Depletion of dark matter within globular clusters

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Abstract. Gravitationally bound group of stars which are identified as globular clusters are known to have a small amount of dark matter. Assuming that globular clusters are formed within dark matter halos, they must have lost significant amount of dark matter. Observations of globular clusters reported flattening velocity dispersion on the outskirts clusters. This could be a sign of existence of dark matter. Theoretically, dynamical processes such as dynamical friction and mass segregation and tidal stripping could be responsible for the depletion of dark matter from the cluster center. Numerical simulations are conducted to follow the evolution of the models of globular clusters composed out of stars and dark matter particles. The results show that the dark matter is depleted from the center of globular clusters due to dynamical friction and mass segregation of stars. An external tidal field from a Milky Way like galaxy effects to deplete the dark matter in the outer part of the clusters. However, within the Hubble time, about 80% of dark matter’s initial values still remain in the outer part of clusters. This might explain the existence of significant amount of dark matter in the outer part of observed clusters.

1. Introduction

The Earth where we are living in, is a member of the solar system, while together with the solar interstellar neighbourhood is a part of the Milky Way galaxy. Milky Way galaxy contains about 2-400 billion stars. Surrounding the Milky Way galaxy there are small stellar systems containing between 10^2 to 10^6 stars which are called as globular clusters.

Observations of a number of globular clusters (o Cen, NGC 7078, NGC6171, NGC 7099, and NGC 6341) by ref. [1],[2],[3] reported that while these massive star 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 could be due to contamination of the stellar sample by background stars or the effect of tidal interaction of a globular cluster with the gravitational field of the Milky Way [4]. However, it might also indicate the presence of a dark matter halo [1].

Formation of globular clusters may have link with formation of ultra-compact dwarf galaxies (UCDs), star cluster size systems with mass in the range of 10^5 solar mass - 10^8 solar mass and half mass radii of 10-100 pc. There are some similarities in their structural and kinematic properties, except the high of mass-to-light (M/L) ratio of UCDs [5].

The higher M/L ratio can be interpreted in a number of ways, one being a significant amount of dark matter in the cluster centres [6]. 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 [7],[8]. Ref. [8] 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 centre of the galaxy. After stripping, part of the dark matter ends up in the UCD.

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.

N-body simulations by ref. [6] showed that the high M/L ratio in UCDs can be caused by the existence of a significant dark matter fraction within the half-mass radius of the present-day UCDs. 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. 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 followed the evolution of globular clusters composed out of a mix of stars and dark matter particles to examine the depletion of dark matter from the cluster centre. 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. Simulation Method and Models

2.1. N-body simulation

Globular clusters are assumed to be composed out of a mix of stars and dark matter particles. Stars and dark matter particles are moving under the mutual gravitational force. The dynamical interaction of a system of N particles interacting gravitationally is determined by Newton’s law plus an external potential field. The force $\vec{F}_i$ acting on a particle $i$ of mass $m_i$ is given by:

$$\vec{F}_i = - \sum_{j \neq i} G \frac{m_i m_j (\vec{r}_i - \vec{r}_j)}{|\vec{r}_i - \vec{r}_j|^3} - \nabla \Phi_{\text{ext}}(\vec{r}_i),$$

(1)

where $G$ is the gravitational constant, $\vec{r}_i$ is the position of particle $i$, $\vec{r}_j$ is the position of particle $j$, and $\Phi_{\text{ext}}$ is the external force. Following Newton’s second law, the force $\vec{F}_i$ is equal with multiplication of the mass $m_i$ times acceleration $\frac{\partial^2 \vec{r}_i}{\partial t^2}$. Therefore equation (1) is a set of non-linear second order ordinary differential equation. Once the initial position $\vec{r}_i$ and initial velocities $\vec{v}_i = \frac{\partial \vec{r}_i}{\partial t}$ of all particles is specified, it exits a unique solution, analytically only up to two bodies, while larger N requires numerical integration.

Gravitational N-body simulation is numerical solutions of the equation of motion for N particles interacting gravitationally. We conduct a number of N-body simulations, using the collisional N-body code NBODY4 [9] on the GRAPE-6 special purpose computers [10].

2.2. Models

Globular clusters are assumed to consist of stars and dark matter particles with number of particles N = 25,000, 50,000 and 100,000.

Dark matter is represented by low-mass particles with masses of 0.1 solar mass. 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 [11].
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 solar mass and 100 solar mass respectively and their distribution follows a Kroupa mass function [12]. The relative mass fraction in dark matter and in stars is 1:1.

In the first model, we study an isolated cluster, without considering the external force. In the second model, we study a tidally perturbed cluster, where the cluster is assumed to orbit in a circular orbit around the Milky Way like galaxy at R=8.5 kpc.

3. Results
We examine how the distribution of mass within layers in the globular clusters changes with time by following the evolution of lagrangian radii, which is cluster’s radii contain certain fraction of the total mass of stars and dark matter. The evolution of lagrangian radii in the model of an isolated and a tidally perturbed globular cluster is depicted in Figure 1. The cluster radii contain 1 %, 5 %, 10%, 20%, 50 %, 70 % of the total mass of stars (red lines) and dark matter particles (blue lines).

Both models show the increase of the lagrangian radii of the dark matter particles (blue lines). This indicates that the dark matter particles are moving to the outer part of the cluster. Comparing to the isolated cluster, the movement of the dark matter particles in the tidally perturbed cluster increases so much after 2 dynamical friction times, especially on the outer part of the cluster. This result shows that the external tidal force from Milky Way galaxy gives a significant effect after 2 dynamical friction time.

Lagrangian radii of the stars (red lines) increase on the outer part, while in the inner part they decrease. In the inner part, the lagrangian radii which contain 20 % or less of the total mass of star shrink slowly with time. This occurs due to dynamical friction and mass segregation of stars.

![Figure 1](image-url). The evolution of lagrangian radii of dark matter particles (blue lines) and star particles (red lines) in an isolated star cluster (left) and a tidally perturbed cluster (right).

Dynamical friction is a process when an orbiting star loses its energy and angular momentum through gravitational interactions with surrounding small objects. Stars whose masses are higher than dark matter particles tend to sink into cluster’s core. Dynamical friction results dynamical mass segregation, the process by which where heavier stars tend to move toward the cluster’s centre while lighter stars tend to move farther away from the centre.

The dynamical friction time for a Plummer model is given by:

\[
t_{fric} = 0.035 \frac{\sqrt{R_i^3}}{m} \frac{\sqrt{M}}{G}
\]  

(2)
where $M$ is the total cluster mass, $R_h$ is the cluster half-mass radius, $G$ is the gravitational constant and $m$ is the mass of an inspiraling star [3].

For a typical globular cluster, the dynamical friction time is given by:

$$t_{fri} = \frac{5.86}{(10^6 M_{\odot})^{\frac{1}{2}} (R_h^{\frac{3}{2}} (M_{\odot})^{-\frac{1}{2}}) Gyr}$$

where $M_{\odot}$ is solar mass. Ref. [6] therefore predicts a dynamical friction time scale of 4-5 Gyr for a typical globular cluster (having a mass of $3 \times 10^5$ solar mass and half-mass radius 3 pc).

Figure 2 shows the change of the fraction of dark matter mass to the stellar mass inside the isolated cluster (green line) compares to the tidally perturbed clusters with $N = 25,000$ (orange lines) and 50,000 (blue lines). The fraction of dark matter to the stellar mass in each cluster is observed inside its core radius, half-mass radius and its cluster radius up to 4 friction times.

The change of the fraction of dark matter inside the core radii of all cluster models shows similarity that after about 2 friction time only less than 10% of initial dark matter mass remains within the core radii.

The fraction of dark matter inside the half-mass radius of tidally perturbed cluster constantly decreases while in the isolated cluster the dark matter fraction remains constant after 2 friction time. Both types of clusters however show that within 2 friction times, about 40 % -- 60 % of initial dark matter mass left inside the half-mass radius.

Considering the fraction of dark matter within the cluster radius, Figure 2 shows that the fraction of dark matter within an isolated cluster does not change. On the contrary, the fraction of dark matter inside tidally perturbed clusters decrease significantly. This shows that the tidal force gives significant influence on the dark matter depletion from the cluster’s core. However, about 80 % of dark matter particles still remain on the outer part of the cluster after 2 – 3 friction times.

![Figure 2](image_url)

**Figure 2.** The fraction of dark matter mass to the stellar mass inside the isolated star cluster (green lines) and the tidally perturbed star clusters (orange lines and blue lines).
We examine also the evolution of the ratio $f(r)$ of observed velocity dispersion to predicted one, which show the effect of decreasing dark matter fraction in the cluster centre on the projected velocity dispersion of stars. The result is shown in Figure 3.

![Figure 3](image_url)

**Figure 3.** Evolution of the ratio of observed velocity dispersion to predicted one in the isolated star cluster.

The observed velocity dispersion profile is determined from bright stars with masses in the range of 0.6 solar mass to 0.9 solar mass, since in a globular star cluster these would be the stars which dominate the cluster light.

Based on the stellar density distribution [11], the predicted velocity dispersion profile is given by:

$$\sigma^2(r) = \frac{-1}{\rho(r)} \int \rho(r') \frac{d\Phi}{dr} dr'$$  \hspace{1cm} (4)

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 so that observed velocity dispersion equals $\sqrt{2}$ of predicted velocity dispersion. As the cluster evolves, dark matter is removed from the centre, so that the velocities of stars in the cluster centre are determined more and more by stars alone. Therefore $f(r)$ decreases. After 5 relaxation time $f(r)$ drops to $\sim 1.25$. By increasing the time, $f(r)$ is getting closer to unity. On the outer part of the isolated cluster, however, the 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.

### 4. Conclusions

Our simulation shows that dark matter is depleted from the center of globular clusters due to dynamical friction and mass segregation of the stars. After about 2 friction times, the globular clusters have expelled almost all amount of the dark matter from their centers. An external tidal field from a Milky Way-like galaxy affects to deplete the dark matter in the outer part of globular clusters. However, within the Hubble time (which is about 2-3 friction times for typical globular cluster) about 80 % of dark matter’s initial amount still remains in the outer part of globular clusters. This might
explain the existence of significant amount of dark matter in the outer part of some observed globular clusters.

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References
[1] Scarpa R, Marconi G, Gilmozzi R and Carraro G 2007 European Southern Observatory Messenger 128 41
[2] Scarpa R, Marconi G, Carraro G, Falomo R and Villanova S 2011 Astronomy and Astrophysics 525 pp 148-158
[3] Lane et al. 2010 Monthly Notices of the Royal Astronomical Society 401 pp 2521-2530
[4] Capuzzo Dolcetta R, Di Matteo P and Miocchi P 2005 Astronomical Journal 129 p 1906
[5] Mieske S et al. 2008 Astronomy and Astrophysics 487 pp 921-935
[6] Baumgardt H and Mieske S 2008 Monthly Notices of the Royal Astronomical Society 391 pp 942-948
[7] Bekki K., Couch W J and Drinkwater M J 2001 Astrophysical Journal 552 L105-108
[8] Goerdt et al. 2008 Monthly Notices of the Royal Astronomical Society 385 pp 2136-42
[9] Aarseth S J 1999 Publication of Astronomical Society of the Pacific 111 pp 1333-1346
[10] Makino J, Fukushige T, Koga M and Nakamura K 2003 Publication of Astronomical Society of Japan 55 p 1163
[11] Binney J and Tremaine S 1987 Galactic Dynamics, Princeton University Press
[12] Kroupa P 2001 Monthly Notices of the Royal Astronomical Society 322 pp 231-246