICMF of present-day massive star clusters differs from that of old GCs. Similar power-law CMFs have been reported by de Grijs et al. (2003c) for the cluster populations in NGC 3310 and NGC 6745. Yet, in those both cases, the cluster mass range coverage coincides only with the high-mass regime of the Gaussian GCMF (i.e. $> 10^5 M_\odot$ and $> 4 \times 10^5 M_\odot$, respectively), so that one cannot distinguish between power-law and Gaussian CMFs for these cluster samples. In contrast to the featureless power-laws uncovered for M51 and the Antennae system, Cresci, Vanzi & Sauvage (2005) report the existence of substructures in the CMF of the YMC population in the central region of NGC 5253, an irregular dwarf galaxy in the Centaurus Group, observed with *HST*/ WFPC2. The derived cluster ages span a range between 3 and 20 Myr. They note that the "young" and "old" clusters[8] of their overall sample show markedly different CMFs. While the "young" population (with mean age $\simeq 8$ Myr) shows a power-law CMF with a spectral index, $\alpha \simeq -1.6$, the "old" clusters (to which they assign a reference age of ~ 20 Myr) display a turn-over at about $5 \times 10^4 M_\odot$, i.e., at a mass some 2.5 times more massive than their 50 per cent completeness limit. Note that according to Fall & Zhang (2001), such a high cluster mass at the CMF turn-over is predicted for a much older age, of 2 Gyr, if one starts from an initial power-law CMF. Considering the very young age of the NGC 5253 clusters, the observed turn-over mass is likely not an imprint of ongoing dynamical evolution, but instead probably a trace of their formation

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[8] They distinguish between young and old clusters on the basis of their presence or absence in Hα.

process. Beyond the turn-over mass, the CMF is consistent with a power-law of spectral index, $\alpha \simeq -1.8$, i.e. in agreement with what is inferred for other YMC systems. As for the "young" clusters, their shallower spectral index, $\alpha \simeq -1.6$, is more reminiscent of what is observed for clumps and star-forming cores in giant molecular clouds (see, e.g., Lada & Lada 2003).

In summary, compact YMCs show power-law CMFs with spectral index $\alpha \lesssim -2$. Whether this behaviour characterises the entire cluster mass range down to, say, $100 M_\odot$, as observed for the less massive open clusters in the Galactic disc (Lada & Lada 2003; and references therein; see also the catalogue by Kharchenko et al. 2005) remains to be seen, however. NGC 5253 (Cresci et al. 2005) and M82 B (de Grijs et al. 2005b) seem to constitute cases for which this is actually not the case. Deeper observations for a larger sample of galaxies are, as always, required.

Finally, prior to proceeding any further, we note that results reported for the CLF itself differ sometimes significantly among studies. It is worth bearing in mind that retrieving the *intrinsic* CLF requires avoiding bright-star contamination and accounting for completeness effects properly. This may prove challenging at the faint end of the luminosity distribution. Existing CLF substructures at low luminosities may therefore remain undetected or lead to discrepant results. For instance, while Whitmore et al. (1999) infer from their *HST*/WFPC2 imaging data a power-law CLF with a spectral index $\alpha \simeq -2.1$ for the YMCs in the Antennae system, Anders et al. (2007) report the first statistically robust detection of a turn-over in its CLF at $M_V \simeq -8.5$ mag. The origin of that discrepancy likely resides in differences in the data reduction and the statistical analysis aimed at rejecting bright-star contamination and disentangling completeness effects from intrinsic CLF substructures.

5.3.2 The Magellanic Clouds: Test Case on Our Door Step

The preceding discussion has illustrated that it is not necessarily straightforward to derive the mass distributions of YMC systems beyond the Local Group. In contrast, the Magellanic Clouds are close enough for a detailed survey of even faint clusters. To derive the CMF of mass-limited LMC cluster subsamples, which are potentially more physically informative than magnitude-limited subsamples, de Grijs & Anders (2006) re-analyse the *UBVR* broad-band SEDs of Hunter et al. (2003). Building on the framework established by Boutloukos & Lamers (2003), they derive that the time-scale on which a $10^4 M_\odot$ cluster is expected to disrupt is $\log(t_4^{\mathrm{dis}}\mathrm{yr}^{-1}) = 9.9 \pm 0.1$ (see also Eq. (1)), which is in agreement with previous determinations of the characteristic cluster disruption time-scale. Such a long cluster disruption time-scale results from the low-density environment of the Magellanic Clouds. It guarantees that the observed cluster mass distributions have not yet been altered significantly by secular dynamical evolution, i.e. clusters already affected by ongoing disruption have faded to below the completeness limit (see de Grijs & Anders 2006, their fig. 8). As a result, the observed mass distributions are the *initial* distributions. Considering clusters older than 60 Myr and more massive than $10^3 M_\odot$, the spectral index of their CMF is $\alpha \simeq -2$, i.e. fully consistent with what is generally inferred for YMC systems. This slope prevails over the age range 100 Myr–6 Gyr (see also de Grijs et al. 2007). Similar results were obtained by Hunter et al. (2003). However, the spectral index of the clusters younger than 60 Myr appears significantly shallower, with $\alpha \simeq -1.7$ for the same mass range and $\alpha \simeq -1$ for clusters less massive than $10^3 M_\odot$. As discussed in Section 2, the origin of these substructures in the young age/low-mass regime is likely to be found in a mass-dependent infant mortality rate, at least for the lowest-mass cluster range. It is important to bear in mind, however that at such a young age, the population of clusters necessarily consists of a mix of bound and unbound clusters. Most of these (~ 60–90 per cent) will disperse by the time their member stars reach an age of a few $\times 10^7$ yr (see Sect. 2, and references therein).

6 SUMMARY AND OUTLOOK

The formation of GCs, which was once thought to be limited to the earliest phases of galaxy formation, appears to be continuing at the present time in starburst, interacting and merging galaxies in the form of star clusters with masses and compactnesses typical of GCs. Whether these YMCs will evolve to become old GCs by the time they reach an age of 13 Gyr depends to a very large extent on their environment, however. For a host galaxy with a smooth logarithmic gravitational potential, the ambient density seems to be the key parameter driving the rate of cluster evolution. This is accelerated in the presence of substructure in the host galaxy, such as that commonly provided by bulge, spiral arm and giant molecular cloud components.

The LMC and the disk of M51 represent strikingly different cases of the cluster ability to survive to old age. The M51 disk is characterised by a cluster disruption time-scale $t^4_{\rm dis} \sim 100\,{\rm Myr}$ (Gieles et al. 2005), which implies that even a $10^6 M_\odot$ cluster will not survive much longer than $\sim 2\,{\rm Gyr}$. In contrast, the more gentle environment of the LMC is conducive to a long cluster disruption time-scale, $t^4_{\rm dis} \sim 8\,{\rm Gyr}$ (de Grijs & Anders 2006), so that the same $10^6 M_\odot$ cluster will survive largely unaffected, except for ~ 30 per cent stellar evolutionary mass loss, over the next Hubble time. Therefore, although survival rates vary significantly as a function of the star cluster system host properties, at least a fraction of the observed YMCs that have recently been formed in starburst environments will likely reach an age typical of that of old GCs.

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 $\langle \log(m_{\rm cl}[M_\odot]) \rangle \sim 5.2 - 5.3$ and a standard deviation of $\sigma_{\log m_{\rm cl}} \simeq 0.5 - 0.6\,{\rm dex}$. 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 2003, for the LMC). Some cluster systems exhibit differently shaped ICMFs, however (M82 B, de Grijs et al. 2005b; 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). Nonetheless, it is worth bearing in mind that present-day GC evolutionary models describe the host galaxy as a *static* gravitational potential. This is most likely an oversimplification when addressing the evolution of star clusters that formed when galaxies were still in the process of being assembled.

Since the present-day CMF appears to be close to the dynamical equilibrium shape (Vesperini 1998), the initial GCMF may also have been a Gaussian similar to that seen today. This GCMF preserves its shape during its evolution, irrespective of the cluster disruption time-scale, and hence of the ambient density. Consequently, the main properties of the GCMF, i.e. the near-invariance among and within galaxies, are retrieved naturally.

Therefore, even though at least a fraction of the observed YMCs will likely evolve into old GC counterparts by the time they reach an age of 13 Gyr (albeit of higher metallicity), GCs and YMCs may differ with respect to the shape of their ICMF. Parmentier & Gilmore (2007) recently explored how the gas-removal phase affects the mapping of the mass function of the gaseous cluster progenitors to the ICMF. As they assume that the SFE is mass independent, which is probably a reasonable assumption for cluster-forming clouds more massive than $10^4 M_\odot$ (Bastian et al. 2005; Fall et al. 2005; de Grijs et al. 2007), they show that a featureless power-law cloud mass function evolves into a featureless power-law of the same slope (because of the assumed independence of the SFE on cloud mass). However, as soon as the power-law mass function of the cluster parent molecular clouds shows a lower mass limit, a bell-shaped ICMF is generated as a result of gas removal, with the turn-over located at a cluster mass on the order of the lower mass limit of the clouds. Specifically, they demonstrate that, if the proto-GC cloud mass distribution is characterised by a mass scale of $10^6 M_\odot$, then *any* proto-GC cloud mass function (e.g., a Gaussian with a mean of $\sim 10^6 M_\odot$ and $\sigma_{\log m_{\rm cl}} \lesssim 0.4\,{\rm dex}$, or a power law truncated at $\sim 6 \times 10^5 M_\odot$) evolves into an initial GCMF with the appropriate turn-over mass (although the detailed shape of the initial GCMF actually depends on the shape of the proto-GC cloud mass function). Therefore, with the mass scale of the cluster gaseous progenitors as its key parameter, Parmentier & Gilmore's (2007) model can account for both the Gaussian initial GCMF and the observed power-law mass spectrum of YMCs formed in starbursts and mergers.

The suggestion that the ICMFs of old GCs and of YMCs may be different is also put forward by Hunter et al. (2003). As they fit cluster population models to the LMC cluster mass distribution integrated over age and to their age distribution integrated over mass, they note that the power-law ICMF with a spectral index $\alpha \gtrsim -2$ which they determine for the young and intermediate-age clusters fails to reproduce the distributions of the oldest clusters, i.e. those similar to Galactic halo GCs in terms of their ages and masses. This suggests a differently shaped ICMF for the old massive LMC clusters, although the limited number of clusters necessarily hampers the significance of this result.

Regardless of the remaining uncertainties with respect to the shape of the initial GCMF, it now appears that, once evolved to an age of 13 Gyr, YMCs will not exhibit a similar universal CMF as the ubiquitous

old GCs (see also the results of Goudfrooij et al. 2004 for the NGC 1316 CLF and CMF as a function of galactocentric radius). This is due to the vastly different cluster disruption time-scales characterising the various environments in which they are found (e.g., Lamers et al. 2005, their fig. 4), and hence to the different rates at which the evolved CMF turn-over mass evolves towards larger cluster masses as a result of the preferential removal of low-mass clusters.

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. Of specific interest is the presence and mass of a turn-over, as this will provide an estimate of the cluster disruption rate. It is also worth following in detail the first ~ 50 Myr of cluster evolution, in order to better probe the process of infant mortality and infer its possible cluster mass dependence for the lowest-mass range. 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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