EFFECTS OF THE DISSOLUTION OF LOW-CONCENTRATION GLOBULAR CLUSTERS ON THE EVOLUTION OF GLOBULAR CLUSTER SYSTEMS

E. Vesperini, S. E. Zepf
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ABSTRACT

We investigate the role of dissolution of low-concentration clusters due to mass loss through stellar evolution on the evolution of the properties of globular cluster systems (GCSs) in elliptical galaxies. Our simulations show that, for an initial mass-concentration relationship based on that inferred from Galactic globular clusters, dissolution of low-concentration clusters leads to the disruption of a large number of clusters. A power-law initial globular cluster system mass function (GCMF) similar to that observed in young cluster systems in merging galaxies is transformed by this dissolution into a bell-shaped GCMF with a mean mass similar to that of old GCSs for all the galaxies investigated. Two-body relaxation and dynamical friction, which are also included in our simulations, subsequently lead to an additional significant evolution and disruption of the population of clusters. As shown previously, when these processes act on a bell-shaped GCMF with a mean mass similar to that of old GCSs, they do not significantly alter the value of the mean mass. The final GCMFs are bell-shaped with similar peaks at different radii within galaxies and between different galaxies, in agreement with current observations.

Subject headings: galaxies: star clusters, globular clusters: general

1. INTRODUCTION

It has long been realized that globular clusters evolve dynamically, and many of the observational effects predicted by theoretical models of the dynamical evolution of globular clusters have been observed (see e.g. Meylan & Heggie 1997 for a review). The dynamical evolution of globular clusters is therefore a fundamental component of the comparison of observations and theories of globular cluster formation to the observed properties of old globular cluster systems.

Observations of starbursts and mergers have shown that clusters with the high luminosities and the compact sizes expected for globular clusters at young ages have formed in these environments (see e.g. Whitmore 2002 for a recent review and references therein). However, the young cluster systems have power-law mass functions while the old cluster systems have roughly log-normal mass functions. A power-law mass function is also suggested by many globular cluster formation models (Harris & Pudritz 1994, Elmegreen & Efremov 1997, Ashman & Zepf 2001, Elmegreen 2002). Therefore, if the systems of massive, dense young clusters are to be specifically associated with globular cluster systems, the difference in mass functions needs to be understood.

Many theoretical works have shown that dynamical processes, by preferentially disrupting low-mass clusters, can easily transform a power-law initial GCMF into a bell-shaped GCMF (e.g. Vesperini 1998 and references therein). However, in order to support the hypothesis that GCSs had a power-law initial GCMF, it is necessary to verify that evolutionary processes can lead to final GCMF parameters consistent with observations. In particular, observations show a small radial variation within individual galaxies of the mean mass of clusters (see e.g. Kundu, Zepf & Ashman 2003 for a detailed study of the M87 GCS), and a small galaxy-to-galaxy variation of the mean mass of clusters in galaxies with different masses and sizes (e.g. Harris 2001, Kundu & Whitmore 2001). Since the efficiency of evolutionary processes is expected to depend both on the properties of the host galaxy and, within individual galaxies, on the galactocentric distance, the lack of a significant galaxy-to-galaxy and radial variation of the mean mass is an interesting question to investigate.

In a number of theoretical investigations the long-term dynamical evolution of GCSs in elliptical galaxies and in the Milky Way (Okazaki & Tosa 1995, Vesperini 1997, 1998, 2001, Murali & Weinberg 1997, Baumgardt 1998) starting with a power-law initial GCMF similar to that observed in young cluster systems has been studied. These studies which include the effects of two-body relaxation, tidal shocks, dynamical friction and mass loss due to stellar evolution and a range of different initial conditions for the orbital distribution of clusters have shown that in models with power-law initial GCMF similar to that observed in young cluster systems, the radial variation within individual galaxies appears to be larger than the observational constraints, the final mean masses smaller, and the galaxy-to-galaxy variation of the final mean mass larger than suggested by the observations.

In the context of the Galactic GCS, Fall & Zhang (2001) proposed that, for models with a power-law initial GCMF, the mild radial variation in the final GCMF might be understood if the initial population of globulars spanned a narrow range of pericentric distances, corresponding to a radial anisotropy strongly increasing with radius. To test whether a velocity distribution with a strong radial anisotropy increasing outwards is a general answer to the absence of large radial mass gradients in the GCMF, Vesperini et al. (2002) studied the dynamical evolution of the M87 GCS: their models incorporated a broad range of initial conditions, including velocity distributions like that proposed by Fall & Zhang for the Galactic GCS. The advantage to studying the M87 GCS is that stringent observational constraints on both the GCMF and
the GCS kinematical properties are available. Vesperini et al. (2002) found that no model of long-term dynamical evolution could fit both the observed radial profile of the GCMF and the observed kinematics of the GCS if a power-law initial GCMF was adopted. Models with strong radial anisotropy at large radii were inconsistent with the kinematics, while isotropic models produced radial mass gradients larger than observed.

Whether dynamical processes can turn a power-law into a bell-shaped GCMF with a final mean mass consistent with observations while satisfying, at the same time, all the observational constraints on other GCS properties is therefore still an open question.

It has been shown in a number of theoretical investigations (see e.g. Chernoff, Kochanek & Shapiro 1986, Chernoff & Shapiro 1987, Chernoff & Weinberg 1990, Fukushige & Heggie 1995, Takahashi & Portegies Zwart 2000) that if a star cluster has initially a low concentration and/or if the stellar IMF contains a sufficient number of massive stars which rapidly evolve leading to a substantial early mass loss, the cluster response to this mass loss is an expansion ending with its complete dissolution. Although mass loss due to stellar evolution is included in most theoretical studies of GCSs evolution, it is always implicitly assumed that individual clusters have an initial concentration large enough to avoid dissolution due to mass loss of massive stars. The goal of this Letter is to study the role of this process on the evolution of the properties of globular cluster systems in elliptical galaxies and, in particular, to explore its effect on the evolution of the GCMF.

2. Method and Initial Conditions

In order to determine the fate of individual clusters we use a method in which the time evolution of clusters is assumed to occur along a sequence of King models with evolving mass, size and concentration. This method, which was introduced by King (1966) and adopted by Prata (1971), Chernoff, Kochanek & Shapiro (1986), Chernoff & Shapiro (1987), Vesperini (1997) to study the evolution of the Galactic GCS, allows to follow the evolution of the concentration of individual clusters and, in particular, to determine whether a cluster evolves toward lower concentrations and eventually dissolves in response to the initial expansion triggered by mass loss due to stellar evolution (we consider a cluster dissolved when its structure is equal to that of a King model with central dimensionless potential, \( W_0 \), smaller than \( 10^{-2} \); see, e.g., Chernoff & Shapiro 1987 for a more detailed description of the method adopted). This additional route to disruption is missing in all the previous investigations studying the evolution of the GCMF.

If its initial concentration is large enough, a cluster survives the initial expansion caused by stellar evolution but it loses mass and it can be disrupted because of complete evaporation due to mass loss caused by internal relaxation or because of dynamical friction. To follow the time evolution of the mass of clusters, we use the results of the N-body simulations carried out by Baumgardt & Makino (2003) (similar results are obtained if the results of N-body simulations by Vesperini & Heggie (1997) are used).

In each simulation carried out we have studied the evolution of a GCS initially made of 400000 clusters with initial masses between \( 10^4 M_\odot \) and \( 10^7 M_\odot \) distributed according to a power-law GCMF with index 1.8, with galactocentric distances ranging from \( 0.16 R_e \) to \( 20 R_e \) where \( R_e \) is the effective radius of the host galaxy. The GCS initial number density distribution is taken equal to a Navarro, Frenk & White (1996) profile with scale radius \( r_s \approx 0.02 R_e \); this is essentially equivalent to a single power-law with index equal to 3. An isotropic initial GCS velocity distribution is adopted.

For the stellar IMF of individual clusters we adopt the function suggested by a recent observational analysis by Kroupa (2001): this is a two-slope power-law function with index equal to 2.3 for \( m_T < m/m_\odot < 15 \) and index equal to 1.3 for \( 0.1 < m/m_\odot < m_T \) with \( m_T = 0.5 m_\odot \). In order to study the dependency of our results on the value of \( m_T \) we have also carried out a set of simulations for \( m_T = 0.9 m_\odot \). Mass loss due to stellar evolution is modeled as in Chernoff & Weinberg (1990).

The initial cluster concentration (the standard concentration, \( c \), used to characterize King models and defined as the logarithm of the ratio of the tidal to the King core radius is adopted here) is assumed to increase with the mass of clusters as observed for globular clusters in the Milky Way (see e.g. Chernoff & Djorgovski 1989, Djorgovski & Meylan 1994). As discussed in McLaughlin (2000), the observed trend between mass and concentration is likely to be primordial. For our simulations we have adopted \( c = -2.8 + 0.75 \log M \) with a uniform dispersion of 0.2 around this correlation; this is based on the trend observed for Galactic clusters located at large galactocentric distances which are those more likely to keep memory of the initial conditions. In deriving this relationship we have considered the possibility that some of the clusters with the highest concentrations could have initially lower concentrations and so we have based our choice on the properties of clusters with lower concentrations. The spread around the adopted \( c - \log M \) relationship is adopted because at least part of the observed broad dispersion in this relationship is likely to be primordial (McLaughlin 2000).

For the host galaxy we have adopted an isothermal model with constant circular velocity and we have studied the evolution of GCS for a sample of 295 host galaxies with values of the effective radius and of the effective mass equal to those determined observationally by Burstein et al. (1997). We have focussed our attention on giant galaxies with log \( M_r > 10.5 \) for which good observational constraints on the GCLF are available (see e.g. Kundu & Whitmore 2001, Larsen et al. 2001).

3. Results

In Figure 1 we plot the final GCS mean masses from our simulations versus the effective mass of the host galaxies. The values of the mean masses plotted are those of clusters with projected galactocentric distances between \( 0.5 R_e \) and \( 1.5 R_e \) which is the range of galactocentric distances covered by observational data. The observational data shown in figure 1 are from the analysis of Kundu & Whitmore (2001) \( (M/L_V = 2 \) has been adopted to convert luminosities to masses).

As discussed in the Introduction above, in previous studies of the evolution of GCSs not including the effect of disruption of low-concentration clusters, it was found that
for GCSs starting with a power-law initial GCMF similar to that observed in young cluster systems, the final GCS mean masses were smaller than those observed, the galaxy-to-galaxy variation of the effective mass of the host galaxy. Crosses (open dots) show the final mean masses from simulations with $m_T = 0.5 \, m_\odot$ ($m_T = 0.9 \, m_\odot$) (see section 2 for the definition of $m_T$). Filled dots show the observed GCS mean masses for a sample of giant elliptical galaxies from Kundu & Withmore (2001) ($M/L_V = 2$ has been adopted to convert luminosities to masses).

Although dynamical friction and mass loss due to two-body relaxation lead to the disruption of a significant fraction of clusters, the process of dissolution of low-concentration clusters considered in this investigation appear to be required to obtain final GCMF properties consistent with observations from a power-law initial GCMF.

As discussed in detail in Vesperini (1998) and in Vesperini (2000), when relaxation and dynamical friction act on a bell-shaped GCMF with a mean mass similar to that of old GCSs (which in this case is produced by disruption of low-concentration clusters) their effects do not manifest themselves in a significant evolution of the mean mass; nevertheless, these processes are always important as they considerably reduce the number of clusters in GCSs and change the properties of those which survive. Note that for the initial GCMF considered in this study, the number of clusters massive enough to be affected by dynamical friction is small and most of the GCMF evolution occurring after the disruption of low-concentration clusters is determined by mass loss and disruption due to relaxation.

Figure 2 illustrates the efficiency of different dynamical processes: this figure shows the fraction of the initial population of clusters disrupted as a result of the dissolution of low-concentration clusters and the fraction of the population unscathed by this process which is subsequently disrupted by evaporation due to two-body relaxation and dynamical friction as a function of the effective mass of the host galaxy.
Dissolution of low-concentration clusters induced by mass loss due to stellar evolution is mostly determined by the initial concentration of individual clusters and it depends only very weakly on the mass of the host galaxy. On the other hand, the efficiency of disruption caused by relaxation and dynamical friction strongly depends on the properties of the host galaxies and the fraction of clusters disrupted by these processes is smaller for more massive galaxies. As already discussed in Murali & Weinberg (1997) and in Vesperini (2000), the dependency of the fraction of surviving clusters on the host galaxy mass can give rise to a trend between cluster specific frequency, defined as the number of clusters per galaxy unit luminosity (Harris & van den Bergh 1981), and the mass or luminosity of the host galaxy consistent with that suggested by observations (see e.g. Ashman & Zepf 1998, Elmegreen 2000 for reviews).

We emphasize that the joint effect of all the dynamical processes considered leads to the disruption of a significant fraction of the initial population of clusters; according to the results of our simulations, for the host galaxies considered in this study the current number of clusters within the whole range of galactocentric distances considered in this study is, depending on the properties of the host galaxy, between 3 and 12 per cent of the initial population. Any investigation using estimates of the current number of clusters in galaxies to study the efficiency of cluster formation should not leave out of consideration the effects of dynamical evolution and the dependence of their efficiency on the properties of the host galaxy and on the galactocentric distance. As to the mass of clusters, the current total mass in clusters located within the range of galactocentric distances considered here is between 10 and 43 per cent of the total initial mass of clusters within the same range of galactocentric distances.

4. CONCLUSIONS

In this paper we have studied the role of the dissolution of low-concentration clusters induced by mass loss due to stellar evolution on the properties of GCSs in elliptical galaxies.

We have found that the dissolution of low-concentration clusters can significantly affect the GCMF evolution; in particular we have shown that this process can transform a power-law initial GCMF similar to that observed in young cluster systems into a bell-shaped GCMF with parameters similar to those observed in old GCSs before the effects of two-body relaxation and dynamical friction become dominant. Relaxation and dynamical friction then lead to the additional disruption of a significant fraction of the remaining clusters with relaxation playing a dominant role; however, as shown in Vesperini (2000), when two-body relaxation and dynamical friction act on a bell-shaped GCMF with parameters similar to those observed in old GCSs, the final values of the GCS mean mass and the galaxy-to-galaxy variation of the GCS mean mass are perfectly consistent with observations.

Dissolution of low-concentration clusters therefore may provide the missing link between the power-law GCMF observed in young cluster systems in merging galaxies and the bell-shaped GCMF required to obtain, after the additional evolution due to two-body relaxation and dynamical friction, final GCMF properties consistent with observations.

In a future work we will study the dependence of the evolution of the GCMF on the initial distribution of cluster concentrations. We will also investigate the time evolution of the GCMF and compare our results to observations of the GCMF in young and intermediate-age GCSs.

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