Young star clusters in external galaxies

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Abstract

I review the characteristics of cluster populations in other galaxies, with particular emphasis on young star clusters and a comparison with the (known) open cluster population of the Milky Way. Young globular cluster-like (compact, massive) objects can still form at the present epoch, even in relatively quiescent spiral discs, as well as starbursts. Comparison with other nearby spiral galaxies, like M83 and NGC 6946, suggests that the Milky Way should host about 20 clusters with masses above 10^5 M$_\odot$ and ages younger than about 200 Myr. No such clusters have been found, however. I discuss the important roles of selection and evolutionary effects that may account for many of the apparent differences between cluster populations in different galaxies. One potentially important difference between ancient GCs and young star clusters is the presence of complex star formation / chemical enrichment histories in the GCs. Little is currently known about the presence or absence of such features in massive ($> 10^5 M_\odot$) young star clusters, but some tantalizing hints of extended star formation histories are now emerging also in young clusters.

1 Introduction

The classification of star clusters as either "open" or "globular" may first have been explicitly adopted by Shapley (1916). However, it is clear that neither the "classical" globular nor open clusters constitute homogeneous classes of objects, and furthermore the boundary between the two classes is somewhat fuzzy. The Galactic globular clusters (GCs) can be grouped into at least two sub-populations, loosely associated with the Galactic halo and bulge/thick disc, that have distinct kinematics, spatial distributions and metallicities (Zinn 1985; Minniti 1996). Even in our Galaxy, the open clusters span large ranges in age, mass and concentration that overlap somewhat with the globular clusters, and making a clear-cut distinction between open and globular clusters becomes increasingly difficult as one moves to external galaxies (e.g. Hodge 1988). This has become particularly true in the last few decades due to the discovery of young star clusters with masses in the range $10^5 - 10^7 M_\odot$, predominantly in interacting galaxies and starbursts (Whitmore 2003; Portegies Zwart et al. 2010), but also

in some normal non-interacting spirals (Larsen & Richtler 2000). To accommodate these objects, terms such as young massive clusters (YMCs), super-star clusters (SSCs), etc., have been introduced.

Although classification is often a natural first step in the study of a new field, there is no generally accepted classification scheme for star clusters that has managed to gain foothold, and it is not clear to what extent the different labels that have been adopted by various authors correspond to physically different objects (see an excellent discussion of this point in Terlevich 2004). It therefore appears more useful to discuss the differences and similarities among cluster systems in different environments in terms of quantifiable parameters. To this end, it is useful to distinguish between three different aspects of a cluster system: 1) The formation efficiency of (long-lived) star clusters relative to field stars, 2) the shape of the initial cluster mass function (ICMF), and 3) dynamical effects. Items (1) and (3) are dealt with extensively elsewhere in these proceedings (e.g. Bastian, Bressert, Gieles, Kruijssen). Here I will mainly concentrate on (2), the ICMF.

2   The initial cluster mass function (ICMF)

The ICMF is analogous to the stellar IMF, and constraining it is subject to many of the same difficulties. Like stars, clusters have finite lifetimes that must be taken into account when trying to infer the ICMF from the observed mass distribution of a cluster sample. It is straight forward to show that if clusters lose mass at a rate $\dot{M} \equiv -M/t_{\rm dis}$, with $t_{\rm dis} \propto M^{\gamma}$, then $dN/dM \sim M^{\gamma-1}$ independently of the ICMF for $t \gg t_{\rm dis}$. Hence, memory of the initial shape of the MF is lost below some mass limit. This is consistent with observations showing that the present-day MF of ancient globular clusters is about flat at $M \lesssim 10^5 M_\odot$ if $t_{\rm dis}$ scales roughly linearly with cluster mass (Fall & Zhang 2001; McLaughlin & Fall 2008; Kruijssen & Portegies Zwart 2009). At younger ages, only the low-mass end of the MF is expected to have been strongly affected by dynamical evolution, although the detailed relation between cluster mass and $t_{\rm dis}$ is more uncertain at younger ages (e.g. Bastian, these proceedings). At high masses, the main empirical difficulty is that the most massive clusters, like the most massive stars, are rare, and as a result there is still considerable uncertainty about the shape and degree of universality of the high-mass end of the ICMF. Care must be taken to separate statistical size-of-sample effects from real physical differences.

It is worth reflecting for a moment on the exact meaning of the term *initial* cluster mass function. The ICMF may be understood as the mass function "at birth" for a cluster population, but this is not a very useful definition in practice. The moment of birth is not well defined, and at young ages the identification of individual star clusters is often difficult (e.g. Bressert, these proceedings). In addition, since the most massive clusters are rare, a cluster sample spanning a very small range of ages will not be very suitable for constraining the behaviour of the ICMF at the high-mass end. A more practical approach is to view the ICMF as a *mean birthrate function*,

$$\Psi(M) \equiv \frac{d^2 N}{dM\, d\tau} \tag{1}$$

i.e., $\Psi(M)$ is the average number of clusters born per unit mass per unit time interval. This may then be integrated over time and mass in order to yield, e.g., the expected number of

clusters born with a given range of masses over a given time interval.

Several studies have constrained the shape of the ICMF over some mass interval. In the Milky Way, the shape of the ICMF is well approximated by a power-law $dN/dM \propto M^{-2}$ for $\lesssim 10^3 M_\odot$ (Elmegreen & Efremov 1997; Lada & Lada 2003; Selman & Melnick 2008). At higher masses the ICMF in the Milky Way is poorly constrained, but the discovery of several young clusters with masses in the range $10^4 - 10^5 M_\odot$ shows that our Galaxy is certainly still capable of forming such objects (Clark et al. 2005; Figer et al. 2006; Davies et al. 2007). The M^{-2} power-law behaviour has been found in other galaxies too, like the LMC (Hunter et al. 2003; de Grijs & Anders 2006; Chandar et al. 2010a), M51 (Bik et al. 2003; Chandar et al. 2011) and the Antennae (Zhang & Fall 1999; Fall et al. 2009), for higher masses than in the Milky Way.

2.1 Range of validity for the M^{-2} ICMF

While the M^{-2} power-law form seems relatively well established for masses up to $\sim 10^5 M_\odot$, the upper and lower limits remain less well constrained. This has to do with statistics in both cases, but of quite different nature. At the low-mass end, the discreteness of the *stellar* IMF becomes an important limiting factor especially when relying on the integrated properties of clusters to determine ages and masses, as is typically the case in extragalactic studies. The light from a $10^4 M_\odot$ cluster is dominated by *on average* only 2–3 supergiants for ages up to several tens of Myr. Since this is an average, some clusters will have no supergiants at all, while others will have more than the average value. This leads to very large fluctuations in the integrated magnitudes colours that are *not* symmetrically distributed around the values predicted for a continuously sampled IMF (Barbaro & Bertelli 1977; Bruzual 2002; Girardi et al. 1995; Cerviño & Luridiana 2004, 2006; Maíz Apellániz 2009; Piskunov et al. 2009; Fouesneau & Lançon 2010; Popescu & Hanson 2010). As an illustration of this, Fig. 1 shows the M_V magnitude vs. stellar mass for simulated star clusters with an age of $\log t/yr = 7.2$. At low masses there is a very large scatter in this relation, and it only starts to narrow down above $\sim 10^4 M_\odot$. This discreteness of the IMF also affects cluster detection itself; a low-mass cluster dominated by a single supergiant star is unlikely to be detected in any survey that uses size information to identify cluster candidates (Silva-Villa & Larsen 2011).

At the high-mass end, the main difficulty is the low birthrates, resulting in poor statistics. Although a large galaxy like the Milky Way may have formed hundreds of clusters with $M > 10^5 M_\odot$ over its lifetime (see below), the numbers that are accessible to detailed study are generally much less than that. Ground-based imaging is generally restricted to ages $< 10^8 - 10^9$ years, when the clusters are bright and blue enough to be separated from foreground stars (Larsen & Richtler 2000; Dowell et al. 2008). HST imaging can use size information to avoid confusion with individual stars, but typically covers only a small fraction of nearby galaxies.

2.2 Hidden massive clusters in the Milky Way?

If the total star formation rate in (long-lived) clusters and the shape of the ICMF are known, we can calculate how many clusters in a given mass range should have formed over some time interval. Observationally, it is challenging to constrain the current formation rate of star
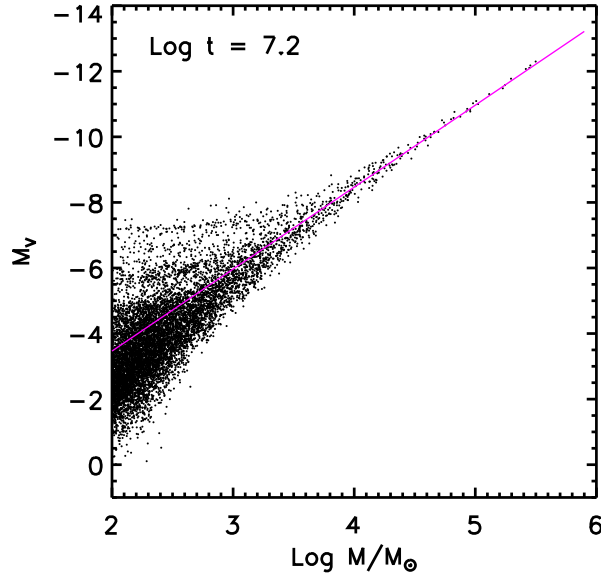
Figure 1: Absolute M_V magnitude as a function of mass for simulated star clusters with an age of $\log t/yr = 7.2$. Note that there is no unique mapping between M_V and masses less than $\log M/M_\odot \sim 4$, even for fixed age.

clusters in the Milky Way. To get an order-of-magnitude estimate, we assume a total star formation rate of the Milky Way of about $1 M_\odot$ yr^{-1} (Robitaille & Whitney 2010) and that about 10% of this is in the form of bound star clusters (Lada & Lada 2003; Bastian 2008; Silva-Villa & Larsen 2010). In order to estimate the expected number of massive clusters for a pure M^{-2} ICMF, it is necessary to adopt upper and lower limits. Plausible values may be $\sim 10 M_\odot$ and $\sim 10^6 M_\odot$. In this case, a cluster formation rate of $0.1 M_\odot$ yr^{-1} yields mean birthrates of ~ 0.9 Myr^{-1} for $M > 10^4 M_\odot$ and ~ 0.08 Myr^{-1} for $M > 10^5 M_\odot$. If the star formation rate was constant in the past, the total number of clusters formed over the past 10 Gyr would then be ~ 8000 and ~ 800 for $M > 10^4 M_\odot$ and $M > 10^5 M_\odot$, respectively. These are likely lower limits, as the SFR may well have been higher in the past, although many of these clusters will have dissolved. However, the fact that only $\sim$one cluster with $M \sim 10^5 M_\odot$ is expected to form every 10 Myr may be consistent with the observation that even the most massive young clusters known in our Galaxy barely reach $10^5 M_\odot$ and all are only a few Myr old. Due to complicated and poorly quantified selection effects, the Milky Way may not be the best place for constraining the ICMF at high masses.

2.3   Constraints from other galaxies

As noted above, a number of studies have attempted to constrain the shape of the ICMF in several external galaxies, often finding it to be well represented by a $dN/dM \propto M^{-2}$ shape *over some mass range*. However, many of these studies have been based on HST pointings covering only a small fraction of the target galaxies, or have been targeting galaxies that are relatively small in the first place (like the LMC) and the behaviour of the ICMF is typically
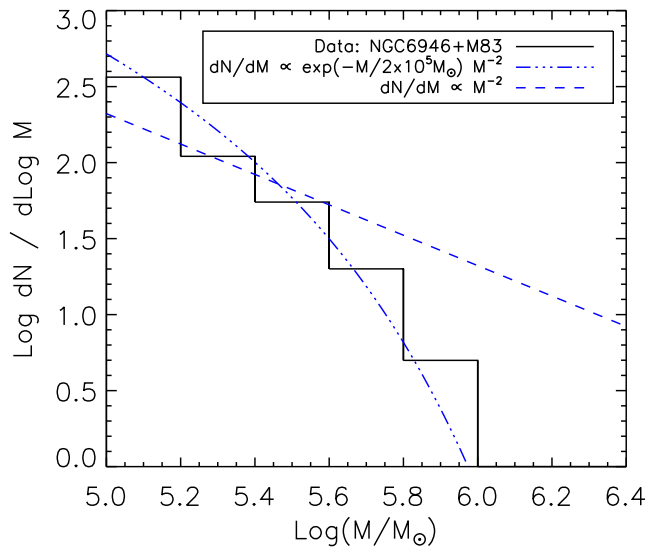
Figure 2: Observed mass function for the combined cluster populations of NGC 6946 and M83 for clusters younger than 200 Myr. The dashed line shows an M^{-2} power-law while the dotted-dashed line is a Schechter function with a cut-off mass at $2 \times 10^5 M_\odot$.

poorly constrained above $\sim 10^5 M_\odot$. In an attempt to obtain better statistics at high masses, Larsen (2009) used the ground-based imaging of Larsen & Richtler (1999) to study the MF of young star clusters in a sample of spiral galaxies. Figure 2 shows the resulting combined mass function for the two spiral galaxies NGC 5236 and NGC 6946, both of which have high current star formation rates and rich populations of young star clusters. The figure includes objects younger than 200 Myr, where the data are still reasonably complete for $M > 10^5 M_\odot$. The MF is here sampled up to $\sim 10^6 M_\odot$, and is poorly fit by a pure $dN/dM \propto M^{-2}$ power-law over the range $10^5 - 10^6 M_\odot$ (dashed line). Instead, a Schechter mass function with a cut-off mass of $2 \times 10^5 M_\odot$, i.e., $dN/dM \propto \exp(-M/2 \times 10^5 M_\odot)M^{-2}$, provides an excellent fit to the data (dotted-dashed line). There is no particular physical reason for choosing the Schechter function as a fitting formula, except that it preserves the M^{-2} shape found at lower masses, and provides a convenient way to parameterize a steepening or "cut-off" at higher masses.

The data in Fig. 2 allow us to make an independent estimate of the number of massive clusters expected in the Milky Way. The combined star formation rate of NGC 6946 and NGC 5236 is about 5 $M_\odot$ yr^{-1} and the sample contains 111 clusters with $M > 10^5 M_\odot$ and ages younger than 200 Myr. Scaling by the SFR, we would thus expect about 20 clusters in the same mass- and age range in the Milky Way. This is in surprisingly good agreement with the birthrate of about one cluster with $M > 10^5 M_\odot$ every 10 Myr estimated above (Sect. 2.2).

Although an attractive attribute of the ground-based data is that they cover the full galaxies, there is clearly some risk that cluster samples may be contaminated by more extended groupings of stars. Although it appears unlikely that contamination would lead to what is essentially a *dearth* of high-mass objects compared to extrapolation of a pure M^{-2}
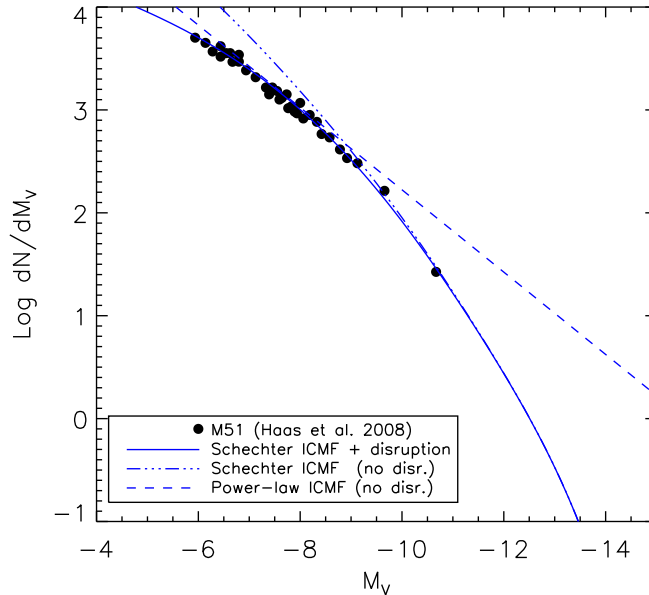
Figure 3: Dots: Observed luminosity function for clusters in M51 = NGC 5194. The dotted line is an L^{-2} power-law, while the solid and dotted-dashed curves are LFs computed for an underlying Schechter ICMF with and without disruption.

power-law, the data shown in Fig. 2 should still be treated with a healthy dose of skepticism. Using HST imaging of NGC 5236, Chandar et al. (2010b) find the MF to be consistent with a cut-off above $10^5 M_\odot$, while Chandar et al. (2011) find cut-offs of $M^\star > 2 \times 10^5 M_\odot$ to be consistent with observations of NGC 5194. Hence, these studies are essentially consistent with a cut-off mass of several $10^5 M_\odot$.

A more indirect way to constrain the ICMF is by means of the cluster *luminosity* function (LF). Although the LF is related to the ICMF, it is in general not possible to directly determine the ICMF from observations of the LF as this would require a detailed knowledge of the cluster formation history and dissolution. However, the LF can be predicted for various scenarios and then compared with observations. As an example, Fig. 3 shows the observed luminosity function for young clusters in NGC 5194, based on a large HST/ACS mosaic covering essentially the complete galaxy (Haas et al. 2008). A very similar LF, based on the same data, has been shown by Hwang & Lee (2008). Also shown in the figure are predicted LFs for various scenarios. The dashed line shows the LF for a pure power-law ICMF ($dN/dM_i \propto M_i^{-2}$) and no disruption. In this case, the LF itself will have a similar form, $dN/dL \propto L^{-2}$, which is not consistent with the data that instead show a considerably steeper slope at the bright end ($dN/dL \propto L^{-2.5}$ for $M_V < -8$; Haas et al. 2008). Instead, a model LF based on a Schechter ICMF with cut-off mass $M^\star = 2 \times 10^5 M_\odot$ provides a good fit to the data, especially if some mass-dependent disruption is included. We have here assumed that cluster lifetimes depend on mass as $t_{\rm dis} = 5 \times 10^8 {\rm yr} (M/10^4 M_\odot)^{0.65}$.

Although luminosity functions are a somewhat indirect way to constrain the ICMF, they are observationally straight forward to determine and do not depend on model-dependent

conversions from the observables to ages and masses. It is therefore not surprising that LFs are available for more cluster systems, compared to the relatively small number of systems where MFs have been derived. It is easy to show that a uniform M^{-2} MF will also yield an L^{-2} LF, if there is no disruption. Unless high-mass clusters are preferentially disrupted, an initial M^{-2} power-law ICMF should therefore always lead to a LF with the same -2 slope or shallower. Instead, most studies tend to find LFs that are *steeper* than this, with slopes getting increasingly steeper if they are measured at brighter magnitudes (Larsen 2002; Gieles 2010).

Both direct ICMF determinations and LF measurements appear to be consistent with a cut-off mass $\sim 2 \times 10^5 M_\odot$ in normal spiral discs (Portegies Zwart et al. 2010), although there is a hint that the cut-off may be somewhat radially dependent in NGC 5236 (Bastian, these proceedings). The cut-off mass does *not* appear to be universal but must be significant higher in starburst galaxies, which often host large numbers of clusters with masses of $10^6 M_\odot$ or above. For the best-studied on-going major merger, the Antennae, Zhang & Fall (1999) suggested a truncation near $10^6 M_\odot$ while a formal fit to their data yields $M_C \sim 8 \times 10^5 M_\odot$ (Jordan et al. 2007). In old GC systems there also appears to be an upper cut-off mass near $\sim 10^6 M_\odot$, with a significant correlation with host galaxy luminosity (Jordan et al. 2007). This may suggest that GCs formed under conditions that were more similar to those in present-day starbursts than quiescent discs.

3 The internal star formation histories of clusters

The preceding discussion does not suggest a natural division between globular and other clusters based on mass alone. Clusters are sampled from a continuous mass distribution that appears to be well approximated by a Schechter function. While the cut-off mass probably depends on environment, it is on the order of $10^5 M_\odot$ even in present-day star forming disc galaxies. Likewise, the sizes of young massive star clusters both in spiral galaxies and in starbursts/mergers appear similar to those of ancient globular clusters, with typical half-light radii of a few (2–4) pc (e.g. Whitmore et al. 1999; Larsen 2004).

Of course, there are potentially other parameters than size and mass to consider. In the Milky Way, most open clusters are (more or less per definition) associated with the disc, and tend to have roughly Solar metallicity (Friel et al. 2002). Most globular clusters, by contrast, have metallicities well below solar and can be grouped into two populations with mean overall metallicities [Fe/H]~ -1.5 and [Fe/H]~ -0.5 (e.g. Zinn 1985), although GCs in giant elliptical galaxies tend to reach near-solar metallicities (Peng et al. 2006). GCs also differ from open clusters by typically having enhanced α-element abundances (relative to Fe). However, these differences mostly reflect the properties of the stellar populations with which the open and globular clusters are associated, and should not necessarily be taken as indications of fundamentally different formation mechanisms.

A perhaps more important clue comes from the degree of *internal* homogeneity of the clusters. Open clusters are generally very homogeneous, with no significant age spreads or star-to-star differences in chemical composition (e.g. Pancino et al. 2010). Globular clusters, instead, are well known for exhibiting internal variations in the abundances of some light elements (Kraft 1979), in particular with anti-correlated abundances of O/Na and Mg/Al (Grat-
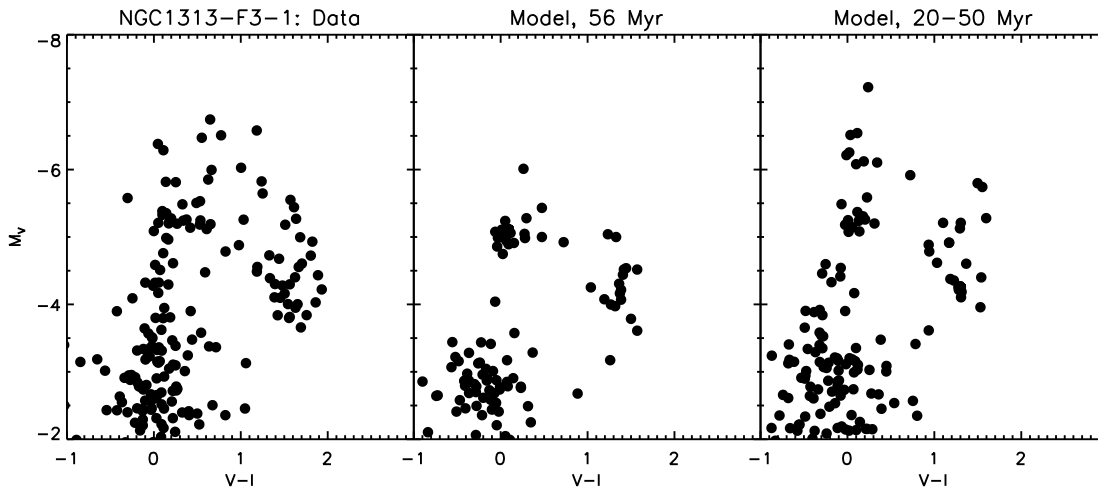
Figure 4: Left: Observed colour-magnitude diagram for the cluster NGC1313-F3-1. Middle: a model based on a single 56 Myr old isochrone. Right: A model including an age range from 20–50 Myr.

ton et al. 2001). This suggests that stars in these clusters formed from material that had been processed to different degrees via the CNO cycle, either in AGB or massive (single or binary) main sequence stars (D'Ercole et al. 2010; Decressin et al. 2007; de Mink et al. 2009). In either case, star formation must then have been an extended process (tens to hundreds of Myr), in contrast to the conventional view that star clusters form very quickly (e.g. Elmegreen et al. 2000) and data for Milky Way open clusters. Furthermore, high-quality colour-magnitude diagrams have now revealed the presence of multiple main sequences and/or sub-giant brances in several globular clusters, seemingly requiring strongly enhanced He abundances in some of the stars (e.g. Piotto 2009; Milone et al. 2010). In summary, globular clusters appear to have experienced complicated star formation- and chemical enrichment histories.

At this point, it is worth recalling that the ancient GCs and present-day open clusters in the galactic disc probe very different regimes of the ICMF. The GCs that have survived until the present day must all have had quite large initial masses, at least $\sim 10^5 M_\odot$. Open clusters, on the other hand, are typically low-mass objects with masses less than $10^3 - 10^4 M_\odot$. It is quite possible that the presence of internal abundance variations is linked to the initial cluster mass, with some scenarios predicting that complex internal star formation histories should mainly occur for initial masses greater than $10^5 - 10^6 M_\odot$ (Pflamm-Altenburg & Kroupa 2009; Conroy & Spergel 2011). The real test of whether GCs have a fundamentally different origin than star clusters in the local universe should thus involve objects of similar mass. Unfortunately, little is currently known about the detailed chemical composition of young massive star clusters in the regime $M > 10^5 M_\odot$, simply because most of them are too far away to study individual stars in detail.

While abundance anomalies have, so far, only been detected in ancient globular clusters, there is emerging evidence that complex star formation histories may not be unique to old GCs. In particular, age spreads of several 100 Myr have been claimed in some massive, intermediate-age (~ 2 Gyr) clusters in the Large Magellanic Cloud (Mackey et al. 2008;

Milone et al. 2009; Girardi et al. 2009), although it has also been suggested that the observed CMD features in these clusters might be at least partially explained by stellar evolutionary effects, e.g. due to stellar rotation (Bastian & de Mink 2009). We have recently presented resolved photometry for a number of younger clusters in several nearby galaxies (Larsen et al. 2011). Figure 4 shows one example, for the cluster NGC 1313-F3-1, with an estimated mass of $\sim 2 \times 10^5 M_\odot$. The left-hand panel shows the photometry, while the centre panel shows a model CMD based on a single isochrone that takes into account observational errors. This model CMD displays a smaller scatter in the luminosities of the supergiant stars, and also exhibits a distinct gap between the main sequence turn-off and the supergiants (the "blue Hertzsprung gap", BHG) that is far less clearly seen in the data. The right-hand panel shows a model CMD that includes an age spread between 20 and 50 Myr, which results in a better match to the data. While the multiple-age model is reasonably successful in reproducing the observed CMD for this particular cluster, there are other clusters in the sample of Larsen et al. (2011) for which an age spread cannot, by itself, reproduce the observed CMD features - in particular, the lack of a BHG seems to be a generic feature of the data, and may also be the result of binary stellar evolution. Mass transfer or mergers in binary systems can produce stars that *appear* to be younger than the actual age of the cluster, and this can produce many of the same effects on the CMD as an age spread. Thus, the case for multiple stellar populations in younger star clusters remains somewhat ambiguous.

4 Summary

Comparison with other nearby spiral galaxies suggests that the Milky Way should contain a significant population of young star clusters with masses above $10^5 M_\odot$. Scaling from the cluster systems of NGC 5236 and NGC 6946, about 20 clusters with $M > 10^5 M_\odot$ and ages younger than 200 Myr are expected. Are these objects young analogues of the ancient globular clusters that populate the halo and bulge of our own and other galaxies? In terms of masses and sizes, the young massive clusters in nearby spirals, as well as in on-going starbursts and mergers, certainly appear similar to their older counterparts. Differences in the "typical" masses may be largely due to a combination of selection effects and dynamical evolution – the "initial cluster mass function" (ICMF) appears to extend well above $10^5 M_\odot$ whenever there are enough clusters to sample the high-mass end, although there appears to be an environmentally dependent truncation that occurs at a few times $10^5 M_\odot$ in present-day, quiescent discs, but at $> 10^6 M_\odot$ in starbursts and ancient GC populations.

A more significant difference between ancient GCs and present-day cluster formation may be the presence of multiple stellar populations in the former. These are now revealed by direct colour-magnitude diagrams, although the presence of abundance anomalies have hinted at this for many decades. It remains unclear, however, whether these phenomena are uniquely related to ancient GCs. The surviving GCs must have had initial masses well above $10^5 M_\odot$, and little is currently known about the detailed star formation histories of young clusters in this mass range, simply because they are generally too distant to observe individual stars in detail. However, there is evidence from CMDs that some young clusters in the Large Magellanic Cloud, as well as in more distant galaxies, may have extended star formation histories, although this is not entirely conclusive yet.

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