The Depletion of Dark Matter from the Center of Globular Clusters

Eliani Ardi (Kyoto International University) and Holger Baumgardt (University of Queensland, Brisbane)

GRAPE-A

1 Introduction

Some massive globular clusters are reported to have some properties in common with Ultra-compact dwarf galaxies (UCDs). UCDs are star cluster size systems with mass in the range of $10^6 M_\odot - 10^8 M_\odot$ and half mass radii of 10-100 pc. Some of the most massive galactic globular clusters have masses and sizes only slightly smaller than UCDs (Rejkuba et al. 2007). A recent paper by Mieske et al. (2008) showed that in the parameter space which gives empirical description of the structural and kinematic properties of stellar spheroids, UCDs are located at the extension of the dwarf galaxies and globular cluster planes. This might indicate a relation between formation of UCDs and globular clusters.

However, observation of UCDs showed that mass-to-light (M/L) ratio of UCDs are on average about twice as large than those of globular clusters at comparable metalicity, and larger than those predicted from stellar populations for their age. The higher M/L ratio can be interpreted in a number of ways, one being a significant amount of dark matter in the cluster centers (Baumgardt & Mieske 2008).

One possible explanation for elevated high mass-to-light ratio in UCDs is by the existence of a substantial amount of dark matter funneling through adiabatic gas infall and later stripping of dwarf galaxies (Bekki, Couch, & Drinkwater (2001) and Goerdt et al. (2008). Goerdt et al. (2008) assumed that a nuclear star cluster was formed in a disk galaxy via cooling of gas. This nuclear star cluster funneled a significant amount of dark matter into the center of the galaxy. After stripping, part of the dark matter ends up in the UCDs.

Following the UCD formation scenario proposed by Goerdt et al. (2008), a recent paper by Baumgardt & Mieske (2008) followed by means of N-body simulations the evolution of star clusters composed out of a mix of stars and dark matter particles. They found that the dark matter gets removed from the central regions due to dynamical friction and mass segregation of stars.

UCDs have inspiral times significantly longer than a Hubble time and therefore a significant dark matter fraction remains within the half-mass

radius of the present-day UCDs. Dark matter therefore seems a viable explanation for the elevated M/L ratio for UCDs.

Globular clusters on the other hand have shorter inspiral times so that only 20 % or less of the original dark matter would remain within their half-mass radius, explaining why their mass-to-light ratios are in agreement with predictions from stellar evolution models.

If some globular clusters formed in a similar way to UCDs, a substantial amount of dark matter might remain in their outer parts, which may cause a flattening of the velocity dispersion.

Observations of a number of globular clusters (ω Cen, NGC 7078, NGC 6171, NGC 7099, and NGC 6341) by Scarpa et al. (2007) reported that while these globular clusters having different sizes, different masses, and different dynamical histories, they have a common property of having constant velocity dispersion at large radii. This flattening of velocity dispersion at the outer parts of clusters could be due to a number of reasons like contamination of the stellar sample by background stars or the tidal interaction of a globular cluster with the gravitational field of the Milky Way (Drukier et al. (1998); Capuzzo Dolcetta, Di Matteo & Miocchi (2005)), but it might also indicate the presence of a dark matter halo.

Detailed simulations are necessary to confirm that the observed flattening of the velocity dispersion in the outer parts of globular clusters is due to a dark matter halo. For this purpose, we follow the evolution of globular clusters composed out of a mix of stars and dark matter particles to examine the depletion of dark mater from the cluster center. We also study the evolution of the velocity dispersion's profile which may indicate the amount of dark matter remaining in their outer parts and the influence of external tidal field on the depletion of dark matter.

2   The Models

We conduct a number of N-body simulations, using the collisional N-body code NBODY4 (Aarseth 1999), to follow the evolution of the dark matter content star clusters in Plummer model. Dark matter is represented by low-mass particles with masses of 0.1 $M_\odot$. Theoretically, the dynamical friction of stars should not depend on the mass of the dark matter particles, as long as the mass ratio between stars and dark matter is high enough (Binney & Tremaine 1987). Stars and dark matter are initially distributed according to the same initial mass function. Minimum and maximum masses of our stars are set equal to 1.0 $M_\odot$ and 100 $M_\odot$ respectively to follow a Kroupa

(2001) mass function. In this present models, we evolved clusters of 25000 particles, consist of 9350 stars and 15650 dark matter particles with relative mass fraction in the dark matter and in star is 1:1. In the first model, we study an isolated cluster, while in the second model the cluster is assumed to orbit in a circular orbit around a Milky Way like galaxy at R=8.5 kpc.

3 Results

Fig.1 depicts the evolution of lagrangian radii in the model of an isolated cluster. Lagrangian radii are radii contain a certain fraction of the total mass of the cluster, i.e. 1 %, 5 %, 10%, 50 %, 70 % of the cluster mass. The dynamical friction time for a Plummer model is given by (Baumgardt & Mieske 2008) :

$$t_{fric} = 0.035 \frac{\sqrt{M}_{tot} R_{half}^{3/2}}{\sqrt{G} m} \qquad (1)$$

where M_{tot} is the total cluster mass, R_{half} is the cluster half-mass radius, G is the gravitational constant and m is the mass of an inspiraling star. The increase of the lagrangian radii of the dark matter particles indicates that they are moving to the outer part of the cluster. On the other hand, in the inner part, when the lagrangian radii contain 20 % or less of the total mass of star, the lagrangian radii of stars shrink slowly with time. This occurs due to dynamical friction and mass segregation of stars.

Fig.2 shows the fraction of dark matter mass to the stellar mass inside the isolated cluster and the tidally perturbed cluster. After about 1 friction time, only about 10 % of initial dark matter mass remains within the core radius of the isolated cluster and about 60 % of initial dark matter mass left inside the half-mass radius. It means that, if not tidally stripped, significant amount of dark matter mass should retain in the outer part of the cluster. An external tidal field removes the dark matter from the cluster and deplete it into about 10 % of the initial value within 3.5 friction time.

Fig.3 depicts the evolution of the ratio f of observed velocity dispersion to predicted one:

$$f = \frac{\sigma_{obs}}{\sigma_{pred}} \qquad (2)$$

which show the effect of decreasing dark matter fraction in the cluster center on the projected velocity dispersion of stars. The observed velocity dispersion profile $\sigma_{obs}(r)$ is determined from bright stars with masses in the range of $0.6 < m < 0.9 \ M_\odot$ since in a globular cluster or UCD, these would be the

stars which dominate the cluster light. Based on the stellar density distribution (Binney & Tremaine 1987) the predicted velocity dispersion profile is given by :

$$\sigma^2(r) = -\frac{1}{\rho(r)} \int \rho(r') \frac{d\phi}{dr} \mid_{r=r'} dr' \tag{3}$$

where $\rho(r)$ is the 3D density distribution of bright stars and $\Phi(r)$ is the potential coming from the stars. Initially, stars and dark matter follow the same density distribution. The factor $f(r) = \sqrt{(M_{DM} + M_{star})/M_{star}} = 1.41$. As the cluster evolves, dark matter is removed from the center, so that the velocities of stars in the cluster center are determined more and more by stars alone. Therefore $f(r)$ decreases and finally $f(r)$ approaches unity. However, on the outer part of the isolated cluster, distribution of stars and dark matter remains same as their initial distribution. This indicates that as long as dark matter is not removed by tidal effects, a significant amount of dark matter mass should retain on the outer part of the cluster and it should be detectable through observation of stellar velocities in the outer part of cluster.

Fig.4 shows the evolution of the ratio f of obseved velocity dispersion to predicted one in the tidally perturbed cluster. In the cluster center, as the cluster evolves, dark matter is removed from the cluster center, so that the observed velocity dispersion of stars decreases and therefore the ratio f decreases. Since dark matter on the outer part of cluster is removed by tidal effect (see fig. 2), the factor f on the outer part of the cluster also decreases. After 7 relaxation time the factor f approaches unity, which means that dark matter has been completely removed from the cluster.

4   Conclusions

Our simulation shows that dark matter is depleted from the center of globular clusters due to dynamical friction and mass segregation of stars. After about 1 friction time, the globular clusters have expelled almost all amount of the dark matter from their centers. An external tidal field from a MilkyWay-like galaxy effects the dark matter to get removed from the cluster and depleted into about 10 % of the initial value within 3.5 friction time. All amount of dark matter inside the tidally perturbed cluster has been removed from the cluster due to the tidal field effects in about 7 relaxation time.
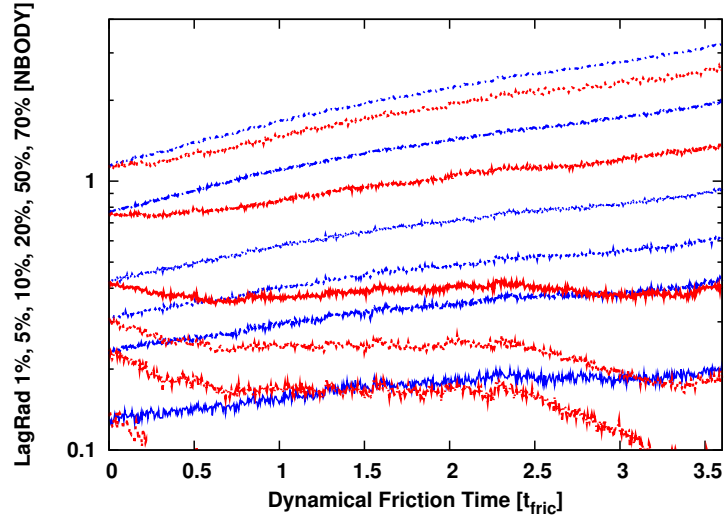
Figure 1: Evolution of lagrangian radii for the isolated cluster. The cluster radii contain a certain fraction of the total mass of stars (red lines) and dark matter particles (blue lines). The increase of the lagrangian radii of the dark matter particles indicates that they are moving to the outer part of the cluster. On the other hand, in the inner part, when the lagrangian radii contain 20 % or less of the total mass of star, the lagrangian radii of stars shrink slowly with time. This occurs due to dynamical friction and mass segregation of stars.
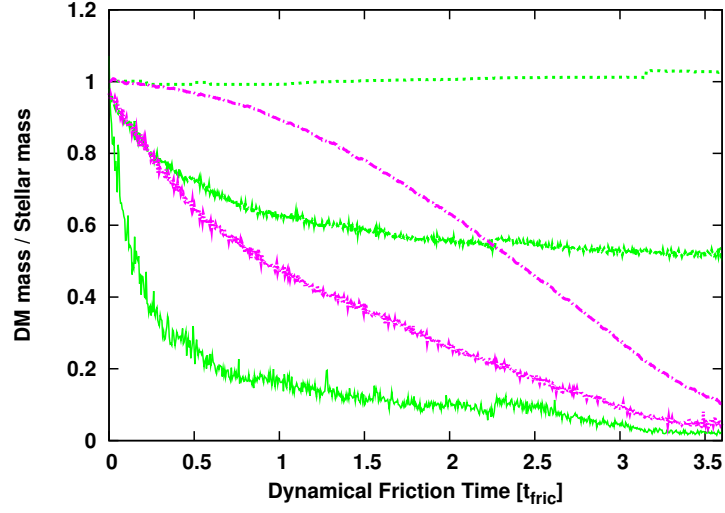
Figure 2: Dark matter fraction inside certain radii of the isolated cluster (green lines) and of the tidally perturbed cluster (pink lines). From up to bottom of the green lines : the cluster radius, the half-mass radius and the core radius of the isolated cluster. Upper and lower of the pink lines : the cluster radius and the half-mass radius of the tidally perturbed cluster. After about 1 friction time, only about 10 % of initial dark matter mass remains within the core radius of the isolated cluster and about 60 % of initial dark matter mass left inside the half-mass radius. It means that, if not tidally stripped, significant amount of dark matter mass should retain in the outer part of the cluster. An external tidal field removes the dark matter from the cluster and deplete it into about 10 % of the initial value within 3.5 friction time.
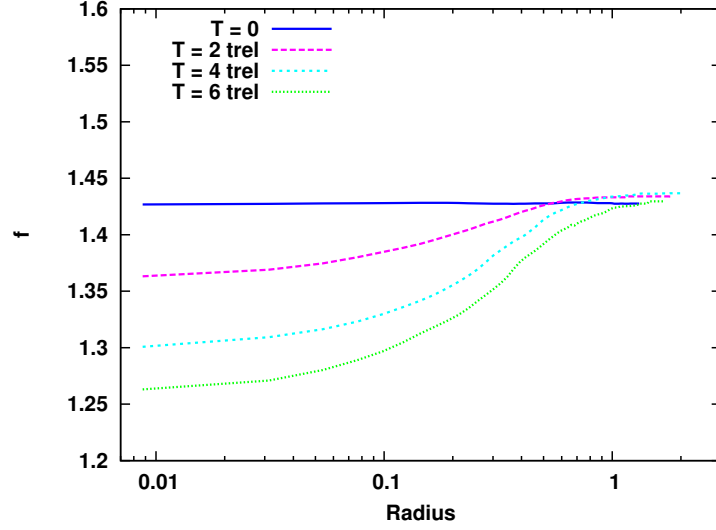
Figure 3: Evolution of the ratio of observed velocity dispersion to predicted one in the isolated cluster. Initially, stars and dark matter follow the same density distribution. The factor $f(r) = \sqrt{(M_{DM} + M_{star})/M_{star}} = 1.41$. As the cluster evolves, dark matter is removed from the center, so that the velocities of stars in the cluster center are determined more and more by stars alone and finally $f(r) = 1$. However, on the outer part of the isolated cluster, distribution of stars and dark matter remains same as their initial distribution. This indicates that as long as dark matter is not removed by tidal effects, a significant amount of dark matter mass should retain on the outer part of the cluster and it should be detectable through observation of stellar velocities in the outer part of cluster.
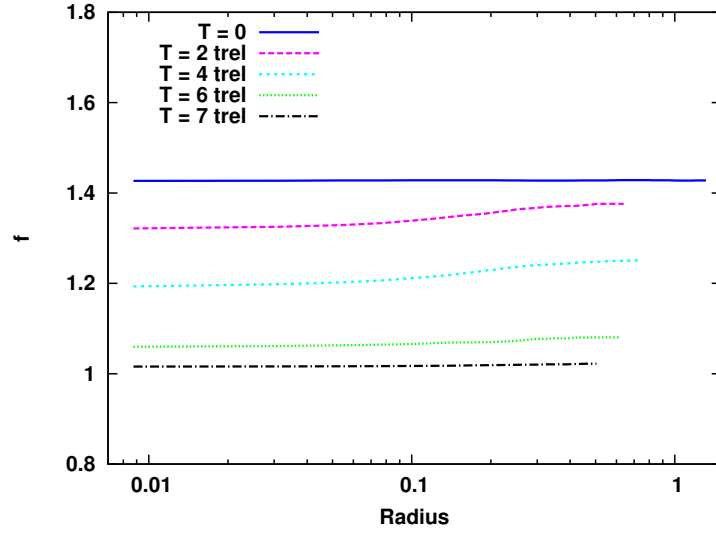
Figure 4: Evolution of the ratio of observed velocity dispersion to predicted one in the tidally perturbed cluster. In the cluster center, as the cluster evolves, dark matter is removed from the cluster center, so that the observed velocity dispersion of stars decreases and therefore the ratio f decreases. Since dark matter on the outer part of cluster is removed by tidal effect, the factor f on the outer part of the cluster also decreases. After 7 relaxation time the factor f approaches unity, which means that dark matter has been completely removed from the cluster.

5 References

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