Halo enrichment by disrupted globular clusters

Holger Baumgardt
Department of Mathematics and Statistics, University of Edinburgh, King’s Buildings, Edinburgh EH9 3JZ, UK

Abstract. We study the evolution of the galactic globular cluster system to determine its initial mass-function and the fraction of halo stars that could have come from disrupted globular clusters. We study the cluster evolution under the influence of two destruction mechanisms: Two-body relaxation and dynamical friction. New results of $N$-body simulations are used for the lifetimes of clusters dissolving under the influence of two-body relaxation.

Two different mass-functions are studied: A gaussian initial distribution in $\log(M_C)$ with mean mass and scatter similar to what one observes for the galactic globular cluster system, and a power-law distribution resembling what is seen for clusters in merging and interacting galaxies. We find that in the inner parts of the galaxy, both distributions evolve in such a way that they are consistent with the observations. In the outer parts, a gaussian initial distribution gives the better fit. This might change however if elliptic orbits are considered, or there are undiscovered low-mass clusters in the galactic halo. In any case, only a small fraction of the stellar halo of the Milky Way originated in globular clusters.

1. Introduction

Globular clusters are among the oldest objects in galaxies, and understanding the details of their formation and evolution can bring valuable insight into the early history of galaxies. One of the most interesting questions concerns the relation of globular clusters to the stellar halos of galaxies. At present, only a small fraction of halo stars are found in clusters. Observations indicate however that the galactic halo has a clumpy structure (Majewski et al. 1996, Helmi et al. 1999), and tidal streams surrounding globular clusters (Grillmair et al. 1995, Leon et al. 2000) have been detected. A significant fraction of the stellar halo might therefore have formed in compact stellar systems, although dwarf galaxies are also possible contributers.

Linked to this question is the determination of the initial mass function of globular clusters. The globular cluster system of the Milky Way as we observe it today is characterized by a gaussian distribution in absolute magnitudes, with mean $M_V = -7.4$ and scatter $\sigma_M = 1.15$ (Harris 2000). Similar distributions have been found for old cluster systems in other galaxies (Kundu et al. 1999). In contrast, young massive clusters in interacting and starburst galaxies have power-law distributions over masses $N(M) \sim M^{-\alpha}$, with slopes close to $\alpha = 2$.
If the globular cluster system of the Milky Way has started with such a mass-function, it contained many low-mass clusters which dissolve completely and cause a stronger enrichment of the stellar halo.

In this paper, we study cluster systems starting with gaussian or power-law mass-functions. We use analytic formulas for the lifetimes of star clusters and remove clusters with lifetimes smaller than a Hubble time. The number and masses of surviving clusters are then compared with the Milky Way globular cluster system in order to determine the mass that must have been initially in the cluster system. This estimate is then compared with the mass of the stellar halo. The paper is organised as follows: In section 2 we discuss the dissolution processes of globular clusters. Section 3 describes the set-up of the cluster system and in section 4 we present the results. In section 5 we draw our conclusions.

2. Dissolution processes of star clusters

Star clusters dissolve due to several processes: In the beginning the loss of gas out of which the cluster was formed and the mass-loss of individual cluster stars are most important. Later clusters dissolve mainly due to two-body relaxation and disc or bulge shocks from the varying external tidal field. Clusters are also affected by dynamical friction, which causes them to sink towards the galactic center where they are destroyed by the strong tidal field. We consider clusters moving in circular orbits and start our simulations after the initial gas is removed from the clusters and massive stars have gone supernova. Hence, we are left with only two dissolution processes: Two-body relaxation and dynamical friction.

2.1. Two-body relaxation

The lifetimes against two-body relaxation are obtained from a fit to the results of N-body simulations made by Sverre Aarseth and Douglas Heggie as part of the ‘Collaborative Experiment’ (Heggie et al. 1998). They performed simulations of multi-mass, King $W_0 = 3.0$ clusters which moved on circular orbits through an external tidal field. Figure 1 shows the half-mass times of their clusters as a function of the particle number $N$. The best fit is obtained by

$$T_{\text{Half}} = 0.375 \left( \frac{N}{\log(\gamma N)} \right)^{0.8} T_{\text{Cross}},$$

where $\gamma = 0.02$ (Giersz & Heggie 1996). The lifetimes are obtained by assuming that they are twice as large as the half-mass times. We note that the lifetimes of clusters in external tidal fields increase more slowly with the particle number than their relaxation times. It has been shown (Fukushige & Heggie 2000, Baumgardt 2001) that this is a consequence of the finite escape time of stars from such clusters. As a result, lifetimes of globular clusters are smaller than previously predicted.

2.2. Dynamical friction

According to Binney & Tremaine (1987, eq. 7-26), the time it takes for a cluster with mass $M_C$ and initial galactocentric distance $R_G$ to sink to the galactic center is given by
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Figure 1. Half-mass times as a function of the number of cluster stars for multi-mass clusters. The data is taken from the ‘Collaborative Experiment’ (Heggie et al. 1998). The solid line shows a scaling proportional to the relaxation time, fitted to the result of the largest run. It does not fit the data. The dashed line shows the fit for the lifetimes used in this work. It increases more slowly with the particle number.

\[ T_{Fric} = \frac{2.64 \times 10^{11}}{\ln \Lambda} \left( \frac{R_G}{2 \text{ kpc}} \right)^2 \left( \frac{v_{\text{circ}}}{250 \text{ km s}^{-1}} \right) \left( \frac{10^6 M_{\odot}}{M_C} \right). \]  

Here \( v_{\text{circ}} \) is the circular velocity of the galaxy and \( \ln \Lambda \) is of order 10.

3. The cluster set-up

The Milky Way is modeled as an isothermal sphere with circular velocity \( v_0 = 220 \text{ km/sec} \). We adopt an age of \( T_{\text{Hubble}} = 12 \text{ Gyr} \) for the age of the galactic globular cluster system. Cluster masses either follow a gaussian distribution with mean \( \log M_C = 5.15 \) and width \( \sigma_M = 0.6 \), or a power-law \( N(M_C) \sim M_C^{-\alpha} \) with slope \( \alpha = 2.0 \). If clusters are distributed according to a power-law, lower and upper limits of \( M_C = 10^4 M_{\odot} \) and \( 10^7 M_{\odot} \) are chosen for the cluster masses. The lower limit has no influence on the final mass-function, since clusters with \( M_C < 10^4 M_{\odot} \) dissolve at all galactocentric radii in less than a Hubble time.

We study the evolution of star clusters between galactocentric distances \( 1 \text{ kpc} < R_{GC} < 40 \text{ kpc} \). At each \( R_{GC} \), we simulate the evolution of 200,000
clusters. We first calculate their dynamical friction time $T_{\text{Fric}}$ according to eq. 2, and remove clusters with $T_{\text{Fric}} < T_{\text{Hubble}}$. For the remaining clusters, we calculate their tidal radius from the cluster mass and the galactocentric distance. We assume that the density distribution of a cluster follows a King $W_0 = 3.0$ profile, in which case the ratio of the half-mass radius of a cluster to its tidal radius is given by $r_h/r_t = 0.268$. We can then calculate the crossing times $T_{\text{Cross}}$ and the dissolution times of the clusters according to eq. 1. If the dissolution time is smaller than a Hubble time, a cluster dissolves completely, otherwise the final mass of the cluster is calculated according to

$$M_{\text{Fin}} = M_{\text{Ini}} \left( 1 - \frac{T_{\text{Hubble}}}{T_{\text{Diss}}} \right),$$

i.e. we assume a constant mass-loss rate.

4. Results

Fig. 2 shows the evolution of the mass-function of globular clusters at two galactocentric radii. A gaussian initial mass-function stays everywhere close to the initial distribution. In the inner parts, the mean mass increases slightly due to the efficient destruction of low-mass clusters. In the outer parts, the distribution changes very little since only few clusters are destroyed.

A power-law distribution shows a stronger depletion of clusters. In the inner parts, it evolves into a distribution which is very similar to the one obtained from a gaussian initial mass-function. The two distributions differ mainly at large galactocentric radii, where the power-law distribution leads to a mass-function with lower mean mass. But even at large radii, the power-law distribution evolves into a bell-shaped curve.

Fig. 3 compares the mean cluster masses with the observations of Milky Way clusters. The properties of galactic globular clusters show no strong variation with galactocentric distance. The mean cluster mass might be slighter larger around $R_{\text{GC}} = 10 \text{ kpc}$, but the differences are small. Independent of the starting condition, the final cluster systems match the Milky Way clusters for $R_{\text{GC}} < 8 \text{ kpc}$ fairly well. Hence, the initial state cannot be decided from observations of the inner clusters. In the outer parts, a gaussian initial distribution is close to the observations while a power-law mass-function produces a cluster system which has too many low-mass clusters. This could change however if elliptic cluster orbits are considered, in which case clusters are destroyed more easily due to the varying tidal field. In addition, undiscovered low-mass clusters could exist in the galactic halo, causing the mean cluster mass to be lower than observed.

The fraction of clusters that survive after 12 Gyr and the mass lost from the globular cluster system depend on the radial distribution of clusters. The number of observed globular clusters decreases as $\rho \sim R_{\text{GC}}^{-3.5}$, at least for $R_{\text{GC}} > 4 \text{ kpc}$ (Harris 2000). If we adopt the same distribution for the initial cluster system, we find that for a gaussian mass-function, $N_f/N_i = 32 \%$ of globular clusters survive over the whole range of distances studied (1 - 40 kpc). They contain 36 % of the mass that was initially in the cluster system. The corresponding numbers for a power-law distribution are 8 \% and 25 \% respectively. As expected much
fewer clusters survive. However, since most of the dissolving clusters are of low mass, the mass-loss rates differ not very much\footnote{If clusters start with a power-law mass-function, the fraction of mass surviving in clusters depends on the chosen lower and upper limits. The dependance is not very strong however. Choosing for example $10^3 M_\odot$ as a lower limit instead of $10^4 M_\odot$, would decrease the mass fraction surviving in clusters to $3/4$ of its original value.}.

According to the McMaster-database of globular cluster parameters (Harris 1996), the galactic globular cluster system contains 132 clusters between 1 and 40 kpc. These clusters have a total mass of $M_{\text{Clus}} = 3.3 \cdot 10^7 M_\odot$. The initial mass in the cluster system was therefore of order $1$ to $2 \cdot 10^8 M_\odot$. According to Suntzeff et al. (1991), the mass of the stellar halo between 4 and 25 kpc is $9 \cdot 10^8 M_\odot$. Assuming a $\rho \sim R_{\text{GC}}^{-3.5}$ density law for the halo stars, the halo

Figure 2. Mass functions of globular clusters for two galactocentric distances. The top panels show the evolution of a gaussian initial mass function, the bottom panels that of a power-law distribution. The dashed lines show the initial distributions, the solid lines the final ones. The number of final clusters in the bottom panels are multiplied by a factor of ten to show their distribution.
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Figure 3. Mean masses of globular clusters as a function of galactocentric distance. Mean masses obtained from a gaussian initial mass function are shown by a solid line, those from a power-law distribution by a dashed line. The dotted line indicates the mean mass of galactic globular clusters, which is also the starting mass of the gaussian distribution. Crosses indicate mean masses of galactic globular clusters for different galactocentric distances.

mass between 1 and 40 kpc turns out to be $2.6 \cdot 10^9 M_\odot$, which is an order of magnitude more than the mass of the globular cluster system in this distance range. Hence, the majority of halo stars was not born in clusters.

5. Conclusions

The evolution of the galactic globular cluster system under the influence of two-body relaxation and dynamical friction was studied. It was found that a gaussian initial distribution fits the present day galactic globular cluster system very well. A power-law initial distribution cannot be ruled out however since it gives a good fit to the observations in the inner parts. The differences in the outer parts could vanish if additional destruction mechanisms are considered. Furthermore, our knowledge of remote halo clusters might not be complete. We cannot constrain the fraction of stars born in low-mass clusters with $M_C < 10^4 M_\odot$, since low-mass clusters dissolve completely even at the largest distances studied.
Depending on the initial mass-function, only between 5 % and 10 % of the halo stars were born in globular clusters. This value is smaller than the fraction of stars formed in young star clusters in starburst and interacting galaxies, which seems to be close to 20 % (Meurer et al. 1995, Zepf et al. 1999). Some of these young clusters might however be unbound, or become unbound due to the mass-loss of individual cluster stars. This could bring both values into agreement.

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