High mass-to-light ratios of UCDs - Evidence for dark matter?

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ABSTRACT
Ultra-compact dwarf galaxies (UCDs) are stellar systems with masses of around $10^7$ to $10^8$ M$_{\odot}$ and half mass radii of 10-100 pc. They have some properties in common with massive globular clusters, however dynamical mass estimates have shown that UCDs have mass-to-light ratios which are on average about twice as large than those of globular clusters at comparable metallicity, and tend to be larger than what one would expect for old stellar systems composed out of stars with standard mass functions.

One possible explanation for elevated high mass-to-light ratios in UCDs is the existence of a substantial amount of dark matter, which could have ended up in UCDs if they are the remnant nuclei of tidally stripped dwarf galaxies, and dark matter was dragged into these nuclei prior to tidal stripping through e.g. adiabatic gas infall.

Tidal stripping of dwarf galaxies has also been suggested as the origin of several massive globular clusters like Omega Cen, in which case one should expect that globular clusters also form with substantial amounts of dark matter in them.

In this paper, we present collisional N-body simulations which study the co-evolution of a system composed out of stars and dark matter. We find that the dark matter gets removed from the central regions of such systems due to dynamical friction and mass segregation of stars. The friction timescale is significantly shorter than a Hubble time for typical globular clusters, while most UCDs have friction times much longer than a Hubble time. Therefore, a significant dark matter fraction remains within the half-mass radius of present-day UCDs, making dark matter a viable explanation for the elevated M/L ratios of UCDs. If at least some globular clusters formed in a way similar to UCDs, we predict a substantial amount of dark matter in their outer parts.

Key words: stellar dynamics, methods: N-body simulations, galaxies: star clusters

1 INTRODUCTION
Ultra-compact dwarf galaxies (UCDs) were discovered in the late 1990s in spectroscopic surveys of the Fornax galaxy cluster (Hilker et al. 1999; Drinkwater et al. 2000) and have since then been found in other nearby galaxy clusters as well (Hasegan et al. 2005; Mieske et al. 2005, 2007; Jones et al. 2006; Firth et al. 2007; Rejkuba et al. 2007). They are bright ($-11 < M_V < -13.5$) and compact (7 < $r_h$ < 100 pc) stellar systems which have ages of at least several Gyr and possibly up to 10 Gyr (Mieske et al. 2006; Efstathiou et al. 2007). The masses and sizes of UCDs are larger than those of Galactic globular clusters, but similar to those of nuclei in dwarf elliptical galaxies (Drinkwater et al. 2003, Bekki et al. 2003).

One of the most remarkable properties of UCDs is that their dynamical mass-to-light ratios are on average about twice as large than those of globular clusters of comparable metallicity, and also tend to be larger than what one would expect based on simple stellar evolution models that assume a standard stellar initial mass function, like e.g. Kroupa (2001), Hasegan et al. 2003, Dabringhausen, Hilker & Kroupa 2008; Mieske et al. 2008).

If not due to a failure of stellar evolution models, this points either to unusual stellar mass functions (Mieske & Kroupa 2008, Dabringhausen, Baumgardt & Kroupa 2008) or possibly to the presence of a significant amount of dark matter in UCDs. We note that most methods used to determine M/L ratios for UCDs rely on the assumptions that mass follows light and isotropic velocity dispersions. How well these assumptions are fulfilled is currently not known. Also due to the large distances of UCDs, only integrated velocity dispersions can be obtained, which in most cases are intermediate between the central and the global velocity dispersions. In
The mean mass density within the half-mass radius of Figure 1. The joint sample of GCs and UCDs from Fig. 5 is plotted vs. their approximate central \((r \lesssim 10\text{pc})\) dark matter densities expected for cuspy dwarf galaxy CDM halos (Gilmore et al. 2007).

Order to determine the mass-to-light ratio, the mass modeling has to take the density profiles of the UCDs as well as the effects of seeing and a finite slit size into account, as done for example in Hilker et al. (2007).

Several formation scenarios have been discussed for UCDs, like e.g. that UCDs are simply massive globular clusters and form in the same way (Hilker et al. 1999; Evstigneeva et al. 2007; Forbes et al. 2008), that they are the nuclei of tidally stripped, originally much more extended galaxies (Bekki, Couch & Drinkwater 2001; Bekki et al. 2003; Thomas, Drinkwater & Evstigneeva 2008; Goerdt et al. 2008), or that they are merged globular clusters (Oh & Liu 2000; Fellhauer & Kroupa 2002; Goerdt et al. 2008). They have shown that funneling of dark matter to the central region of a disk galaxy, due to gas-infall, can significantly increase the M/L ratios in the nuclear region, and hence may explain the elevated M/L ratios of UCDs, provided that UCDs formed by tidal stripping. Indeed, it has been suggested that also GCs may have originated as centers of individual primordial dark matter halos (e.g. Carraro & Lia 2000, Lee et al. 2007, Bekki et al. 2007). If dark matter funneling is an efficient mechanism (Goerdt et al. 2008), one may therefore expect both UCDs and GCs to be formed with a significant fraction of dark matter. It is important to note that such an increase of dark matter density by some kind of funneling mechanism is necessary to explain a significant amount of dark matter in UCDs or GCs, since their present-day stellar mass of GCs and UCDs is formed with the same non-zero dark-to-stellar-mass-fraction. We then investigate how the dynamical co-evolution of dark matter and stars changes the observed dark matter fraction as a function of time. We assess whether the observed rise of M/L ratios from the regime of GCs to that of UCDs can be explained by our working hypothesis and the subsequent dynamical evolution.

2 THE MODELS

In our simulations, we assume that stars and dark matter particles follow the same density distribution initially, which was given by a Plummer (1911) model. Determinations of mass-to-light ratios of globular clusters or UCDs rely mainly on stars located inside the half-mass radius (Hilker et al. 2007; Mieske et al. 2008) or even closer within (McLaughlin & van der Marel 2003). Tidal effects are therefore not likely to have a strong influence on determined mass-to-light ratios. Also, due to their high mass and corresponding large dissolution times, tidal interactions probably play only a minor role for UCDs. In our simulations we therefore neglect the influence of an external tidal field.

We assume that the stars initially follow a Kroupa (2001) mass function with lower and upper mass limits of 0.1 and 100 \(M_\odot\). Stellar evolution changes the mass function of stars, however most of this change happens within the first \(10^8\text{ yrs}\) (see e.g. the grid of models by Baumgardt & Makino (2003)), i.e. on a timescale short against the lifetime of globular clusters or UCDs. We therefore also neglect stellar evolution and immediately transform stars to the assumed age of GCs and UCDs, \(T=12\text{ Gyrs}\). For the transformation, we assume that stars with mass larger than 25 \(M_\odot\) form black holes and assume that the black hole mass is 10% of the mass of the initial star. This way, black hole masses in our models are compatible with observed masses for stellar mass black holes (e.g. Casares (2006)). Stars with masses between 8 \(M_\odot\) and 25 \(M_\odot\) are assumed to form neutron stars (e.g. Casares (2006)). Stars between 0.8 \(M_\odot\) and 8 \(M_\odot\) are assumed to form white dwarfs due to stellar evolution. The masses of the white dwarfs are obtained from Kalirai et al. (2008), who found, based on observations of white dwarfs in star clusters, the following relation between the initial and final mass of white dwarfs:

\[
m_{\mathrm{wd,rem}} = 0.109m + 0.394M_\odot
\]

Neutron stars and probably also black holes receive kicks at the time of their birth due to asymmetric supernova explosions. The size of these kicks is a few hundred km/sec (Lyne & Lorimer 1994), which is large enough that most will be lost from globular clusters or UCDs (Pfalz et al. 2002). We therefore assume only a small neutron star and black hole retention fraction of 20% in our simulations. With
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3 RESULTS

3.1 Mass segregation timescale: analytical estimate

In the following we derive an analytical estimate of the mass segregation timescale in compact stellar systems.

Massive stars will segregate against dark matter particles and lighter stars as a result of dynamical friction and energy equipartition. Since the masses of stars are much higher than the mass of the dark matter particles, the frictional drag on the stars is given by (see Binney & Tremaine [1987], Eq. 7-18):

\[
\frac{dv}{dt} = -\frac{4\pi}{v^3} \ln \frac{\Delta G^2 \rho(r) m}{\sigma^2} \left[ \text{erf}(X) - \frac{2X}{\sqrt{\pi}} e^{-X^2} \right] \bar{v}
\]

where \(\rho(r)\) is the background density of dark matter and stars, \(m\) the mass of an inspiraling star, \(\ln \Lambda\) the Coulomb logarithm, and \(X = \bar{v}/(\sqrt{2}\sigma)\) is the ratio between the velocity of a star and the (1D) stellar velocity dispersion \(\sigma\). If we assume \(v \approx \sigma\), it follows that \(X = 1/\sqrt{2}\). Setting \(\ln \Lambda = 12\) for globular clusters (Binney & Tremaine [1987], Tab. 7-1), the eq. 2 can be rewritten as:

\[
\frac{dv}{dt} = -29.96 \frac{G^2 \rho(r) m}{v^2}.
\]

The resulting energy change is \(dE = \frac{d}{dt} (\frac{1}{2} mc^2) = mc \frac{dv}{dt}\). For a distribution of stars in virial equilibrium, an energy change \(dE\) corresponds to a change in potential energy \(md\Phi = 2dE\). Hence

\[
\frac{d\Phi}{dt} = -59.93 \frac{G^2 \rho(r) m}{v}.
\]

For a Plummer model, the density \(\rho\), circular velocity \(v_c\) and specific potential \(\Phi\) at point \(r\) are given by:

\[
\rho(r) = \frac{3M_{\text{Tot}} a^2}{4\pi} (a^2 + r^2)^{-5/2}
\]

\[
\Phi(r) = -\frac{GM_{\text{Tot}}}{(a^2 + r^2)^{1/2}}.
\]

\[
v_c(r) = \sqrt{\frac{GM_{\text{Tot}} r^2}{(a^2 + r^2)^{3/2}}}
\]

where \(M_{\text{Tot}}\) is the total cluster mass and \(a\) is the scale radius of the Plummer model. With these equations, the above relation can be rewritten as:

\[
\frac{dr}{dt} = -14.31 \frac{\sqrt{Ga^2 m}}{\sqrt{M_{\text{Tot}} r^2 (a^2 + r^2)^{1/2}}}.
\]

For an order of magnitude estimate of the inspiral time scale, one can approximate \((a^2 + r^2)^{1/4} \approx a^{1/2}\). One can then solve the above relation and obtains as time which a star starting at radius \(R_0\) needs to reach the centre:

\[
T_{\text{Fric}} = 0.023 \frac{\sqrt{M_{\text{Tot}}}}{\sqrt{G a^{3/2} m}} R_0^3
\]

For a Plummer model, \(a = 0.766 R_H\), so the inspiral time for stars near the half-mass radius is given by:

\[
T_{\text{Fric}} = 0.035 \frac{M_{\text{Tot}} R_H^{3/2}}{G m}
\]

For a globular cluster or UCD we thus obtain:

\[
T_{\text{Fric}} = 5.86 \left( \frac{M_{\text{Tot}}}{10^5 M_\odot} \right)^{1/2} \left( \frac{R_H}{5 \text{pc}} \right)^{3/2} \left( \frac{m}{M_\odot} \right)^{-1} \text{ Gyr}
\]

The resulting dynamical friction time agrees to within 20% with what Binney & Tremaine found for the inspiral time of an isothermal sphere (their eq. 7-26). Eq. 9 predicts a dynamical friction time scale of 4-5 Gyr for a typical GC \((3\times10^5 M_\odot, r_h = 3\text{pc})\), and about 400 Gyr for a typical UCD \((10^7 M_\odot, r_h = 20\text{pc})\). That is, after a Hubble time most of the dark matter in globular clusters should have been pushed out of the centre, while in UCDs the inspiral of stars should be far from complete and a significant fraction of DM should still reside in their centres, leading to high mass-to-light ratios.

3.2 N-body results

Fig. 2 shows the evolution of Lagrangian (lag.) radii, i.e. radii which contain a certain fraction of the total mass, of stars and dark matter particles in our first simulation, which had a dark matter particle mass of \(m = 0.03 M_\odot\) and an equal amount of mass in stars and dark matter. The effect of dynamical friction and mass segregation is clearly visible since the lag. radii of dark matter particles increase with time while those of the stars shrink. In N-body units, the total cluster mass and constant of gravity are both unity. With a mean stellar mass of \(m = 6.0 \cdot 10^{-5}\), we predict a dynamical friction timescale of \(T_{\text{Fric}} = 391\) in N-body units according to eq. 8. It can be seen that by this time the cluster center is indeed nearly free of dark matter: inside the lag. radius of 10% of the stars, only 1% of the dark matter particles are located. At the end of the simulation, the 10% lag. radius of the dark matter particles is almost equal to the half-mass radius of the stars, i.e. only 20% of the cluster mass is still made up of dark matter inside the (visible) half-mass radius of the cluster. The core of the cluster is even stronger depleted and is nearly free of dark matter by the end of the simulations. It would therefore be difficult to detect the remaining dark matter by its effect on stellar velocities if mainly stars from the cluster center or inside
the half-mass radius are used to determine the line-of-sight velocity dispersion.

The right panel of Fig. 2 depicts the evolution of lag radii as a function of cluster age to the actual relaxation time. In order to allow for a better comparison with observations, the relaxation time is calculated from the stellar component according to Spitzer (1958):

$$T_{RH} = 0.138 \frac{\sqrt{M_\ast R_H^3}}{\sqrt{Gm_\ast} \ln \gamma N_\ast}$$

(10)

where $M_\ast$ is the total stellar mass of the cluster, $R_H$ is the half-mass radius of the stellar distribution, $m_\ast$ and $N_\ast$ are the mass and number of stars and $\gamma$ a constant in the Coulomb logarithm which is taken to be $\gamma = 0.11$ (Giersz & Heggie 1994). Eq. (10) would be the relaxation time inferred by an observer who can only determine the stellar distribution and does not know about the dark matter. It has the same dependence on cluster mass and radius as the friction timescale and can therefore also be used to judge the dynamical state of a cluster.

The right panel of Fig. 2 shows that once a cluster is two to three apparent relaxation times old, the centre is free of dark matter and by the time the cluster has become ten relaxation times old, there is little dark matter left inside the half-mass radius. Since most globular clusters have relaxation times of only a few Gyr, their mass-to-light ratios should be within 20% of those of pure stellar populations if mainly stars inside the clusters half-mass radius are used to determine the velocity dispersion. Since this is within the uncertainty of measured mass-to-light ratios and current stellar population models, such a small dark matter cannot be detected kinematically in globular clusters. UCDs on the other hand have relaxation times significantly larger than a Hubble time and should therefore still have large mass-to-light ratios if they formed as a mix of dark matter and stars.

This is confirmed by the upper panel of Fig. 3 which depicts the dark matter fraction inside the cluster core (assumed to be the region inside the 5% lag, radius of the stars) and inside the half-mass radius of the cluster stars. It can be seen that after about 1.5 to 2 friction times, the cluster core is almost completely free of dark matter. Within the half-mass radius, only about 30% of the initial dark matter amount remains after this time. The lower panel of Fig. 3 depicts the evolution of the average mass of stars in the core and inside the half-mass radius. At both radii, the average mass of stars is increasing since, while stars segregate against the dark matter particles, heavy-mass stars also segregate against the lighter ones. After about 2 dynamical friction timescales, the mass of stars has reached a near constant value of about 0.65 $M_\odot$, which is significantly higher than the average mass of stars. Clusters which have expelled dark matter out of their centres should therefore also be mass segregated.

### 3.3 Comparison with observations

Fig. 1 shows the effect which the decreasing dark matter fraction in the center has on the projected velocity dispersion of stars. In order to determine this effect, we first calculate the velocity dispersion profile $\sigma_{\text{obs}}(r)$ of bright stars with masses in the range $0.6 < m < 0.9 M_\odot$ as a function of projected radius. We restrict ourselves to this mass range since in a globular cluster or UCD, these would be the stars which dominate the cluster light. After determining the velocity dispersion profile of bright stars, we calculate...
the expected velocity dispersion profile based on the stellar density distribution according to (Binney & Tremaine 1987, eq. 4-54):
\[
\sigma^2(r) = \frac{1}{\rho(r)} \int \rho(r') \frac{d\Phi}{dr} \bigg|_{r=r'} \, dr',
\]
where \(\rho(r)\) is the (3D) density distribution of bright stars and \(\Phi(r)\) is the potential coming from the stars alone. Eq. 11 assumes a spherical cluster potential and an isotropic velocity dispersion of stars. After projecting \(\sigma(r)\) we can calculate the correction factor \(f\) needed so that the predicted velocity dispersion matches the true velocity dispersion of the clusters in the N-body simulations, i.e. \(f(r) = \sigma_{\text{Obs}}(r)/\sigma_{\text{Pred}}(r)\). The resulting correction factor is plotted in Fig. 4 for the first run from Table 1. Initially, dark matter and stars follow the same density distribution, so the velocity dispersion is a factor \(f(r) = \sqrt{(M_{DM} + M_\star)/M_\star} = 1.41\) higher than predicted by eq. 11. As the cluster evolves, dark matter is removed from the center, so the velocities of stars in the center are determined more and more by the stars alone and \(f\) approaches unity. After 3 relaxation times, the central velocity dispersion is only 10% higher than what one would expect based on the stars alone and after 10 relaxation times the difference is less than 1%. Most globular clusters should therefore have central M/L ratios which are close to those predicted by stellar population models. Beyond 10 half-mass radii, \(f\) remains close to the initial value even after 10 relaxation times. As long as dark matter is not removed by tidal effects (Mashchenko & Sills 2003), it should therefore be detectable in globular clusters through the observation of stellar velocities in the outer cluster parts.

We finally discuss the influence of the dark matter on the global mass-to-light ratios. In order to compare our simulations with observed clusters, we again calculate true and expected velocity dispersions of stars with masses in the range \(0.6 < m < 0.9 \, M_\odot\). Since mass-to-light ratios of UCDs are determined from stellar velocities covering a significant fraction of the cluster area (see e.g. discussion in Hilker et al. (2007)) and measured mass-to-light ratios of globular clusters are based mainly on stars in the inner cluster parts (McLaughlin & van der Marel 2003), we determine global velocity dispersions in the simulations for all stars located inside the projected half-light radius. The resulting mass-to-light ratios of our model clusters are then given by
\[
M/L = f^2 M_{L\star},
\]
where \(M_{L\star}\) is the mass-to-light ratio which a pure stellar population would have and \(f\) is again \(f = \sigma_{\text{Obs}}/\sigma_{\text{Pred}}\).

Fig. 4 depicts the evolution of \(M/L\) with cluster age for runs 1 and 2 of Table 1, and compares it with observed M/L ratios of UCDs and GCs from Mieske et al. (2008). Note that the literature M/L estimates are normalised to the same (solar) metallicity, to allow direct intercomparison. Time is again expressed in terms of age divided by the relaxation time as determined from the stars alone.

The observed normalised M/L ratios show a clear trend in the sense that dynamically more evolved systems have on average lower M/L values. The mass-to-light ratios in our simulations also decrease as the dynamic age increases, since, as the dark matter is depleted from the cluster centers, the velocity dispersion is determined more and more by the stars alone, so M/L approaches \(M_{L\star}\). Depending on whether a stellar \(M_{L\star}\) of 2.5 or 2.0 is assumed, a run with a primordial dark matter content equal to or twice as high as the stellar mass provides an acceptable fit to the data, making dark matter a viable alternative to explain the elevated mass-to-light ratios of UCDs. We note that if the observed decrease of M/L with dynamical age is due to the dynamical depletion of non-luminous particles from the cluster centers, the dark matter particles have to be of lower mass than the stars, ruling out e.g. a central concentration of black holes in UCDs as the explanation for their high M/L ratios.

The stellar mass-to-light ratios we have to assume in order to fit the data for GCs are marginally lower than predicted by simple stellar population models for 12 Gyr old, solar-metallicity star clusters. For example, the Bruzual & Charlot (2003) models predict an M/L of 2.5 for a 8-9 Gyr old stellar population. The difference to a 12 Gyr old population (M/L=3.5) is still within individual error bars for the literature estimates, and there is also some uncertainty in the underlying stellar mass functions and stellar population models. Nevertheless, we note that the slightly too low M/L ratios may also be interpreted as signs of preferential loss of low-mass stars in the Galactic tidal field (Baumgardt & Makino 2003, Kuij Jens 2008). If this was the case, then less dark matter would be needed to explain the elevated mass-to-light ratios of UCDs, implying a DM mass of \(~50-80\%\) of the stellar mass. However, it is unclear whether the actual dissolution times of the GCs...
clusters half-mass radius, assuming stellar mass-to-light ratios of calculated from the velocity dispersion of bright stars inside the dashed curves show predicted M/L values for two of our runs relaxation time. There is a clear trend towards lower M/L values clusters (triangles) as a function of their age divided by the Figure 5. Mass-to-light ratios of UCDs (circles) and globular clusters (triangles) as a function of their age divided by their relaxation time. There is a clear trend towards lower M/L values for dynamically more evolved systems. The red solid and blue dashed curves show predicted M/L values for two of our runs calculated from the velocity dispersion of bright stars inside the clusters half-mass radius, assuming stellar mass-to-light ratios of $M/L_\star = 2.0$ and $M/L_\star = 2.5$ for the two runs. It can be seen that the resulting theoretical curves provide a good fit to the combined globular cluster/UCD sample.

with available M/L measurements are short enough to have experienced significant evaporation (Mieske et al. 2008). A case-by-case analysis for Galactic GCs will be necessary to assess this, based on measured absolute proper motions and orbital parameters (Allen et al. 2008).

3.4 Scaling issues

We finally discuss a possible biasing of our results due to the finite mass of the dark matter particles. Fig. 6 depicts the evolution of Lagrangian radii in simulations with different dark matter particle masses. All simulations had an equal amount of mass in stars and dark matter and the mass of the dark matter particles was set to be $m = 0.1 \, M_\odot$ (blue lines), $m = 0.03 \, M_\odot$ (red lines) and $m = 0.015 \, M_\odot$ (green lines). Since the mass of heavy stars which drive the inspiral is in all cases much higher than the mass of the dark matter particles, eq. 8 should still apply for the inspiral timescale. In all three simulations, the mass of individual stars if expressed in $N$-body units was the same, so according to eq. 8, the inspiral timescale of the stars should be the same in the three simulations.

It can be seen that the inspiral of stars and the ejection of dark matter particles happens in all three clusters in a very similar way. The agreement is especially good between the two simulations with the lightest dark matter particles. We therefore conclude that the adopted mass $m = 0.03 \, M_\odot$ for the dark matter particle does not influence the results presented in Figs. 2 to 5. Our simulations should therefore give a correct picture of the dynamical ejection of dark matter from the centers of globular clusters and UCDs.

4 CONCLUSIONS

We have performed collisional $N$-body simulations of the evolution of compact systems composed out of a mix of stars and dark matter particles. Our simulations show that dark matter is depleted from the centers of these systems due to dynamical friction and energy equipartition between stars and dark matter particles. The inspiral time of stars is short enough that only 20% of the original dark matter would remain within the half-mass radius in typical globular clusters. If mainly stars from the inner cluster parts are used to determine mass-to-light ratios, the resulting increase in the mass-to-light ratio is within the errors with which mass-to-light ratios are typically determined for globular clusters and would therefore be difficult to detect.

If not tidally stripped, dark matter should also reside in the outer parts of globular clusters. For a number of globular clusters, (Scarpa et al. 2007) have indeed reported a flattening of the velocity dispersion in the outer cluster parts. This could however be due to a number of reasons like contamination of the sample by background stars or the tidal interaction of a star cluster with the gravitational field of the Milky Way (Drukier et al. 1998; Capuzzo Dolcetta et al. 2002). Detailed simulations would be necessary to exclude these possibilities and confirm that the observed flattening is due to a dark matter halo.

UCDs on the other hand have inspiral times significantly longer than a Hubble time and therefore still contain most of the dark matter in their centers. Dark matter therefore seems a viable explanation for the elevated M/L ratios of UCDs, provided that UCDs originate from the centers of dark matter halos and have seen their dark matter content being increased by dark matter funneling, through e.g. adiabatic gas infall (Goerdt et al. 2003).

A prediction of our simulations, which can in principle
be tested by observations, is that globular clusters which have expelled the dark matter from their centers should also be mass segregated. Non-mass segregated clusters with velocity dispersions and mass-to-light ratios in agreement with simple stellar population models, would therefore have formed without significant amounts of dark matter in their centers.

Also, if dark matter existed in a globular cluster at the time of its formation, it should still reside in its outer parts, especially if tidal stripping due to external tidal forces from the host galaxy (Mashchenko & Sills 2005) and relaxation driven internal mass loss was not important for the cluster evolution. In this case, the measured mass-to-light ratio should increase towards the outer cluster parts, which can in principle be detected with dedicated radial velocity or proper motion surveys. The future astrometric satellite GAIA would be an excellent tool for such a search since it will provide accurate proper motions for thousands of stars in the halos of nearby globular clusters.

ACKNOWLEDGEMENTS

REFERENCES

Aarseth, S. J., 1999, PASP, 111, 1333
Allen, C., Moreno, E., & Pichardo, B. 2006, ApJ, 652, 1150
Baumgardt, H., Makino, J., 2003, MNRAS, 340, 227
Bekki, K., Couch, W.J., Drinkwater, M.J., 2001, ApJ, 552, 105
Bekki, K., Couch, W.J., Drinkwater, M.J., Shioya, Y., 2003, MNRAS, 344, 399
Binney, J., Tremaine, S., 1987, Galactic Dynamics, Princeton Univ. Press, Princeton, p. 425
Bruzual, G., Charlot, S., 2003, MNRAS, 344, 1000
Carraro, G., Lia, C., 2000, A&A, 357, 977
Casares, J., 2006, in Observational evidence for stellar-mass black holes, IAU Symposium 238 in press, arXiv:astro-ph/0612312
Capuzzo Dolcetta, R., Di Matteo, P., Miocchi, P., 2005, AJ, 129, 1906
Dabringhausen, J., Hilker, M. & Kroupa, P., 2008, MNRAS, 386, 864
Dabringhausen, J., Baumgardt, H. & Kroupa, P., 2008, MNRAS submitted
Drinkwater, M.J., Jones, J.B., Gregg, M.D. & Phillipps, S., 2000, PASA, 17, 227
Drukier, G., et al., 1998, AJ, 115, 708
Evstigneeva, E.A., Gregg, M.D., Drinkwater, M.J. & Hilker, M., 2007, AJ, 133, 1722
Fellhauer, M., Kroupa, P., 2002, MNRAS, 330, 642
Firth, P. et al. 2007, MNRAS, 382, 1342
Forbes, D. et al. 2008, MNRAS submitted, arXiv:0806.1090
Giersz, M., Heggie, D.C., 1994, MNRAS, 268, 257
Gilmore, G. et al. 2007, ApJ, 663, 948
Goertt, T. et al., 2008, MNRAS, 385, 2136
Hasegan, M. et al., 2005, ApJ, 627, 203
Heggie, D.C., Hut, P., 2002, The Gravitational Million-Body Problem, Cambridge University Press, p. 8
Hilker, M., Infante, L., Viera, G., Kissler-Patig, M. & Richtler, T., 1999, A&AS, 134, 75
Hilker, M., et al., 2007, A&A, 463, 119
Jones, J. B et al. 2006, AJ, 131, 312
Kalirai, J.S. et al., 2008, ApJ, 676, 594
Kroupa, P., 2001, MNRAS 322, 231
Kruijssen, J. M. D. 2008, A&A letters in press, arXiv:0806.0852
Lyne, A.G., Lorimer, D.R., 1994, Nature, 369, 127
Makino, J., Fukushige, T., Koga, M., & Namura, K., 2003, PASJ, 55, 1163
Mashchenko, S., Sills, A. 2005, MNRAS, 619, 258
McLaughlin, D. E & van der Marel, R. P. 2005, ApJS, 161, 304
Mieske, S., et al., 2005, A&A, 430L, 25
Mieske, S., Hilker, M., Infante, L. & Jordán, A. 2006, AJ, 131, 2442
Mieske, S., Hilker, M., Jordán, A., Infante, L. & Kissler-Patig, M. 2007, A&A, 472, 111
Mieske, S., et al., 2008, A&A in press, arXiv:0806.0374
Oh, K.S., Lin, D.N.C., 2000, ApJ, 543, 620
Pfalz, E., Rappaport, S., Podsiadlowski, P., 2002, ApJ, 573, 283
Plummer, H.C., 1911, MNRAS 71, 460
Rejkuba, M., Dubath, P., Minniti, D., & Meylan, G. 2007, A&A, 469, 147
Scarpa, R., Marconi, G., Gilmozzi, R., & Carraro, G. 2007, ESO Messenger 128, 41, arXiv:0707.2469
Spitzer, L., 1987, Dynamical Evolution of Globular Clusters, Princeton University Press
Thomas, P.A., Drinkwater, M.J. & Evstigneeva, E., 2008, MNRAS in press, arXiv:0801.4840
Thorsett, S.E., Chakrabarty, D., 1999, ApJ, 512, 288
Table 1. Details of the $N$-body models. The second column gives the initial number of stars, the third column the initial number of dark matter particles. The fourth column gives the mass of a dark matter particle and the fifth column gives the relative mass fraction in dark matter and in stars. The last columns give the fraction of dark matter remaining inside the 5% lagrangian radius and inside the half-mass radius after one, two and ten apparent relaxation times (eq. (10)) have passed.

| Nr | $N_*$ | $N_{DM}$ | $m_{DM}$ | $M_*$ : $M_{DM}$ | $f_{DM}|T=R_{RH}$ | $r < R_{5\%}$ | $r < R_{H}$ | $f_{DM}|T=2R_{RH}$ | $r < R_{5\%}$ | $r < R_{H}$ | $f_{DM}|T=10R_{RH}$ | $r < R_{5\%}$ | $r < R_{H}$ |
|----|-------|---------|---------|----------------|----------------|-------------|-----------|----------------|-------------|-----------|----------------|-------------|-----------|
| 1  | 8224  | 91776   | 0.030   | 1:1           | 0.39           | 0.78        | 0.22      | 0.63           | 0.01       | 0.26      |                |             |           |
| 2  | 4285  | 95715   | 0.030   | 1:2           | 0.57           | 1.51        | 0.29      | 1.27           | 0.03       | 0.55      |                |             |           |
| 3  | 8223  | 27528   | 0.100   | 1:1           | 0.38           | 0.81        | 0.20      | 0.70           | 0.01       | 0.35      |                |             |           |
| 4  | 8224  | 183576  | 0.015   | 1:1           | 0.40           | 0.78        | 0.18      | 0.61           | 0.01       | 0.27      |                |             |           |