Mass Loss from Stars and the Evolution of Stellar Clusters
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Observational Constraints on Cluster Evolution

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Abstract. Current observational constraints on the dynamical evolution of star clusters are reviewed. Theory and observations now agree nicely on the mass dependency and time scales for disruption of young star clusters in galactic disks, but many problems still await resolution. The origin of the mass function of old globular clusters, and its (near) invariance with respect to host galaxy properties and location within the host galaxy remain prominent puzzles. Most current models fail to reproduce the globular cluster mass function as a result of dynamical evolution from an initial power-law, except under very specific conditions which are not generally consistent with observations. How well do we actually know the proper initial conditions? The cluster initial mass function (CIMF) seems to be consistent with a power-law with exponent $\alpha \approx -2$ in most present-day star forming galaxies, but the limits of the mass range over which this approximation is valid remain poorly constrained both observationally and theoretically. Furthermore, there are hints that some dwarf galaxies may have CIMFs which deviate from a power-law.

1. A Bit of Historical Background

The idea that star clusters evolve dynamically has been around for nearly as long as the very concept of star clusters itself. The first to discuss the general properties of clusters in some detail was William Herschel, who attributed their various degrees of "central concentration" to an evolutionary sequence in which the globular clusters represented the final stage (Herschel 1789). At that time, however, a real theory of stellar dynamics was still far in the future and the subject of cluster evolution remained dormant for well over a century.

In the early 20th century, the attention was mostly focussed on external perturbations. Jeans (1916) remarked that "A cluster of stars will suffer continual disintegration from its encounters with other stars or clusters". In his monograph on "Star Clusters", Shapley (1930, p. 208) devoted only a brief statement to dynamical evolution, noting that "some of the globular clusters may be affected in freedom, form, and eventual survival by contacts with galaxies or other clusters." The stability of "moving clusters" was investigated by Jeans and later by Bok (1934). The important effect of internal two-body encounters was first studied by Ambartsumian (1938) who noted that stars in the high-velocity tail of the Maxwellian velocity distribution will gradually escape, leading to disruption of typical open clusters on time scales of a few Gyrs, depending on cluster mass. With remarkable foresight, Ambartsumian also realised that low-mass stars will escape preferentially, and suggested that more evolved clusters might be recognisable by their lack of low-mass stars. Similar conclusions were reached (in the context of old globular clusters) by Spitzer (1940). These ideas have been continuously refined ever since and it would lead too far to review the relevant literature on models for the dynamical evolution of star clusters here. Excellent reviews on the dynamical evolution of open and globular clusters are in King (1980), Spitzer (1987) and Meylan & Heggie (1997) and the field remains very active as illustrated by several contributions in this volume. The remainder of this review concentrates on observational constraints on cluster evolution.

In order to address dynamical evolution in a meaningful way observationally, a method to age-date individual star clusters becomes a necessity. The catalogue of open clusters compiled by Trumpler (1930) listed the spectral types of the brightest stars in 100 Milky Way open clusters, but the use of this information as a suitable chronometer had to await the emergence of the first detailed sets of stellar model calculations in the 1950s. Once it became possible to derive cluster ages from colour-magnitude diagrams, it quickly became clear that the number of old open clusters is lower than one would naively predict from a continuous formation rate, even taking into account the fact that younger clusters are more easily detected than older ones because they contain brighter stars.

The relative paucity of old open clusters was noted almost simultaneously in at least three papers (van den Bergh 1957, Oort 1958, von Hoerner 1958), all of which were based on Trumpler's catalogue. It appears that they all arrived at the same conclusion quite independently (van den Bergh, priv. comm.). All three papers also singled out disruption as the most likely cause of the decline in number of clusters with ages greater than $\sim 10^8 - 10^9$ years. Considering the effects of stellar mass loss, a tidal field and relaxation due to stellar encounters, von Hoerner (1958) estimated an average cluster lifetime of 10^9 years, in reasonable agreement with his best observational estimate of 500 Myrs. Spitzer (1958) calculated cluster disruption times of $10^8 - 10^9$ years for typical open cluster densities, in fair agreement with the observational estimates, and also noted that encounters between clusters and interstellar clouds might play an important role for cluster disruption. Thus, one might argue that theoretical and observational estimates of cluster disruption times were in agreement to within a factor of 2 already 50 years ago! In the context of this meeting, it is also interesting to note that the connection between stellar mass loss and the evolution of star clusters was recognised early on. Of course, many of the details still remained (and remain!) to be worked out.

Using more recent compilations of open cluster data, Wielen (1971) estimated that about 50% of open clusters in the Milky Way disintegrate within about 200 Myrs. He also noted a significant scatter in the disruption times, with 2% of the clusters surviving for longer than a Gyr, and suggested that the disruption time probably depends on the size and mass of the cluster (as anticipated by Ambartsumian). Observational support for the importance of giant molecular cloud (GMC) encounters was provided by van den Bergh & MacClure (1980) who pointed out that the oldest open clusters (> 1 Gyr) are strongly concentrated towards the galactic anti-centre direction, where the density of GMCs is lower. This observation, as well as the fact that old open clusters tend to be found further from the Galactic plane than young ones, has since been confirmed by several studies (Friel 1995, and references therein). Theoretically, further support for the importance of GMC encounters came from N-body simulations by Terlevich (1987).

The first observational evidence that cluster disruption times depend on mass came from Janes & Adler (1982). However, it has also been clear for some time that the disruption times may not be the same in all galaxies. Both the LMC and SMC show a less pronounced lack of old clusters than the Milky Way (Elson & Fall 1985, Hodge 1987), and already Wielen (1985) suggested that different GMC densities in the Milky Way, SMC and LMC might play a role. However, a direct comparison with the Milky Way remained somewhat hampered by different detection limits and the bursty star formation history of the LMC. Prior to the launch of the *Hubble Space Telescope* in 1990, little was known about the detailed properties of (young) cluster populations in other galaxies, and even in the Local Group spirals M33 and M31 the data were insufficient to strongly constrain cluster lifetimes.

Little has been said explicitly thus far about the *globular* clusters (GCs), which present a number of interesting problems. In the Milky Way, they are associated with the spheroidal component(s) and thus considered typical "Population II" objects (Baade 1944). In fact, every major galaxy is surrounded by ancient GCs akin to those found in the Milky Way. The mass distribution of GCs is markedly different from that of Milky Way open clusters, with a relative deficit of low-mass GCs (Sect. 3, (van den Bergh & Lafontaine 1984)). This difference has sometimes led to the notion that GCs may be fundamentally different from star clusters forming today, and might have formed by quite different processes which were unique in the early Universe (Peebles & Dicke 1968). However, the young "populous" star clusters in the LMC, some of which have GC-like masses, have remained a puzzle since the early 20th century (Shapley 1930), and continue to serve as a reminder that the distinction between open and globular clusters is not necessarily as clear-cut in other galaxies as it may seem in our own.

The idea that GC formation may not have been restricted to the early Universe received renewed interest when Schweizer (1987) suggested that new GCs form in galaxy mergers. This might solve the "specific frequency problem" (i.e., the fact that elliptical galaxies contain many more GCs per unit host galaxy luminosity than do spirals), which had been raised as a major objection against the idea that elliptical galaxies form from spiral-spiral mergers (van den Bergh 1982) as suggested by Toomre & Toomre (1972). The subsequent discovery by HST observations of young "super" star clusters in a number of interacting and merging galaxies in the 1990s (as reviewed by Whitmore 2003) further stimulated interest in this idea, but the problem remains that the "cluster initial mass function" (the CIMF) seems very different from that of the ancient GCs. Besides other objections to the major merger picture (e.g. Forbes, Brodie & Grillmair 1997) this still represents a major challenge, as I will discuss shortly.

2. Evolution of Cluster Populations in Star-forming Galaxies

Over the last 1–2 decades, it has become abundantly clear that the basic division into "open" and "globular" clusters as it applies in the Milky Way quickly becomes inadequate when a wider variety of host galaxy types are considered. Young clusters with masses in the range $10^4 - 10^6$ $M_\odot$ or greater have now been found in many different types of external galaxies (Larsen 2005). Furthermore, HST observations of some lenticular (S0) galaxies have revealed populations of old ($\gtrsim$ 8 Gyrs) star clusters with larger effective radii than normal open and globular clusters, and with a mass distribution that does not display the turn-over observed in classical old GC systems (Larsen & Brodie 2000, Brodie & Larsen 2002, Peng et al. 2006). These "faint fuzzy" clusters are clearly associated with the disks of their host galaxies, and do not easily fit the classical description of either open or globular clusters.

Ultimately, the dynamical evolution of all flavours of star clusters must be governed by the same basic laws of stellar dynamics. We must therefore demand from any successful theory of cluster evolution that it is able to account for the observed properties of *all* types of star clusters without too much tweaking. The fact that the luminosity function of old globular clusters is (nearly) universal may be an important clue to the mechanisms that shaped it, as will be discussed further below (§3.). However, before seeking to explain the *evolution* of clusters, we must make sure that we know their *initial* properties.

2.1. The Cluster (Initial) Mass Function

Was the difference between the MFs of young and old ("globular") star clusters set up at formation, or is it a result of dynamical evolution? That GCs formed with a MF that was different from that observed in young cluster systems today (Parmentier & Gilmore 2005) is perhaps not an entirely unreasonable idea, given that conditions in the early Universe were likely quite different from those prevalent today. However, this is unattractive for several reasons: First, direct observations of the formation of individual GCs at cosmological distances to test this hypothesis (over a mass range that allows useful constraints on the CIMF) will not be possible for a long time to come. Second, it would be a return to the notion that GCs are "special", and thus make them less attractive as general tracers of the star formation histories of galaxies. At the end it may of course turn out that this is how Nature really works. But alternatively, we may seek to understand the present-day MF of GCs as a result of dynamical evolution from the MFs observed in young cluster systems. It is then worthwhile to ask whether there *is* a universal CIMF, and what it might look like.

Even after more than a decade of HST observations, the number of galaxies where the MF of young star clusters is known well is still in the single digits. Direct application of the virial theorem requires reliable measurements of both the size and velocity dispersion of each individual cluster, and is impractical for large samples of clusters. Most determinations of the masses of extragalactic star clusters rely on assumptions about the mass-to-light (M/L) ratio, usually from simple stellar population (SSP) models which assume a "standard" stellar mass function (e.g. Salpeter 1955, Kroupa 2001). The major complication here is that the M/L ratios are strongly age-dependent, so that knowledge of individual cluster ages is required in order to convert the observed luminosities into a MF. SSP models provide predictions for the evolution of broad-band colours as a function of age, which can be used to infer the ages of star clusters for (in principle) arbitrary combinations of passbands. However, for clusters younger than about a Gyr, optical colours are only weakly sensitive to age, and strongly degenerate with respect to reddening, making imaging in the U-band a necessity for reliable age (and hence mass) determinations.

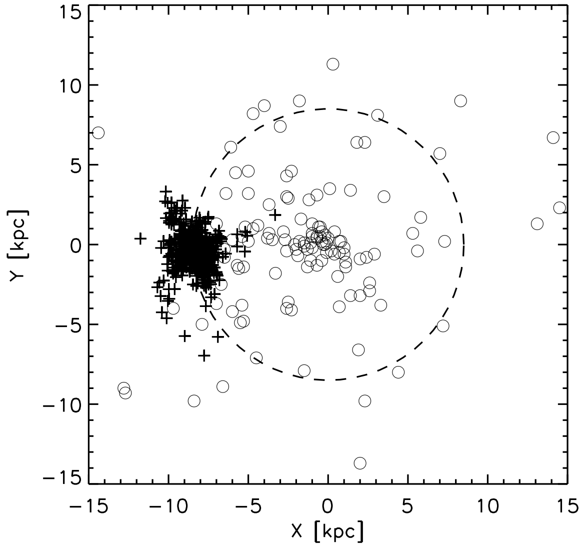

Figure 1. The spatial distribution of catalogued open clusters (plus markers) and globular clusters (open circles) in the Milky Way. The Sun is at (X,Y) = (-8.5, 0) kpc.

Galaxies where the MF has been determined for young clusters include the Milky Way (Elmegreen & Efremov 1997), the LMC and SMC (Hunter et al. 2003), the nearby interacting spiral M51 (Bik et al. 2003), the starburst galaxies NGC 3310 and NGC 6745 (de Grijs et al. 2003a) and the "Antennae galaxies" (Zhang & Fall 1999). In all these cases, the MF is consistent with a power-law of the form $dN/dM \propto M^{\alpha}$ with $\alpha \approx -2$, although the mass ranges probed by the different studies differ substantially. In the Antennae and in NGC 3310/NGC 6745, the lower limits are at $> 10^4\ M_{\odot}$, but these are purely observational limits and there is no reason to suspect that lower-mass, "open" clusters are absent in these galaxies. This lower limit coincides roughly with the mass of the most massive young clusters known in the Milky Way (with a couple of exceptions), but again this may be an observational selection effect due to the limited volume of the Galactic disk probed by current open cluster catalogues.

Fig. 1 shows the spatial distribution of open and globular clusters in the Milky Way from the catalogues of Kharchenko et al. (2005) and Harris (1996), projected onto the Galactic plane. The median distance of the open clusters from the Sun is 1.1 kpc, and more than 80% have distances < 2 kpc, a strong indication that the current sample is highly spatially incomplete beyond ~ 1 kpc. Indeed, a few young clusters with masses of $\sim 10^5\ M_{\odot}$ have recently been identified in the Milky Way, including Westerlund 1 (Clark et al. 2005) and an object detected in the 2MASS survey (Figer et al. 2006). Both are located at distances of several kpc (but still closer than the Galactic centre), and subject to large amounts of foreground extinction. The existence of these objects at distances of a few kpc is fully consistent with extrapolation from the MF of open clusters in the Solar neighbourhood, and strongly suggests that several young clusters with masses of $10^4 - 10^5\ M_\odot$ or greater remain undiscovered in the disk of our Galaxy (Larsen 2006). The known globular clusters, on the other hand, are more or less symmetrically distributed with respect to the Galactic centre, suggesting that the sample does not suffer from severe spatial incompleteness.

2.2. The Poor Man's Approach: Luminosity Functions

Luminosity functions (LFs) are more readily obtained for large samples of clusters than MFs. Generally, these also show power-law behaviours although often with slightly steeper slopes than the MFs (Whitmore et al. 1999, Larsen 2002). One way such a difference could arise is if the MF is truncated at some upper limit $M_{\rm max}$. Whitmore et al. (1999) noted a "bend" in the LF of young clusters in the Antennae galaxies at $M_V \sim -10.4$, with a slope of $\alpha = -2.6$ above the bend. For an age of 10 Myr, the bend corresponds to a mass of $\sim 10^5\ M_\odot$, tantalisingly close to the turn-over of the globular cluster MF. However, Zhang & Fall (1999) found that the MF of young clusters in the Antennae is, in fact, consistent with a power-law with $\alpha = -2$ over the range $10^4 - 10^6\ M_\odot$, and noted that the bend in the LF could be due to a truncation of the MF near $10^6\ M_\odot$.

The relation between the presence of a bend in the LF and a truncation of the MF has been investigated in more detail by Gieles et al. (2006a,b), who suggested that the MF in the spirals M51 and NGC 6946 is truncated at $M_{\rm max} = 0.5 - 1 \times 10^6\ M_\odot$, and at about $2 \times 10^6\ M_\odot$ in the Antennae galaxies. Thus, while direct data for the MF are preferable, studies of the LF may still hold interesting clues to the underlying MF, albeit not without some assumptions.

It must be mentioned that some dwarf galaxies host a few star clusters which appear too luminous (and massive) to simply form the high-mass tail of a power-law distribution. Most conspicuous among these is NGC 1705, in which there is a gap of 3 magnitudes between the two brightest clusters, but a similar effect is observed in other dwarfs (Billett, Hunter, & Elmegreen 2002, Johnson 2005). In an HST study of a sample including 36 dIrr galaxies, Sharina, Puzia, & Makarov (2005) noted a possible turn-over in the LF of young star clusters, and speculated that different cluster formation mechanisms might be at work in isolated dwarf galaxies. Such differences would be particularly interesting in view of the idea that some GCs may have formed in dwarf-like fragments (Searle & Zinn 1978, Prieto & Gnedin 2006). Inevitably, studies of star clusters in dwarf galaxies tend to be complicated by small number statistics, and a systematic study of an even larger sample of star-forming dwarfs would be desirable.

In summary, the current (limited) evidence suggests that the CIMF is consistent with a power-law $dN/dM \approx M^{-2}$ *over some mass range* in most galaxies. So far, there is no indication for any significant difference in the shape of the CIMF in the Milky Way and more actively star-forming galaxies. If an upper limit to the CIMF exists in our Galaxy it is probably at $10^5\ M_\odot$ or greater, and the apparent lack of "super star clusters" in the Milky Way disk may be, at least to some extent, a size-of-sample effect due to the limited volume we are sampling. More generally, whether or not the CIMF has an upper limit, and how it might depend on host galaxy properties, is only now starting to be explored. However, we must also remain open to the possibility that cluster populations do not *everywhere* form with a single power-law MF.

2.3. Cluster Disruption in Disks

Although the basic mechanisms responsible for the disruption of star clusters were identified already half a century ago, a detailed framework to compare observations and theory has only recently become available.

Boutloukos & Lamers (2003) derived the "disruption time", $t_{\rm dis}$, for star clusters in M51, M33, the SMC and the Solar neighbourhood under the assumption that $t_{\rm dis}$ could be parameterised as a simple analytic function of cluster mass: $t_{\rm dis} = t_4(M/10^4 M_\odot)^\gamma$, where t_4 is the disruption time of a 10^4 $M_\odot$ cluster. By explicitly including the dependence on mass, they could compare disruption times in different galaxies more directly than had been done before. The longer cluster disruption time in the SMC (by about an order of magnitude) was confirmed, and Boutloukos & Lamers (2003) also found a significantly shorter disruption time in the central parts of M51. Interestingly, the parameter γ was found to have a value close to 0.60. This is significantly shallower than expected from classical two-body relaxation, which predicts that a star cluster should lose mass at a roughly constant rate and thus $\gamma \approx 1$ (Spitzer 1987, Fall & Zhang 2001). However, a value of $\gamma \approx 0.62$ is consistent with N-body simulations for clusters with a realistic stellar mass function (albeit with concentrations typical of GCs), evolving in an external tidal field (Baumgardt & Makino 2003, Lamers, Gieles, & Portegies Zwart 2005a). The scaling factor t_4 appears to depend on the mean ambient density as expected from N-body simulations, although the disruption time derived for the central regions of M51 by Lamers et al. (2005a) remained too short by about an order of magnitude compared to the predictions. The shorter disruption time-scale near the centre of M51 might be caused by a high density of GMCs there (Gieles et al. 2006c).

Boutloukos & Lamers (2003) assumed that clusters disrupt instantaneously at $t_{\rm dis}$, but in later papers a more realistic treatment of gradual mass loss has been included. Lamers et al. (2005b) showed that the present-day age- and mass distributions of Milky Way open clusters can both be very well fitted in a scenario where clusters form at a (nearly) constant rate and disrupt on a timescale proportional to $M^{0.62}$. They derived a disruption time for a 10^4 $M_\odot$ cluster in the Solar neighbourhood of 1.3 Gyr, based on the Kharchenko et al. (2005) catalogue. For masses in the range $10^2 < M/M_\odot < 10^3$, this corresponds to disruption times between 75 and 300 Myrs, consistent with the earlier studies.

A few words on the concept of a high degree of "infant mortality" for star clusters, which has become popular in recent years: This idea is inspired by the facts that 1) the formation rate of embedded star clusters in the Milky Way over-predicts the number of observed open clusters by a large factor (Lada & Lada 2003) and 2) many studies of extragalactic young star clusters find a disproportionately large number of objects with ages $< 10^7$ years (Fall, Chandar, & Whitmore 2005, Bastian et al. 2005). The objection has been raised that these young objects may not be gravitationally bound, and thus do not deserve the label "star clusters" to begin with (Schweizer 2006). Certainly, young clusters tend to be located in crowded regions, and the identification of individual clusters

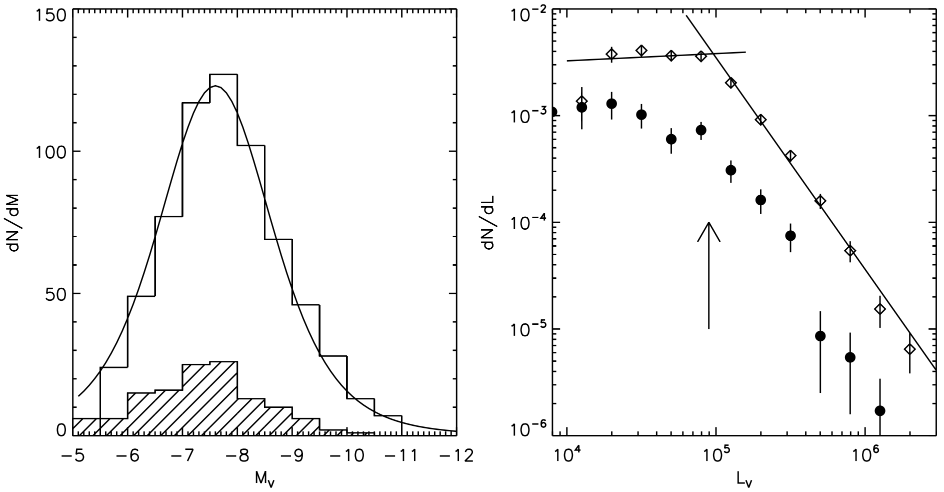

Figure 2. The luminosity functions for GCs in the Sombrero galaxy (data from Spitler et al. 2006) and the Milky Way ($R_{gc} < 80$ kpc). Left: number of GCs per magnitude bin and the best fitting Student's t_5-function. The Milky Way GCLF is shown as a hashed histogram. Right: Same data, but shown as number of GCs per luminosity bin. Milky Way data are shown with filled circles. The arrow marks the luminosity corresponding to the peak of the t_5 fit. The straight lines are power-law fits to the Sombrero data below and above the peak of the t_5 fit.

becomes challenging even with HST at distances greater than a few Mpc (Larsen 2004). Ultimately, whether or not the definition of a star cluster should include the requirement that it be gravitationally bound may depend on the context, and for very young, still embedded objects it may be impossible to apply this criterion. In any case, this initial round of destruction appears to be independent of mass, and should not strongly affect the shape of the MF.

3. The Globular Cluster Mass Function

One of the more remarkable and puzzling facts about old GCs is the (near) universality of their luminosity function – the GCLF. Assuming that GCs in most galaxies display at most a small age spread, the GCLF is a good proxy for the MF. Fig. 2 compares the Milky Way GCLF (data from Harris (1996)) with data for the Sombrero galaxy, based on HST/ACS observations (Spitler et al. 2006). In the left panel, the two GCLFs are plotted in the traditional way, i.e. as a histogram of number of clusters per magnitude bin. The best Student's t_5 function fit to the Sombrero data from Spitler et al. is overplotted. Clearly, the GCLFs in the two galaxies are very similar. That the GCLF may have a universal shape was suggested early on by Harris & Racine (1979), and it is now clear that the variations, if any, are small over a large range of Hubble type and luminosity (e.g. Richtler 2003, Strader et al. 2006). It should be noted that there *are* subtle radial trends in the GCLF within the Milky Way GC system.

In particular, the luminosity function of GCs with galactocentric distances > 80 kpc may be bimodal (van den Bergh 2003). These outer halo clusters have been omitted from Fig. 2 although they are relatively few in numbers and would not strongly affect the comparison.

The impression of a characteristic GC mass is driven to some extent by the logarithmic binning of the data (McLaughlin 1994, Richtler 2003). When the GCLF is plotted as number of clusters per luminosity bin it can be equally well fitted by a broken power-law as illustrated in the right-hand panel of Fig. 2. The arrow marks the peak of the t_5 function fit and the two straight lines are power-law fits to the Sombrero GCLF on either side of the arrow. At the high-mass end, the slope is $dN/dL \propto L^{-1.98\pm0.08}$, very close to the "canonical" $\alpha = -2$ value for the MF in young cluster systems. Similar results have been found for many other GC systems (Harris & Pudritz 1994, Larsen et al. 2001), although the exact slope evidently depends on the mass range over which the fit is carried out. The detailed behaviour of the GCLF below the turn-over is less well constrained, which is unfortunate since this is where the MFs of young and old cluster systems differ. It probably cannot yet be ruled out that some variations are present. In the case of the Sombrero galaxy, the fit in Fig. 2 indicates an essentially flat distribution, but possibly slightly steeper for the Milky Way.

3.1. Radial Trends (or lack thereof)

Fig. 3 shows the Sombrero galaxy GCLF in three radial bins, corresponding roughly to (projected) galactocentric distances of $0 < R < 5$ kpc, $5 < R < 10$ kpc and $R > 10$ kpc. It is clear that the GCLF does not change much with radial distance, although a visual inspection of the histograms might suggest a slight shift of the peak towards fainter magnitudes in the outer bins. However, differences in the turn-over are not statistically significant (Spitler et al. 2006)

Although it has long been clear that dynamical evolution will lead to preferential survival of star clusters with certain combinations of mass and size (e.g. Fall & Rees 1977), this invariance of the GCLF with galactocentric radius is a challenge in most models for the dynamical evolution of the MF. Qualitatively, most models develop a bend or turn-over as the low-mass clusters disrupt, but disruption should be more effective closer to the centre, invariably leading to a decrease in turn-over mass with galactocentric distance. Fall & Zhang (2001) found that the absence of a significant radial trend in the Milky Way GCLF turn-over could be explained if the velocity distribution becomes more radially anisotropic with galactocentric distance. However, the required degree of radial anisotropy is inconsistent with the observed GC kinematics, although the authors argued that an initial population of GCs on highly radial orbits might have been disrupted by now. In their model the cluster disruption time scales linearly with mass (i.e. $\gamma = 1$), contrary to the empirical findings of Boutloukos & Lamers (2003) and Gieles et al. (2005) and the N-body simulations of Baumgardt & Makino (2003). For the GC system of M87, Vesperini et al. (2003) again found that the observed constancy of the GCLF turn-over requires strongly radial orbits beyond a few kpc, at odds with kinematic data (Côté et al. 2001).

One shortcoming of many models is the assumption of a single concentration parameter. In fact, for GCs in the Milky Way the concentration parameter

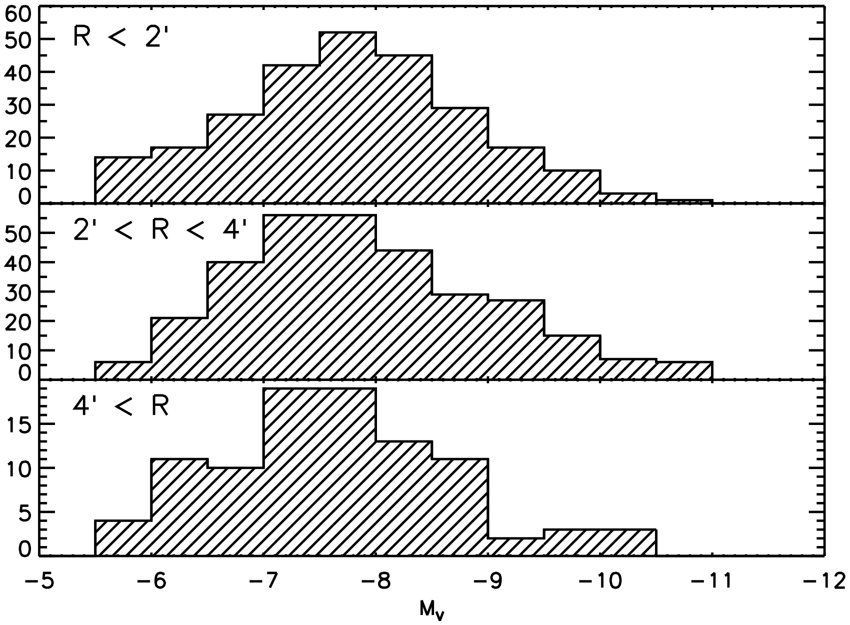

Figure 3. Luminosity function for GCs in the Sombrero galaxy in three radial bins. At a distance of 9.0 Mpc, the bins correspond to $0 < R < 5.2$ kpc, $5.2 < R < 10.4$ kpc and $R > 10.4$ kpc. There is no statistically significant difference between the GCLFs in the three bins.

displays a correlation with M_V magnitude. Fig. 4 shows the King (1966) concentration parameter W_0 versus M_V for the Galactic GCs. While there is a significant scatter in W_0 at any given M_V, there is also a clear trend of decreasing concentration for fainter clusters. Vesperini & Zepf (2003) found that early stellar mass loss may lead to disruption of low-concentration clusters, causing a turn-over in the MF at about the right mass. Since this early disruption is mainly driven by processes internal to the cluster, the lack of dependence on external parameters would be naturally explained. However, a detailed study of this effect on the time evolution of the MF is yet to be carried out.

3.2. Departures from a Universal GCLF?

Although the previous paragraphs have stressed the similarity of the GCLF in different environments, there are some hints that the GCLF may not be truly universal. As already noted, the GCLF in the outer part of the Milky Way halo shows some differences with respect to the canonical shape illustrated in Fig. 2 and appears skewed towards fainter luminosities. A similar effect may be present in the sample of GCs in dwarf galaxies studied by Sharina et al. (2005). In a sample of five spiral galaxies, Chandar, Whitmore, & Lee (2004) noted an excess of faint, red star clusters in M101 and, perhaps, NGC 6946. In the case of M101 this excess was confirmed by Barmby et al. (2006), but these authors

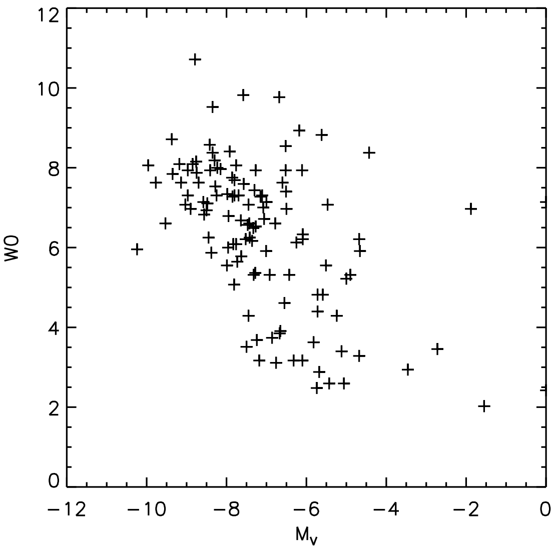

Figure 4. Concentration parameter versus M_V magnitude for Milky Way globular clusters [data from Harris (1996)].

suggested that many of the fainter clusters might be reddened young objects masquerading as old GCs. Further data will be needed before a clear picture emerges.

Other important clues to the role of disruption processes in shaping the GCLF may come from the populations of faint extended star clusters recently discovered in several S0-type galaxies (Larsen & Brodie 2000, Larsen et al. 2001, Peng et al. 2006). These clusters have disk-like orbits (at least in one case; Brodie & Larsen 2002) and spatial distributions and effective radii of 7–15 pc, much larger than the $\sim$ 3 pc typical of GCs (Jordán et al. 2005). Interestingly, these objects are mostly *fainter* than the GCLF turn-over, and their LF does not display a turn-over down to the detection limit of current studies ($M_V \sim -6$). Being more extended, the two-body relaxation time will be longer, and disk-like orbits would reduce the role of disk- and bulge shocks. However, GMC encounters and spiral arm shocks might still have been important at earlier stages in the history of the host galaxies. Thus, these clusters might provide clues to both dynamical destruction processes and the evolution of S0-type galaxies.

3.3. Intermediate-age Cluster Populations

Important insight into the dynamical evolution of the MF might be gained from populations of clusters with intermediate ages (∼several Gyrs) and a small age spread. Among the best candidates for hosting such populations are remnants of major spiral-spiral mergers. These are known to produce rich populations of star clusters, although confusion with ancient GCs remains a difficulty. The nearest such system is NGC 1316, a ~ 3 Gyr old merger remnant, whose cluster population has been studied in detail by Goudfrooij et al. (2004) using deep HST/ACS imaging. The metal-poor GCs have a normal GCLF, while Goudfrooij et al. found that the metal-rich clusters (believed to have been formed in the merger) displayed a LF more consistent with a power-law down to the 50% completeness limit at $M_V \sim -6$. Only in the central regions did they see some evidence for a flattening of the GCLF at the faint end for the metal-rich GCs. This would be consistent with the expectation that dynamical processes should first start to erode the MF near the centre, but also raises the problem that a radial gradient in the GCLF in NGC 1316 would be contrary to observations of old GCs and the early disruption scenario of Vesperini & Zepf (2003). So the implications for understanding the evolution of the GCLF are unclear.

Another candidate for hosting an intermediate-age cluster population is M82. Based on HST $BVIJH$ imaging, de Grijs, Bastian, & Lamers (2003b) derived ages of about 1 Gyr for clusters in the "fossil starburst" region B. Their derived MF displays a turn-over at $10^{5.3} M_\odot$ which they could not explain as a result of dynamical evolution from a power-law CIMF, thus suggesting that the CIMF may have been approximately log-normal. However, since M82 is seen nearly edge-on the extinction correction remains a concern, and another question is whether a starburst would still remain observable as a coherent region after ~ 1 Gyr. HST U-band observations are currently under way (P.I. L. Smith), and should help resolve the issue.

In summary, studies of intermediate-age cluster systems, while potentially promising, have not yet solved the problem of whether or not a power-law CIMF can evolve towards the mass function of old GCs.

4. Summary and Outlook

For several decades it has been clear that a star cluster, even if left in isolation, will gradually disrupt as the velocity distribution approaches a Maxwellian form and stars in the high-velocity tail escape. This process can be greatly accelerated in the presence of external perturbations such as the tidal field of the host galaxy, or tidal shocks from encounters with bulges, disks, spiral arms and/or GMCs. In the context of this meeting, it is also worth emphasising that stellar mass loss may play an important part for the dynamical evolution of star clusters, especially in the earliest stages.

There is now excellent agreement between the observed mass- and age distributions of open clusters in the Milky Way and theoretical predictions, assuming evolution from an initial power-law mass function. It also appears that we are well under way to understanding differences in disruption time-scales in different environments. However, explaining the mass distribution of ancient globular clusters remains an unsolved problem, and this is probably where most work lies in the future. Once again, the effect of stellar mass loss may turn out to be important, possibly in combination with a more realistic treatment of the structural properties of star clusters. An additional complication is that ancient GCs are subject to destruction mechanisms which are unimportant for star clusters forming today and evolving in disk galaxies (bulge, disk shocks), while in contrast the role of other mechanisms which may now be important (spiral arm passages, GMC encounters) is difficult to assess for GCs.

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