Dynamical Evolution of Dense Stellar Systems
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Why Haven't Loose Globular Clusters Collapsed yet?

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Abstract. We report on the discovery of a surprising observed correlation between the slope of the low-mass stellar global mass function (GMF) of globular clusters (GCs) and their central concentration parameter $c = \log(r_t/r_c)$, i.e. the logarithmic ratio of tidal and core radii. This result is based on the analysis of a sample of twenty Galactic GCs, with solid GMF measurements from deep HST or VLT data, representative of the entire population of Milky Way GCs. While all high-concentration clusters in the sample have a steep GMF, low-concentration clusters tend to have a flatter GMF implying that they have lost many stars via evaporation or tidal stripping. No GCs are found with a flat GMF and high central concentration. This finding appears counter-intuitive, since the same two-body relaxation mechanism that causes stars to evaporate and the cluster to eventually dissolve should also lead to higher central density and possibly core-collapse. Therefore, severely depleted GCs should be in a post core-collapse state, contrary to what is suggested by their low concentration. Several hypotheses can be put forth to explain the observed trend, none of which however seems completely satisfactory. It is likely that GCs with a flat GMF have a much denser and smaller core than suggested by their surface brightness profile and may well be undergoing collapse at present. It is, therefore, likely that the number of post core-collapse clusters in the Galaxy is much larger than thought so far.

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The dynamical evolution of globular clusters (GCs) is governed by the two-body relaxation process, whereby stars exchange energy via repeated distant encounters (see Spitzer 1987 and Elson, Hut & Ingaki 1987 for a review). Two-body encounters lead to the expansion of the outer regions of the cluster, while driving the stellar density in the central regions to increase dramatically towards an infinite value during the so-called core-collapse. The most visible effect of core-collapse is the appearance of a central cusp in the surface brightness profile of the cluster (Djorgovski & King 1986) and, correspondingly, an increase in the central concentration parameter $c = \log(r_t/r_c)$, i.e. the logarithmic ratio of tidal and core radii. Therefore, c has traditionally been seen as a gauge of the dynamical state of a cluster, with values of c in excess of ~ 2 indicating a post-core-collapse phase (Djorgovski & Meylan 1993; Trager, Djorgovski & King 1995).

Besides driving a cluster towards core-collapse, equipartition of energy through two-body relaxation also alters over time the mass distribution. More massive stars tend to transfer kinetic energy to lighter objects and sink towards the cluster centre, while less massive stars migrate outwards. The resulting mass segregation implies that the local stellar mass function (MF) within a cluster changes with time and place. Even if the stellar initial mass function (IMF) was the same everywhere when the cluster formed (a condition that does not seem to be true in some very young rich clusters where more massive stars are already more centrally concentrated; see e.g. Sirianni *et al.* 2002), after a few relaxation times there will be proportionately more low-mass stars in the cluster periphery and proportionately less in the core. The first tentative evidence of mass segregation in 47 Tuc (Da Costa 1982) has been fully confirmed by early HST observations in this and other clusters (see e.g. Paresce, De Marchi & Jedrzejewski 1995; De Marchi & Paresce 1995) and is now acknowledged in all observed GCs.

Finally, another important effect of the two-body relaxation process is that it drives the velocity distribution towards a Maxwellian and, therefore, an increasing number of stars in the tail of the velocity distribution will acquire enough energy to exceed the escape velocity and leave the cluster. This phenomenon, called evaporation, happens even in an isolated cluster, but its extent is greatly enhanced by the presence of the tidal field of the Galaxy, in a way that depends on the cluster's orbit. Evaporation, coupled with tidal truncation, is the leading cause of mass loss for most GCs after the first few billion years of their formation (see e.g. Gnedin & Ostriker 1997) and causes a preferential loss of low-mass stars, since these have typically higher velocities. The result is a selective depletion at the low-mass end of the cluster's stellar global MF (GMF). This effect, integrated over the orbit and time, implies a progressive departure of the GMF from the stellar IMF (Vesperini & Heggie 1997), namely a flattening at low masses that is now well established observationally (De Marchi *et al.* 1999; Andreuzzi *et al.* 2001; Koch *et al.* 2004; De Marchi, Pulone & Paresce 2006; De Marchi & Pulone 2007).

It would, therefore, appear natural to expect that, as clusters evolve dynamically, the increase in their central concentration should correspond to the flattening of their GMF, as both effects result from the same two-body relaxation process. To test this hypothesis, we have built a sample of 20 GCs for which reliable estimates exist of both c and the shape of the GMF (see De Marchi, Paresce & Pulone 2007 for details). The former comes from accurate surface photometry (Harris 1996), while the latter has been determined by us using high-quality HST and VLT photometry as briefly explained here below.

In order to obtain the GMF of a cluster, one would need to measure the MF of its entire stellar population, since MF measurements limited to a specific location need to be compensated for the effects of mass segregation. We have shown, however, that if the MF is measured at various locations inside the cluster (e.g. near the core, at the half-light radius and in the periphery), the GMF can effectively be derived by constraining a model MF to reproduce simultaneously three observables: the radial variation of the MF, the surface brightness profile and the velocity dispersion profile. Details on how this is done, using multi-mass Michie–King models, can be found in De Marchi *et al.* (2006) and references therein. Our analysis of clusters with an almost complete radial coverage of the MF (De Marchi *et al.* 2006; De Marchi & Pulone 2007) proves the long cherished belief that the local MF near the half-light radius is for all practical purposes indistinguishable from the GMF (Richer *et al.* 1991; De Marchi & Paresce 1995; De Marchi, Paresce & Pulone 2000).

In this work we have limited our analysis of the GMF to the mass range 0.3–0.8 $M_\odot$, in which a power-law distribution of the type $dN/dm \propto m^\alpha$ appears to adequately reproduce the observations. This choice of the mass range is dictated by the fact that below $\sim 0.3\,M_\odot$ the GMF of GCs departs from a simple power-law (see Paresce & De Marchi 2000 and De Marchi, Paresce & Portegies Zwart 2005) and, more importantly, because the number of clusters with reliable photometry at those masses is still limited.

In Fig. 1 we show the run of the GMF index α as a function of c for the clusters in our sample, as indicated by the labels. Besides the 20 GCs mentioned above (see De Marchi, Paresce & Pulone 2007 for details on the sample), we have also included in Fig. 1 the old open clusters NGC 188 and M 67 (NGC 2682), whose values of c and α (for stars in the range 0.6–1.2 $M_\odot$) were derived from the photometric studies of Stetson, McClure & VandenBerg (2004) and Fan *et al.* (1996), respectively.

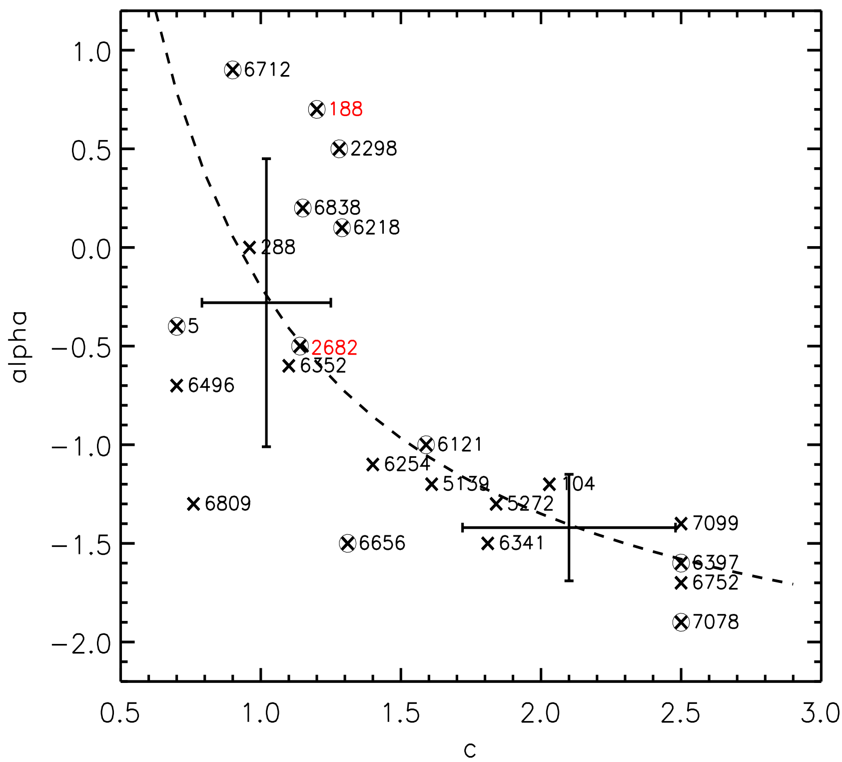

Figure 1. Observed trend between MF index α and the central concentration parameter c. Clusters are indicated by their NGC (or Pal) index number. Objects for which a GMF index is available are marked with a circled cross. For all others, the value of α is that of the MF measured near the half-light radius.

It is immediately obvious that the data do not follow the expected correlation or trend between increasing central concentration and flattening GMF mentioned above, as there are no high-concentration clusters with a shallow GMF. The median value of c (1.4) splits the cluster population roughly in two groups, one with lower and one with higher concentration. The mean GMF index of the first group is $\alpha = -0.3 \pm 0.7$, while the second has a much tighter distribution with $\alpha = -1.4 \pm 0.3$ (see large thick crosses in Fig. 1). The relationship $\alpha + 2.5 = 2.3/c$, shown as a dashed line in Fig. 1, is a simple yet satisfactory eye-ball fit to the distribution.

Fig. 1 suggests that a relatively low concentration is a necessary condition (although probably not also a sufficient one) for a depleted GMF. It appears, therefore, that mass loss, even severe, via evaporation and tidal truncation has not triggered core-collapse for low-concentration clusters (hence the title of this contribution). This finding is unexpected and counter-intuitive. Although no satisfactory explanation presently exists for the observed behavior, we briefly address here below some hypotheses. Some of the ideas put forth here are still preliminary, as they emerged from discussions during this Symposium.

IMF variations could explain the existence of clusters with a very depleted GMF and a loose core. Some clusters with shallow IMF have undergone severe stellar mass-loss and have therefore expanded considerably. This has led to a lower c and a shallower GMF because puffed-up systems of this type were more prone to tidal truncation. Most of these

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clusters have already disrupted but some survive for a long time in a state of low c and large α. This hypothesis, however, does not explain the absence of clusters with a dense core and a shallow GMF, as the most massive clusters with an originally shallow IMF should have long collapsed and still be visible in the upper-right portion of Fig. 1.

Alternatively, it is possible that the clusters with a depleted GMF and a loose core have in fact undergone core-collapse and have already recovered a normal radial density and surface brightness profile. Core re-expansion thanks to the energy released by hardening binaries has long been predicted (Hut 1985). However, the timescale for re-expansion, at least according to the predictions of Murphy, Cohn & Hut (1990), seems too long to account for the observed distribution. It is more likely that burning of primordial binaries may have halted the collapse altogether. Calculations by Trenti (2007; 2008) suggest that a binary fraction $\gtrsim 10\,\%$ in the core of loose clusters could be sufficient to avoid their collapse, without preventing further mass loss via evaporation or tidal stripping. This explanation seems particularly appealing in light of the discovery that many loose clusters appear to have a significant ($\gtrsim 6\,\%$) binary fraction in their cores (Sollima *et al.* 2007). However, the problem remains that some of the most depleted objects in the upper-left quadrant of Fig. 1 have too narrow a main sequence in the colour–magnitude diagram to account for a binary fraction in excess of a few percent (Pulone & De Marchi, in preparation; see also Davis & Richer 2008).

Another explanation for the depleted clusters with a loose core is that proposed by Kroupa (2008) and Baumgardt (2008), in which the low concentration is the result of rapid gas expulsion from the cores of primordially segregated clusters in the early phases of their lives. Such a violent process would deplete the low-mass end of the GMF and could leave the GCs in an almost collisionless state, in which further dynamical evolution via two-body relaxation is prevented. The problem with this scenario, however, is how to explain why even the most depleted clusters such as NGC 2298 or NGC 6218 are in a condition of energy equipartition (De Marchi & Pulone 2007; De Marchi *et al.* 2006), unless the observed mass stratification is the residue of primordial segregation.

The apparently simple dependence of α from c in Fig. 1 might also suggest that the observed distribution in practice represents an evolutionary sequence. In this scenario, the value of c at the time of cluster formation determines its evolution along two opposite directions of increasing and decreasing concentration. Clusters born with sufficiently high concentration ($c \gtrsim 1.5$) evolve towards core-collapse. Mass loss can be important via stellar evolution in the first ~ 1 Gyr, and to a lesser extent via evaporation or tidal stripping throughout the life of the cluster, but the GMF at any time does not depart significantly from the IMF. Clusters with $c \lesssim 1.5$ at birth also evolve towards core-collapse, but mass loss via stellar evolution and, most importantly, via relaxation and tidal stripping proceeds faster, particularly if their orbit has a short perigalactic distance or frequent disc crossings. Therefore, as the tidal boundary shrinks and the cluster loses preferentially low-mass stars, the GMF progressively flattens. This speeds up energy equipartition, but c still decreases, since the tidal radius shrinks more quickly than the luminous core radius (although the central density, particularly that of heavy remnants, is increasing). These clusters could eventually undergo core-collapse, but this might only affect a few stars in the core, thereby making it observationally hard to detect. The signature of core-collapse might only be present and should therefore be searched in the radial distribution of heavy remnants (Mark Gieles, private communication).

In summary, while no conclusive explanation still exists for the unexpected observed trend between central concentration and shape of the GMF, Fig. 1 should serve as a warning that the surface brightness profile and the central concentration parameter of GCs are not as reliable indicators of their dynamical state as we had so far assumed. In fact, if a central cusp in the surface brightness profile were the signature of a cluster's post core-collapse phase, it would be hard to explain why only about 20 % of the Galactic GCs show a cusp when the vast majority of them are an order of magnitude older than their half-mass relaxation time (Ivan King, private communication). Our current estimate of the fraction of post core-collapse clusters may therefore need a complete revision as a large number of them may be lurking in the Milky Way. A more reliable assessment of a cluster's dynamical state requires the study of the complete radial variation of its stellar MF and of the properties of its stellar population, particularly in the core.

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