Evidence for two populations of Galactic globular clusters from the ratio of their half-mass to Jacobi radii

Holger Baumgardt,1⋆ Geneviève Parmentier,1,2 Mark Gieles3 and Enrico Vesperini4

1Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
2Institute of Astrophysics & Geophysics, University of Liège, Allée du 6 Août 17, B-4000 Liège, Belgium
3European Southern Observatory, Casilla 19001, Santiago 19, Chile
4Department of Physics, Drexel University, Philadelphia, PA 19104, USA

Accepted 2009 September 21. Received 2009 August 28; in original form 2009 July 8

ABSTRACT
We investigate the ratio between the half-mass radii $r_h$ of Galactic globular clusters and their Jacobi radii $r_J$ given by the potential of the Milky Way and show that clusters with galactocentric distances $R_{GC} > 8$ kpc fall into two distinct groups: one group of compact, tidally underfilling clusters with $r_h/r_J < 0.05$ and another group of tidally filling clusters which have $0.1 < r_h/r_J < 0.3$. We find no correlation between the membership of a particular cluster in one of these groups and its membership in the old or younger halo population. Based on the relaxation times and orbits of the clusters, we argue that compact clusters and most clusters in the inner Milky Way were born compact with half-mass radii $r_h < 1$ pc. Some of the tidally filling clusters might have formed compact as well, but the majority likely formed with large half-mass radii. Galactic globular clusters therefore show a similar dichotomy as was recently found for globular clusters in dwarf galaxies and for young star clusters in the Milky Way. It seems likely that some of the tidally filling clusters are evolving along the main-sequence line of clusters recently discovered by Küpper et al. (2008) and are in the process of dissolution.

Key words: globular clusters: general.

1 INTRODUCTION
It is well known that most, if not all, stars form in star clusters. Star clusters are therefore important probes of the star formation process (Kroupa 2005; Parmentier 2009). This is especially the case for globular clusters which, due to their large ages and low metallicities, are relics of star formation processes in the early universe.

Observations show that in nearby galaxies star clusters form compact, with half-mass radii of $r_h < 1$ pc, at the centres of giant molecular cloud cores (Lada & Lada 2003). They then undergo a significant expansion as a result of gas expulsion driven by stellar winds and UV radiation from bright stars and supernovae explosions (Hills 1980; Bastian & Goodwin 2006; Baumgardt & Kroupa 2007) and later also by mass loss from stellar evolution (Chernoff & Weinberg 1990; Fukushima & Heggie 1995; Vesperini & Zepf 2003). As a result, the radii of star clusters show a steady increase with cluster age within the first 20 Myr (Bastian et al. 2008; Pfalzner 2009).

Globular clusters are dynamically evolved systems, so in addition to the early evolution due to gas expulsion and stellar evolution, cluster radii are also subject to dynamical cluster evolution due to two-body relaxation. As a result of mass segregation and core collapse, the core radius shrinks while the half-mass radius stays roughly constant before core collapse. After core collapse, stellar binaries provide a central heat source and the cluster expands self-similarly (Goodman 1984; McMillan, Hut & Makino 1990; Gao et al. 1991; Giersz & Heggie 1994; Baumgardt, Hut & Heggie 2002; Heggie, Trenti & Hut 2006). This process continues until the cluster runs into the external tidal field, at which point cluster expansion is balanced by the loss of outer stars over the tidal boundary. As a result, the ratio of half-mass radius to Jacobi radius $r_h/r_J$ evolves along a common sequence which, at least for single-mass clusters, depends only on current cluster mass (Küpper, Kroupa & Baumgardt 2008). The ratio of the half-mass to Jacobi radius for individual clusters therefore contains important information on the dynamical state of a star cluster.

In the current paper, we examine the distribution of half-mass to Jacobi radii of Galactic globular clusters in order to better understand the formation and evolution of Galactic globular clusters. The paper is organized as follows. In Section 2, we present the data and show that outer globular clusters fall into two distinct groups. In Section 3, we discuss the relation of these groups to different subsamples of Galactic globular clusters like old and younger halo

⋆E-mail: holger@astro.uni-bonn.de

1 Throughout the paper, we will denote the distance from the centre of a star cluster to the first Lagrangian point as the Jacobi radius $r_J$, while the term tidal radius $r_t$ refers to the limiting radius of King (1962) or King (1966) models.
clusters or globular clusters believed to be accreted from dwarf galaxies and use additional information like half-mass relaxation times and cluster orbits to determine the degree of dynamical cluster evolution. In Section 4, we finally draw our conclusions.

2 GLOBULAR CLUSTER DATA

In order to investigate the degree of tidal filling, one has to obtain an estimate of the Jacobi radius of a cluster. Most investigations so far used the tidal radius \( r_t \) obtained by fitting the observed surface density profile with an empirical profile like King (1962) or a theoretical one like King (1966) as an estimate of the Jacobi radius. Surface density data for most globular clusters is however either not available near the Jacobi radius or becomes unreliable in the outer parts due to the low number of cluster stars and the uncertain density of background stars. In addition, due to the high number of stars, surface densities can be much better determined in the inner cluster parts, so that the published tidal radii \( r_t \) of globular clusters are determined more by the density profile inside a few half-mass radii and might not reflect the true tidal radius of a cluster. Baumgardt et al. (2009), for example, found that in case of NGC 2419 the best-fitting King model has a nominal tidal radius of 150 pc, while they estimated that the Jacobi radius \( r_J \) of the cluster is around 800 pc.

An additional problem of fitting King models to determine Jacobi radii is depicted in Fig. 1. This figure shows the ratio between the projected half-mass radius and the tidal radius \( r_{hp}/r_t \). The main disadvantage is that the Jacobi radius varies along the line connecting the Lagrangian points:

\[
\frac{r_{hp}}{r_t} = \left( \frac{G M_c}{2 V^2_{GC}} \right)^{1/3} R_{GC}^{2/3}.
\]

Here \( M_c \) is the mass of the cluster, \( V_{GC} \) the circular velocity of the galaxy and \( R_{GC} \) the distance of the cluster from the galactic centre. We assumed a spherically symmetric density distribution for the Milky Way with a constant circular velocity of \( V_{GC} = 220 \text{ km s}^{-1} \). Cluster masses were calculated from the absolute luminosities of the clusters and an assumed \( V_- \) band mass-to-light ratio of \( M/L_V = 2.0 \). The cluster data (projected half-light radii, total luminosities, galactocentric distances) were taken from the 2003 version of the globular cluster data base of Harris (1996), supplemented by additional data for a few clusters from Bonatto & Bica (2008). We exclude Omega Cen, M54 and NGC 2419 from our analysis since these clusters might be stripped nuclei of dwarf galaxies rather than genuine globular clusters.

Fig. 2 depicts the ratio of 3D half-mass radius \( r_{hp} \) to Jacobi radius \( r_J \) as a function of galactocentric distance. It can be seen that the distribution of Galactic globular clusters is not uniform in this plane. First, clusters with large values of \( r_{hp}/r_J > 0.5 \) are basically absent. Since such clusters would be subject to strong tidal forces and have consequently small dissolution times, if they ever existed they should be quickly destroyed and not be present any more after
Figure 2. Ratio of half-mass radius $r_h$ to Jacobi radius $r_J$ as a function of galactocentric distance $R_{GC}$ for Galactic globular clusters. It can be seen that clusters outside $R_{GC} = 8$ kpc fall into two distinct groups, clusters with $r_h/r_J < 0.05$ and clusters with $0.07 < r_h/r_J < 0.3$. The dashed line depicts the position that an $M_e = 10^5 M_\odot$ with $r_h = 3$ pc would have at different galactocentric distances. Compact clusters outside 8 kpc and most clusters inside this radius fall on to this line.

| Name             | $r_h$ (pc) | $r_h/r_J$ | $M_e$ (M$_\odot$) | $T_{RH}$ (yr) | $R_{GC}$ (kpc) | $R_{Per}$ (kpc) |
|------------------|------------|-----------|-------------------|---------------|----------------|-----------------|
| NGC 362          | 2.67       | 0.023     | 5.60              | 9.09          | 9.4            | 0.8             |
| NGC 1261         | 4.77       | 0.032     | 5.36              | 9.37          | 18.2           |                 |
| Pal 2            | 7.17       | 0.029     | 5.44              | 9.67          | 35.4           |                 |
| NGC 1851         | 2.44       | 0.015     | 5.57              | 9.02          | 16.7           | 5.7             |
| NGC 1904         | 4.00       | 0.026     | 5.38              | 9.27          | 18.8           | 4.2             |
| NGC 2298         | 3.24       | 0.038     | 4.75              | 8.87          | 15.7           | 1.9             |
| NGC 2808         | 2.83       | 0.016     | 5.99              | 9.29          | 11.1           | 2.6             |
| NGC 3201         | 5.20       | 0.062     | 5.22              | 9.37          | 8.9            | 9.0             |
| NGC 4147         | 3.22       | 0.032     | 4.70              | 8.85          | 21.3           | 4.1             |
| NGC 4590         | 6.13       | 0.070     | 5.17              | 9.46          | 10.1           | 8.6             |
| NGC 5024         | 7.66       | 0.039     | 5.71              | 9.83          | 18.3           | 15.5            |
| NGC 5272         | 4.52       | 0.028     | 5.81              | 9.52          | 12.2           | 5.5             |
| NGC 5286         | 2.94       | 0.026     | 5.68              | 9.19          | 8.4            |                 |
| NGC 5634         | 5.28       | 0.033     | 5.31              | 9.42          | 21.2           |                 |
| NGC 5694         | 4.44       | 0.022     | 5.36              | 9.32          | 29.1           |                 |
| NGC 5824         | 4.47       | 0.017     | 5.77              | 9.50          | 25.8           |                 |
| NGC 6205         | 4.45       | 0.037     | 5.71              | 9.47          | 8.7            | 5.0             |
| NGC 6229         | 4.36       | 0.020     | 5.45              | 9.35          | 29.7           |                 |
| NGC 6341         | 3.47       | 0.031     | 5.51              | 9.23          | 9.6            | 1.4             |
| NGC 6779         | 4.54       | 0.053     | 5.19              | 9.27          | 9.7            | 0.9             |
| NGC 6864         | 3.77       | 0.023     | 5.65              | 9.34          | 14.6           |                 |
| NGC 6934         | 3.65       | 0.034     | 5.22              | 9.14          | 12.8           | 6.0             |
| NGC 6981         | 5.80       | 0.062     | 5.05              | 9.37          | 12.9           |                 |
| NGC 7006         | 6.12       | 0.026     | 5.31              | 9.51          | 38.8           | 18.2            |
| NGC 7078         | 4.23       | 0.027     | 5.90              | 9.52          | 10.4           | 5.4             |
| NGC 7089         | 4.15       | 0.028     | 5.84              | 9.48          | 10.4           | 6.4             |

Table 1. Basic data for Galactic globular clusters with $R_{GC} > 8$ kpc belonging to both groups.

The dashed line in Fig. 2 depicts the position which an $M_e = 10^5 M_\odot$ with $r_h = 3$ pc would have in the $r_h/r_J$ versus $R_{GC}$ plot at different galactocentric distances. It can be seen that clusters in the lower group outside 8 kpc and most clusters inside this radius fall on to this line. Most clusters in the lower group are therefore relatively massive and compact, something which can also be seen in Table 1. Clusters in the upper group strongly feel the tidal field of the Galaxy. It can be seen that this group is more diverse since it

10 Gyr of evolution. The absence of such clusters in our distribution therefore serves as a sanity check of our method.

Secondly, most clusters inside $\sim 8$ kpc exhibit a relatively broad distribution of $r_h/r_J$ values between 0.02 < $r_h/r_J < 0.2$ without any noticeable separation. Outside about 8 kpc, the Galactic globular clusters can be split into two groups, one group of clusters with $r_h/r_J < 0.05$ and a second group of clusters with $0.08 < r_h/r_J < 0.3$. A Kolmogorov–Smirnov (KS) test gives only a 14 per cent chance that clusters beyond 8 kpc follow a lognormal distribution in $\log r_h/r_J$. In addition, the average mass of extended clusters in the outer Milky Way is significantly lower than the mass of the more compact clusters (see Fig. 4), the mean mass of compact clusters is $\log M_e = 5.44 \pm 0.11$ while the extended group has a mean mass of only $\log M_e = 4.38 \pm 0.06$. Both results indicate that two distinct groups of globular clusters exist in the Milky Way. The dividing line between both groups seems to be around $r_h/r_J = 0.07$ and Table 1 lists the basic parameters of clusters having $r_h/r_J$ ratios smaller or larger than this value. Different orbits seem unlikely to be an explanation for this dichotomy since clusters of both groups are located within the same interval of galactocentric distances and, at least for those clusters with orbital information, the average ratios of $R_{GC}/R_{Per}$ are similar.
is made up of massive and extended as well as low-mass compact clusters. In the following, we will discuss possible reasons for the origin of both groups.

3 DISCUSSION

3.1 Correlation with old and younger halo membership

The Galactic globular cluster system consists of different subsystems. While bulge/disc globular clusters differ from halo clusters with respect to their metallicity ([Fe/H] \geq -0.8 and [Fe/H] < -0.8, respectively), the halo subsystem itself is made of clusters with more than one origin. It is traditionally split up into two groups, referred to as the old halo and the younger halo (van den Bergh 1993; Zinn 1993; Mackey & Gilmore 2004), based on differences in horizontal branch (HB) morphology, age, kinematics and spatial distribution (see Parmentier et al. 2000, their section 2, for a review). Because of their predominant location beyond the solar circle, Young Halo (YH) clusters are assumed to have been accreted – along with the dwarf galaxies which used to host them – after the main body of the Galaxy was built up. Depending on how late they were accreted into the Galactic halo, their evolutionary history may be different from what in situ Old Halo (OH) clusters have experienced in the Milky Way tidal field. The current accretion of the Sagittarius dwarf galaxy and of its small globular cluster system is the smoking gun of this process (Ibata, Gilmore & Irwin 1994).

In Fig. 3, data points are symbol-coded to highlight these different cluster origins. Filled circles depict disc globular clusters ([Fe/H] \geq -0.8), open triangles show globular clusters associated to the merging dwarf galaxy Sagittarius (Ter7, Arp2, Ter8, Pal12, NGC4147; see Da Costa & Armandroff 1995; Martinez-Delgado et al. 2002 and Bellazzini et al. 2003 for cluster membership). Plus signs stand for globular clusters with no HB morphology index. A list of OH clusters (filled squares) is provided in Parmentier & Grebel (2005, their table 1). Other clusters are sorted in the YH group (open squares). Mackey & Gilmore (2004) emphasize that accreted clusters could also contribute a small fraction of the OH component. Based on either large core radius reminiscent of those observed for globular clusters in satellite galaxies (their fig. 16) or spatial motions more typical of YH objects (see also Dinescu, Girard & van Altena 1999), they identify 11 OH globular clusters which might have been accreted (NGC 6809, 6101, 7492, 5897 and Pal 15 in the first category and NGC 1904, 2298, 5024, 5904, 6205, 7089 in the second category). These ill-defined status clusters are shown as filled squares with open circles in Fig. 3. Clusters from Bonatto & Bica (2008) are finally shown as filled triangles.

It can be seen that there is no correlation among the classification of a cluster into either younger or old halo group and its \(r_h/r_J\) value. The compact cluster group contains 11 younger halo clusters and 10 old halo clusters unsuspected of having been accreted. They represent each \(\sim 40\) per cent of the total number of clusters (26) in the compact cluster group. The tidally filling cluster group contains 10 younger halo clusters and five old halo clusters unsuspected of having been accreted. The higher fraction of younger halo clusters, however, is mostly driven by the four clusters with \(R_{GC} \sim 100\) kpc. Considering the same radial extent as for the compact group, i.e. \(R_{GC} = 8–50\) kpc, younger and old halo clusters contribute similarly to the tidally filling group, with six and five clusters, respectively, out of 22 clusters. Corresponding number fractions (\(\sim 25\) per cent) agree with the previous ones within the statistical uncertainties. Moreover, both compact and tidally filling groups are characterized by the same number fraction of clusters accreted or suspected of having been accreted (i.e. younger halo clusters or Sagittarius clusters or old halo clusters suspected of having been accreted – see above), namely, \(\sim 60\) per cent. We therefore conclude that the \(r_h/r_J\) dichotomy is not due to a different origin of the two cluster populations.

3.2 Origin of the compact cluster group

Table 1 lists the basic parameters of clusters belonging to either group, including the 3D half-mass radius, current mass and galactocentric distance. It also shows the current relaxation time, calculated according to Spitzer (1987):

\[
T_{RH} = 0.138 \frac{\sqrt{M_{\text{H}}}^{3/2}}{G(m) \ln 0.11 M_{\odot}(m)}.
\]

(2)

where \(\langle m \rangle = 0.4 M_{\odot}\) is the average mass of stars and \(G\) the gravitational constant. It can be seen that the compact clusters mostly have very large relaxation times. The average relaxation time for a cluster in this group is about 2.8 Gyr, and nearly all clusters have relaxation times larger than 1 Gyr. According to Girkan, Freitag & Rasio (2004), it takes about seven to 10 initial half-mass relaxation times until star clusters with a narrow mass spectrum where the massive stars are about twice as massive as the average cluster star, which is typical for globular clusters, have gone into core collapse. The compact clusters should therefore still be mostly in their pre-core-collapse phase and should not have started post-core-collapse expansion.

Table 1 also lists the perigalactic distances of the globular clusters as determined by Dinescu et al. (1999), Allen, Moreno & Pichardo (2006) and Casetti-Dinescu et al. (2007). Although there are clusters which have perigalactic distances of less than 2 kpc, for the majority of the compact group clusters, the perigalactic distances are within a factor of 3 of the current galactocentric distance. The estimates of \(r_J\) would therefore decrease by no more than a factor of 2 if we used the perigalactic distance to calculate \(r_J\). Most compact clusters therefore have \(r_h/r_J < 0.1\) also at perigalactic and are at most moderately influenced by the Galactic tidal field. Hence, their small half-mass radii are likely not due to tidal stripping at perigalacticon but must have been the result of the formation process.
Figure 4. Half-mass radius $r_h$ versus cluster mass for globular clusters with $R_{\text{GC}} < 8$ kpc (green triangles) and for clusters $R_{\text{GC}} > 8$ kpc that are weakly influenced by the Galactic tidal field ($r_T/r_J < 0.07$, red crosses) and for strongly tidally influenced clusters ($0.07 < r_T/r_J < 0.3$, blue dots). Clusters weakly influenced by the tidal field are all massive and compact while strongly tidally influenced clusters have significantly smaller masses. Inner clusters also have smaller masses on average, which might be a result of their stronger dissolution. Dashed lines show where clusters with a given half-mass relaxation time are located in this plot.

We conclude that clusters in the compact group also formed very compact. $N$-body simulations show that the expansion factor due to gas expulsion is typically a factor of 2–3 for moderate star formation efficiencies of 30–40 per cent (Baumgardt & Kroupa 2007), and stellar evolution will increase this value by another factor of 2 if mass is lost adiabatically. Hence, the initial half-mass radius of clusters in the compact group must have been around 1 pc or less. Since most star clusters inside 8 kpc have half-mass radii very similar to compact group star clusters, it seems likely that most globular clusters in the Milky Way formed compact and with half-mass radii of 1 pc or less, which is comparable to the half-mass radius of embedded star clusters in the Milky Way (Lada & Lada 2003).

3.3 Origin of the tidally filling cluster group

Fig. 4 depicts the position of inner clusters (green triangles) and of clusters with $r_T/r_J < 0.07$ (red crosses) and clusters with $r_T/r_J > 0.07$ (blue dots) in a half-mass radius versus mass diagram. It can be seen that clusters with $r_T/r_J < 0.07$ are mostly massive clusters with half-mass radii of a few pc, while clusters with $r_T/r_J > 0.07$ have larger radii and also smaller masses. Due to the smaller masses, clusters in the tidally filling group should on average be closer to dissolution. This is confirmed by observational data for a few clusters like Pal 5, which has very pronounced tidal tails and might be on its final orbit before dissolution (Odenkirchen et al. 2001; Dehnen et al. 2004). Clusters in the inner Milky Way also have smaller masses than compact outer clusters which might be due to stronger cluster dissolution in the inner Milky Way as a result of the stronger tidal field (Vesperini & Heggie 1997; Baumgardt & Makino 2003).

One way to explain the large radii of the tidally filling clusters would be that they also formed extended. Indeed, Elmegreen (2008) has recently discussed different modes of star formation and attributed the difference between star formation in bound clusters and loose groupings to a difference in cloud pressure and different background tidal forces. This could explain why clusters with low densities are only found far away from the centres of major galaxies or in dwarf galaxies. The fact that Milky Way globular clusters are clearly separated in $r_T/r_J$ is however more difficult to understand if cluster radii are set at formation time. An alternative viewpoint would be that the tidally filling clusters expanded from smaller radii, possibly, for example, through post-collapse expansion driven by a population of stellar binaries in the cluster core. Goodman (1984) and Baumgardt et al. (2002) (their equation 4) estimated that during post-core-collapse expansion, the half-mass radius of an isolated cluster satisfies

$$r_h(t) = r_{h0} \left( \frac{t}{\tau_{\text{cc}}} \right)^{3(2+v)/3},$$

where $r_{h0}$ is the initial half-mass radius, $\tau_{\text{cc}}$ the time of core collapse and $v \approx 0.1$ a constant related to the cluster mass loss. Gieles & Baumgardt (2008) found that the above relation also holds for clusters in a tidal field as long as $r_T/r_J < 0.05$. For clusters with a narrow mass spectrum, core collapse happens after seven to 10 initial half-mass relaxation times (Gürkan et al. 2004), in which case the above relation would predict that expanding clusters should have relaxation times which are roughly 1/10th of their current age, i.e. of the order of $T_{\text{BH}} \approx 10^3$ yr. The majority of clusters in the tidally filling group however have relaxation times $T_{\text{BH}} > 3 \times 10^9$ yr, which is too large to be explained by binary-driven expansion from small radii. Also the fact that tidally filling clusters have on average larger relaxation times than compact clusters argues against post-collapse expansion from smaller radii.

Merritt et al. (2004) and Mackey et al. (2007) have shown that stellar mass black holes (BHs), if present in sufficient numbers, can cause strong cluster expansion. For clusters retaining all the black holes formed in them, Mackey et al. (2008) found that the core radius can reach values up to 8 pc after 10 Gyr of evolution and is almost as large as the half-mass radius. This value is large enough to explain the half-mass radii of a significant fraction of clusters in the tidally filling group (see Fig. 4). Interestingly, in such a case clusters of the tidally filling group would have been the most compact clusters initially such as to be able to retain their BHs. However, some clusters in the tidally filling group have half-mass radii too large to be explained by BH-driven expansion and there is no significant difference in metallicity between compact and tidally filling clusters, as might be expected if BH kick velocities depend on metallicity, which both argue against BH-driven expansion. Central intermediate-mass black holes can also act as an efficient heat source, but judging from the results of Baumgardt, Makino & Ebisuzaki (2004), the half-mass radii of most clusters in the tidally filling group are too large to be explained by intermediate-mass black hole driven expansion. Strong expansion is also possible by stellar evolution if star clusters are initially mass segregated since the fractional loss of potential energy can in such a case be much larger than the mass fraction lost by stellar evolution (Vesperini, McMillan & Portegies Zwart 2009).

The question of whether clusters in the tidally filling group were born compact and later expanded or already formed with the large half-mass radii we see today therefore remains open. If they formed with large half-mass radii, their initial relaxation times were also quite large and the clusters should be dynamically less evolved. In this case, they would not be mass segregated, so measuring

© 2009 The Authors. Journal compilation © 2009 RAS, MNRAS 401, 1832–1838
stellar mass functions at different radii might be one way to test the formation scenario. In this context, it is interesting to note that Jordi et al. (2009) recently found that the stellar mass function of Pal 14, which is one of the clusters with the longest relaxation time in our sample, differs from a Kroupa initial mass function inside the clusters half-mass radius. Unfortunately, no information on the stellar mass function in the outer cluster parts is available at the moment to test whether this is due to dynamical cluster evolution.

We note that the tidally filling clusters, due to the large half-mass radii and galactocentric distances of many of them, are partly responsible for driving the correlation between $r_h$ and $R_{GC}$ found by Mackey & van den Bergh (2005). A linear least-squares fit gives a relation between half-mass radius and galactocentric distance $\log r_h = 0.50 \times \log R_{GC} + 0.27$ for all Galactic globular clusters. This relation flattens to $\log r_h = 0.25 \times \log R_{GC} + 0.38$ if we exclude the tidally filling clusters, indicating that globular clusters in the compact group formed with similar parameters nearly everywhere in the Galaxy.

4 CONCLUSIONS

We have studied the distribution of the ratio of half-mass radius $r_h$ to Jacobi radius $r_J$ for Galactic globular clusters and have shown that clusters with distances larger than ~8 kpc fall into two distinct groups: One group of compact clusters with $r_h/r_J < 0.05$ and a group of more extended clusters with $0.08 < r_h/r_J < 0.30$. Compact clusters are mainly massive clusters with half-mass radii of a few pc. The half-mass radius and density of the compact clusters in the outer halo seem not to be adjusted to the Jacobi radius, so they were probably also born compact with half-mass radii $r_h < 1$ pc, comparable to the half-mass radii of embedded clusters and young open clusters in the Milky Way. Tidal radii derived from fitting King profiles to the surface density profiles of these clusters can be significantly smaller than their Jacoby radii since the $r_h/r_J$ ratios of these clusters are smaller than what can be reached with any King profile.

Some of the tidally filling clusters might also have formed compact and could have expanded later due to dynamical heating by binary stars, stellar-mass black holes or intermediate-mass black holes, although it is unclear if this holds for all clusters in this group since about half of the tidally filling clusters have relaxation times of the order of a Hubble time or larger.

Da Costa et al. (2009) have recently found a bi-modality of the globular cluster size distribution in dwarf galaxies. The average radii of clusters in both of their groups agree quite well with the radii of Milky Way globular clusters in our compact and tidally filling group, showing that globular clusters formed under similar conditions in different galaxies. Furthermore, Pfalzner (2009) has recently shown that open clusters in the Milky Way evolve along two sequences in the age versus radius plane, one group of clusters starting compact with half-mass radii $r_h < 1$ pc and reaching sizes of a few pc after 20 Myr of evolution and a second group of clusters starting with half-mass radii larger than a few pc and reaching ~20 pc after 20 Myr. The latter value agrees quite well with the sizes of most clusters in the tidally filling group. Galactic globular clusters therefore show the same dichotomy seen for globular clusters in dwarf galaxies and for young star clusters in the Milky Way. Extended star clusters appear therefore as an ubiquitous feature of star cluster systems hosted by a variety of galaxies. It would be interesting to see how the extended globular clusters of the Milky Way relate to other star clusters with large $r_h$ values, like the Faint Fuzzy star clusters in lenticular galaxies (Larsen & Brodie 2000), the diffuse star clusters found by Peng et al. (2006) in early-type galaxies of the Virgo cluster and those hosted by dwarf galaxies (Da Costa et al. 2009).

Küpper et al. (2008) found that initially compact star clusters in a tidal field expand after core collapse until they reach a mass-dependent $r_h/r_J$ value and then evolve along a common sequence towards dissolution. They dubbed the latter phase the main-sequence evolution of star clusters. During the main-sequence phase, the $r_h/r_J$ values increase slowly with decreasing cluster mass. Extrapolating from the results of Küpper et al. (2008) to $M^* = 10^7 M_{\odot}$, we expect that globular clusters should have approximately $r_h/r_J \approx 0.1$ when on the main sequence, which fits observed $r_h/r_J$ of clusters in the tidally filling group rather well. It is therefore likely that part of the clusters in the tidally filling group, especially those with small relaxation times, have reached the main-sequence stage of their evolution and are evolving towards dissolution. As for those with long relaxation times, however, whether their large half-mass radius is an imprint of their formation process or a result of cluster expansion remains an open question.

We finally note that it is possible that the extended clusters were initially much more numerous, since due to their large sizes, they are effectively destroyed by the Galactic tidal field, especially in the inner part of the Milky Way.

ACKNOWLEDGMENTS

We thank the referee for comments which improved the presentation of the paper. HB acknowledges support from the German Science Foundation through a Heisenberg fellowship. GP acknowledges support from the Belgian Science Policy Office in the form of a Return Grant and from the Alexander von Humboldt Foundation in the form of a Research Fellowship. EV was supported in part by NASA grant NNX08AH15G. We acknowledge the support of the KITP during the programme ‘Formation and Evolution of Globular Clusters’, which was supported in part by the United States National Science Foundation under Grant No. PHY05-51164.

REFERENCES

Allen C., Moreno E., Pichardo B., 2006, ApJ, 652, 1150
Balbinot E., Santiago B. X., Bica E., Bonatto C., 2009, MNARS, 396, 1596
Bastian N., Goodwin S. P., 2006, MNARS, 369, L9
Bastian N., Gieles M., Goodwin S. P., Trango G., Smith L. J., Konstantopoulos I., Efremov Y., 2008, MNARS, 389, 223
Baumgardt H., Makino J., 2003, MNARS, 340, 227
Baumgardt H., Kroupa P., 2007, MNARS, 380, 1589
Baumgardt H., Hut P., Heggie D. C., 2002, MNARS, 336, 1069
Baumgardt H., Makino J., Ebisuzaki T., 2004, ApJ, 613, 1143
Baumgardt H., Côté P., Hilker M., Rejkuba M., Mieske S., Djorgovski S. G., Stetson P., 2009, MNARS, 396, 2051
Bellazzini M., Ibata R., Ferraro F. R., Testa V., Constandopoulos I., Efremov Y., 2008, MNARS, 389, 223
Balbinot E., Santiago B. X., Bica E., Bonatto C., 2009, MNARS, 396, 1596
Bonatto C., Bica E., 2008, MNARS, 479, 741
Casertani-Dinescu D. I., Girard T. M., Herrera D., van Altena W. F., López C. E., Castillo D. J., 2007, AJ, 134, 195
Chernoff D. F., Weinberg M. D., 1990, ApJ, 351, 121
Da Costa G. S., Armandroff T. E., 1995, AJ, 109, 2533
Da Costa G. S., Grebel E. K., Jerjen H., Rejkuba M., Sharina M. E., 2009, AJ, 137, 436
Dehnen W., Odenkirchen M., Grebel E. K., Rix H. W., 2004, AJ, 127, 2753
Dinescu I. D., Girard T. M., van Altena W. F., 1999, AJ, 117, 1792
Elmegreen B. G., 2008, ApJ, 672, 1006
Fukugesi T., Heggie D. C., 1995, MNARS, 276, 206
Gao B., Goodman J., Cohn H., Murphy B., 1991, ApJ, 370, 567
Gieles M., Baumgardt H., 2008, MNARS, 389, 28
Giersz M., Heggie D. C., 1994, MNARS, 270, 298
Goodman J., 1984, ApJ, 280, 298
Gürkan M. A., Freitag M., Rasio F. A., 2004, ApJ, 604, 632
Harris W. E., 1996, AJ, 112, 487
Heggie D. C., Trenti M., Hut P., 2006, MNRAS, 368, 677
Hills J. G., 1980, ApJ, 235, 986
Ibata R. A., Gilmore G., Irwin M. J., 1994, Nat, 370, 194
Innanen K. A., Harris W. E., Webbink R. F., 1983, AJ, 88, 338
Jordi K., Hilker M., Baumgardt H., Frank M., Kroupa P., Haghi H., Côté P., Djorgovski S. G., 2009, AJ, 137, 4586
King I., 1962, AJ, 67, 471
King I., 1966, AJ, 71, 64
Kroupa P., 2005, in Turon C., O'Flaherty K. S., Perryman M. A. C., eds, Proc. Gaia Symp. The Three-Dimensional Universe with Gaia. ESA Publications, Noordwijk, p. 629
Küpper A. H. W., Kroupa P., Baumgardt H., 2008, MNRAS, 389, 889
Lada C. J., Lada E. A., 2003, ARA&A, 41, 57
Larsen S. S., Brodie J. P., 2000, AJ, 120, 2938
Mackey A. D., Gilmore G. F., 2004, MNRAS, 355, 504
Mackey A. D., van den Bergh S., 2005, MNRAS, 360, 631
Mackey A. D., Wilkinson M. I., Davies M. B., Gilmore G. F., 2007, MNRAS, 379, 40
Mackey A. D., Wilkinson M. I., Davies M. B., Gilmore G. F., 2008, MNRAS, 386, 65
McLaughlin D. E., van der Marel R. P., 2005, ApJS, 161, 304
McMillan S., Hut P., Makino J., 1990, ApJ, 362, 522
Martinez-Delgado D., Zinn R., Carrera R., Gallart C., 2002, ApJ, 573, 19
Merritt D., Piatek S., Portegies Zwart S., Hensendorf M., 2004, ApJ, 608, L25
Odenkirchen M. et al., 2001, ApJ, 548, L165
Parmentier G., 2009, in Röser S., ed., Rev. Modern Astron. 21. Wiley, New York, in press (arXiv:0901.3140)
Parmentier G., Grebel E. K., 2005, MNRAS, 359, 615
Parmentier G., Jehin E., Magain P., Noels A., Thoul A. A., 2000, A&A, 363, 526
Peng E. et al., 2006, ApJ, 639, 838
Pfalzner S., 2009, A&A, 498, 37
Spitzer L. Jr., 1987, Dynamical Evolution of Globular Clusters. Princeton Univ. Press Princeton
Vesperini E., Heggie D. C., 1997, MNRAS, 289, 898
Vesperini E., Zepf S. E., 2003, ApJ, 587, L97
Vesperini E., McMillan S. L. W., Portegies Zwart S., 2009, ApJ, 698, 615
van den Bergh S., 1993, ApJ, 411, 178
Wilson C. P., 1975, AJ, 80, 175
Zinn R., 1993, in Smith G. H., Brodie J. P., eds, ASP Conf. Ser. Vol. 48, The Globular Clusters-Galaxy Connection. Astron. Soc. Pac., San Francisco, p. 38

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.