Extragalactic Star Clusters
IAU Symposium Series, Vol. 207, 2002
Doug Geisler, Eva K. Grebel, and Dante Minniti, eds.

Evolution of Globular Cluster Systems in Elliptical Galaxies

Enrico Vesperini

Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA

Abstract. We study the evolution of the main properties of globular cluster systems in elliptical galaxies. In particular, we focus our attention on the evolution of the mass function of globular cluster systems (GCMF), on the fraction of surviving clusters and on the ratio of the final to initial total mass in clusters and we explore the dependence of these properties on the structure of the host galaxy and on the initial GCMF. We show that the observed universality of the GCMF parameters in galaxies with different structures can be reconciled with the effects of evolutionary processes and with the significant differences in the efficiency of evolutionary processes in different host galaxies; the final mean masses of globular cluster systems in massive galaxies can be very similar to each other with a small galaxy-to-galaxy dispersion in spite of large differences in the fraction of surviving clusters.

1. Introduction

A large number of observational investigations on the properties of globular cluster systems (hereafter GCS) in elliptical galaxies (see e.g. Ashman & Zepf 1998 and Harris 2001) have been carried out and they have provided many indications on the relations between the properties of GCS and those of the host galaxies as well as on the dependence of the properties of individual GCs on the position inside their host galaxies. Although most theoretical studies of the evolution of GCS predict that evolutionary processes should have a significant effect on the properties of individual clusters and of those of GCS, several observational findings seem to be at odds with these predictions; for example the mass function of the GCS (hereafter we will indicate the mass function and the luminosity function of a GCS by GCMF and GCLF respectively) of many galaxies with structures markedly different from each other, in which the efficiency of evolutionary processes should be different, are very similar to each other and they are all well fitted by a log-normal function with a small galaxy-to-galaxy variation of the mean mass.

As to the radial variations of the GCMF parameters inside individual galaxies, while some observational analyses have shown that inner clusters tend to be more luminous than outer clusters, most observational studies fail to report any significant radial trend in the GCMF parameters.

https://doi.org/10.1017/S0074180900224509 Published online by Cambridge University Press

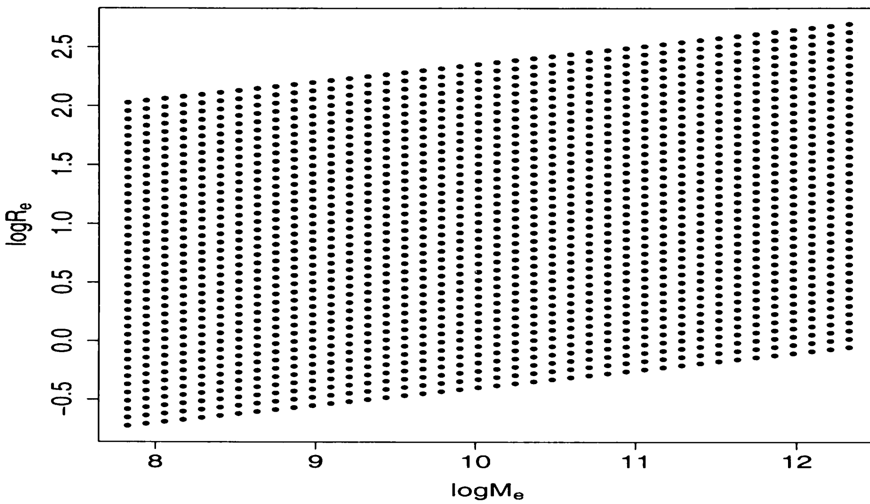

Figure 1. Set of values of the effective mass, M_e ($M_{\odot}$), and of the effective radius, R_e (kpc), of the host galaxies considered in this investigation.

The main issue addressed here is whether it is possible to reconcile theoretical predictions concerning the effects of evolutionary processes with the observational findings showing small or negligible differences between the properties of GCS in galaxies in which the efficiency of evolutionary processes is different.

We have studied the dependence of the evolution of the GCMF, of the fraction of surviving clusters and of the ratio of the final to the initial total mass of clusters on the structure of the host galaxy. Both a log-normal initial GCMF with parameters equal to those observed in the external regions of some elliptical galaxies where evolutionary processes are unlikely to have altered the initial conditions of the GCS and a power-law initial GCMF similar to that observed for young cluster systems in merging galaxies have been considered. Further details on the results of this investigation can be found in Vesperini (2000) and in Vesperini (2001).

2. Method and Initial Conditions

The evolution of the masses of individual globular clusters in a GCS has been calculated using the expressions derived by means of a large set of N-body simulations by Vesperini & Heggie (1997) and already used to study the evolution of the Galactic GCS in Vesperini (1998). The evolutionary processes considered are the mass loss associated with the evolution of individual stars in a cluster, two-body relaxation, the presence of the tidal field of the host galaxy and dynamical friction. For the host galaxy we will assume a simple isothermal model with constant circular velocity.

The effects of dynamical friction at any time t are included by removing, at that time, all clusters with time-scales of orbital decay (see e.g. eq. 7.26 in Binney & Tremaine 1987) smaller than t.

Each host galaxy we have considered is characterized by a value of the effective radius, R_e, and of the effective mass M_e. For each GCS we have explored, we have drawn 20000 random values of M_i according to the initial GCMF chosen and the distances of clusters from the center of the host galaxy are such that the number of cluster per cubic kpc is proportional to $R_g^{-3.5}$ with R_g ranging from $0.16R_e$ to $5R_e$. We have studied the evolution of GCS in a large set of different host galaxies: figure 1 shows all the pairs $(\log M_e, \log R_e)$ considered. The evolution of each GCS has been followed for one Hubble time here taken equal to 15 Gyr.

3. Results

Log-normal initial GCMF

We have adopted a log-normal initial GCMF with mean mass $\overline{\log M_i} = 5.25$ and dispersion $\sigma_i = 0.6$ which is similar, for example, to the GCMF of outer clusters in M87 (see e.g. McLaughlin, Harris & Hanes 1994, Gnedin 1997). The four panels of figure 2 show the contour plot of the final mean mass $\overline{\log M_f}$, of the final dispersion, σ_f, of the ratio of the final to the initial total number of clusters, N_f/N_i, and of the ratio of the final to the initial total mass of clusters, $M_{GCS,f}/M_{GCS,i}$ in the $\log M_e - \log R_e$ plane. It is interesting to note that for a large number of host galaxies, $\overline{\log M_f}$ and σ_f do not differ significantly from their initial values. A comparison of the contour plot of the fraction of surviving clusters (figure 2c) with the contour plots of $\overline{\log M_f}$ and of σ_f (figures 2a and 2b) clearly shows that, in general, *the disruption of a large number of clusters by evolutionary processes does not necessarily produce a significant evolution of the GCMF parameters.*

In order to determine the implications of these results for real galaxies, the values of M_e and R_e provided by Burstein et al. (1997) for a sample of elliptical galaxies have been superimposed to the contour plots of figure 2. It is important to emphasize that the fraction of the initial population of clusters which survive after one Hubble time for the sample of galaxies considered spans the entire range of possible values; in contrast with such a broad range of values of N_f/N_i figure 2a shows that most real galaxies occupy a region of the $\log M_e - \log R_e$ plane corresponding to a very narrow range of $\overline{\log M_f}$: *a small range of values of $\overline{\log M_f}$ in galaxies with different structures implies neither that the fraction of the initial number of clusters which have been disrupted in these galaxies is similar nor that evolutionary processes did not alter the initial conditions of individual clusters.* In particular, for galaxies with $\log M_e \gtrsim 10-10.5$, we find that $\overline{\log M_f}$ is approximately constant ($\overline{\log M_f} \simeq 5.16$ or $M_V = -7.3$ for $M/L_V = 2$) with a small galaxy-to-galaxy dispersion consistent with that found in observational analyses (see e.g. Harris 2001). The results obtained thus clearly show that *it is possible to reconcile the observed universality of the GCMF proper-*

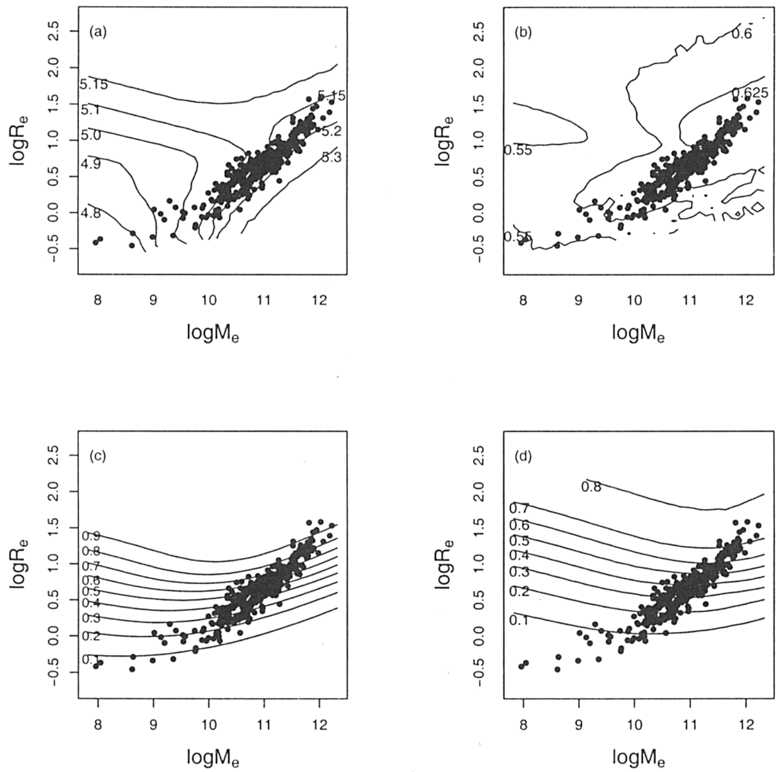

Figure 2. Contour plots of (a) $\overline{\log M_f}$, (b) σ_f, (c) N_f/N_i, (d) $M_{GCS,f}/M_{GCS,i}$ in the plane $\log M_e - \log R_e$ with the observational values of $\log M_e$ and $\log R_e$ for elliptical galaxies (data from Burstein et al. 1997) superimposed as filled dots.

ties with the effects of dynamical evolution and with differences in the efficiency of evolutionary processes in different galaxies. Evolutionary processes , while causing the disruption of a large number of clusters and producing significant changes in the properties of many of the surviving clusters, can leave the GCMF parameters approximately unchanged or lead to similar final values in galaxies in which their efficiency is significantly different; as discussed in Vesperini (1998), the equilibrium of the GCMF parameters is a dynamical equilibrium which results from the balance between disruption of low-mass clusters by two-body relaxation, disruption of high-mass clusters by dynamical friction and evolution of the masses of the clusters which survive.

As for the dependence of the fraction of surviving clusters on the effective mass of the host galaxy, our analysis shows that, although with a large scatter, a power-law scaling $N_f/N_i \sim M_e^{0.35}$ fits the theoretical results well. This implies that for $N_i \sim M^{\alpha}$ and $M/L \sim L^{\beta}$, $N_f \sim M^{\alpha+0.35}$ or $N_f \sim L^{(1+\beta)(\alpha+0.35)}$; for

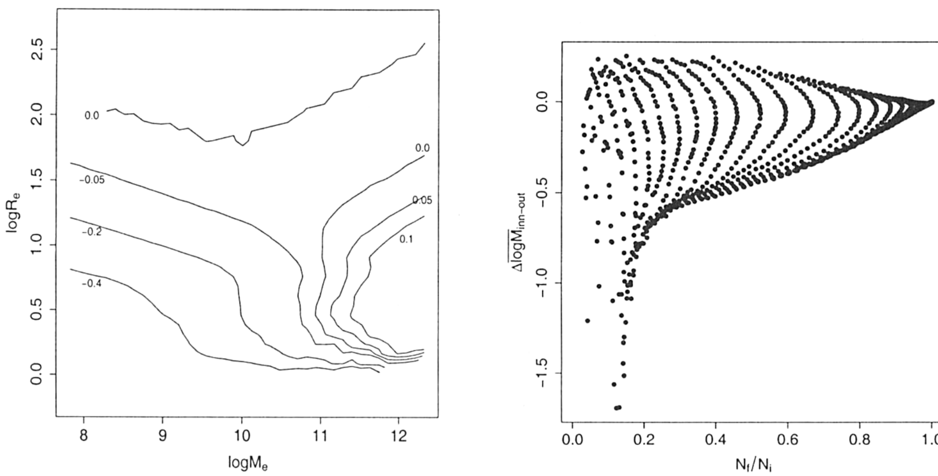

Figure 3. Left-hand panel: contour plot of the difference between the final mean mass of inner clusters ($R_g < R_e$) and of outer clusters ($R_g > R_e$), $\Delta\overline{\log M}_{inn-out}$, in the plane $\log M_e - \log R_e$. Right-hand panel: $\Delta\overline{\log M}_{inn-out}$ versus the fraction of surviving clusters after 15 Gyr, N_f/N_i, for all the host galaxies plotted in figure 1.

$N_i \sim L^{\lambda}$, $N_f \sim M^{\left(\frac{\lambda}{1+\beta}+0.35\right)}$ or $N_f \sim L^{0.35(1+\beta)+\lambda}$. For example, either assuming $N_i \propto M$ or $N_i \propto L$, our results imply that evolutionary processes will lead to a dependence of the current specific frequency on the mass (and on the luminosity as well) of the host galaxy: in particular, for $N_i \propto L$ we obtain $N_f \sim M^{1.16}$ or, adopting $M/L \sim L^{0.24}$ (see e.g. Faber et al. 1987), $N_f \sim L^{1.43}$; for $N_i \propto M$ we obtain $N_f \sim M^{1.35}$ or $N_f \sim L^{1.67}$. We thus conclude that, starting with a mass- (or luminosity-) independent specific frequency, evolutionary processes can lead to a trend of mass (or luminosity)-specific frequency consistent with that observed. The possible role of evolutionary processes in producing a luminosity-specific frequency correlation has been pointed out also by Murali & Weinberg (1997) and this result is in agreement with their conclusion.

It is important to remark that our analysis shows that evolutionary processes can lead to a trend of mass (or luminosity)-specific frequency without producing, at the same time, any correlation (which would be in contrast with observations) between the mean mass of clusters and the mass of the host galaxy for galaxies with $\log M_e \gtrsim 10.5$.

The left-hand panel of figure 3 shows the contour plot of the difference, $\Delta\overline{\log M}_{inn-out}$, between the mean mass of inner clusters (defined as those with galactocentric distance smaller than R_e) and outer clusters (those located at galactocentric distances larger than R_e).

Since the efficiency of evolutionary processes depends on the galactocentric distance, the formation of a radial gradient in the GCMF parameters has to be expected; nevertheless, as shown in figure 3, in several cases (and in particu-

https://doi.org/10.1017/S0074180900224509 Published online by Cambridge University Press

lar for values of M_e and R_e corresponding to those of real elliptical galaxies) this gradient is very weak. Moreover, since the observed positions of globular clusters in external galaxies are not real galactocentric distances but projected distances, any radial gradient will appear even weaker and its detection is likely to be difficult (see e.g. Harris 2001). The right-hand panel of figure 3 shows that while all GCS characterized by a large value of $\Delta\overline{\log M}_{inn-out}$ have had their initial population of clusters significantly depleted by evolutionary processes, *a weak or negligible radial gradient of the mean mass does not imply that evolutionary processes have not played an important role in modeling the properties of individual clusters and in disrupting a significant fraction of the initial number of clusters.*

Other bell-shaped initial GCMF

Initial GCMFs different from a log-normal but still bell-shaped when binned in $\log M$ have been investigated; in particular we have studied the evolution of the GCS with an initial GCMF equal to a t_5 distribution (see e.g. Secker 1992) with mean mass and dispersion equal to those considered above and with an initial GCMF equal to a two-index power-law in M with index $\alpha_1 = 0.2$ for $M < 10^{5.25} M_\odot$ and $\alpha_2 = 1.8$ for $M > 10^{5.25} M_\odot$ (this GCMF has a bell shape with a turnover at $\log M = 5.25$ if binned in $\log M$). The evolution of these GCMFs has been studied for GCS in elliptical galaxies with values of M_e and R_e equal to the observational values provided by Burstein et al. (1997); the difference between the final mean mass obtained when a log-normal initial GCMF is adopted and that obtained using either the t_5 or the two-index power-law is for almost all the host galaxies considered around 1 per cent and all the conclusions obtained for a log-normal initial GCMF hold also for these other GCMFs.

Dependence on the initial mean mass

To study the dependence of the results on the initial mean mass we have restricted our attention to galaxies with $\log M_e > 10.5$. We have adopted the following values of $\log M_e$ and $\log R_e$: $(\log M_e, \log R_e) =$ (12,1.4), (11.75,1.18), (11.5,1), (11.25,0.8), (11.0,0.64), (10.75,0.52), (10.5,0.4); these values span the entire strip of the $\log M_e - \log R_e$ plane covered by real galaxies with $\log M_e >$ 10.5. The main evolutionary process responsible for the disruption of clusters is evaporation due to internal relaxation for GCS with low values of $\overline{\log M}_i$, or, as $\overline{\log M}_i$ increases, disruption of high-mass clusters by dynamical friction. As discussed in Vesperini (1998), $\overline{\log M}_f$ is larger or smaller than $\overline{\log M}_i$ depending on the balance between disruption of low-mass clusters by evaporation, disruption of high-mass clusters by dynamical friction and evolution of the masses of the clusters which survive: for low values of $\overline{\log M}_i$ most of the disrupted clusters are low-mass clusters and, in general, $\overline{\log M}_f > \overline{\log M}_i$ while, as $\overline{\log M}_i$ increases, disruption by dynamical friction becomes the most important process and most of the disrupted clusters are those in the high-mass tail of the initial GCMF which leads to $\overline{\log M}_f < \overline{\log M}_i$.

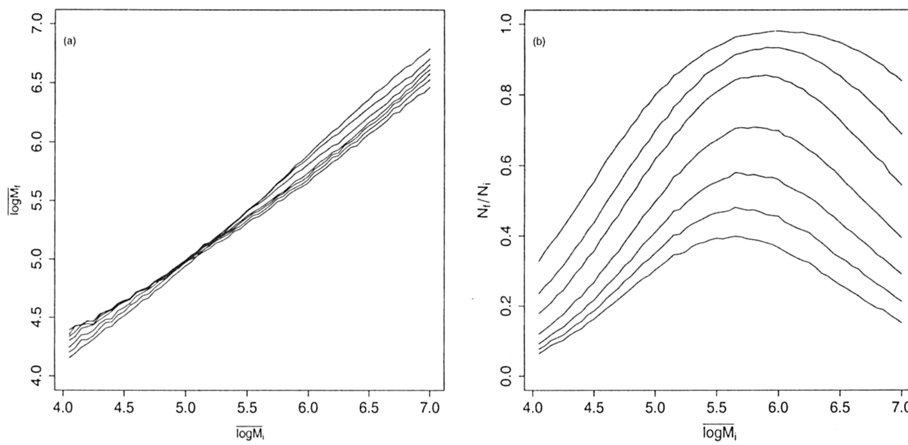

Figure 4. (a) $\overline{\log M}_f$, (b) N_f/N_i versus the initial value of $\overline{\log M}$ (assuming a log-normal initial GCMF with $\sigma = 0.6$) for the seven host galaxies with $\log M_e > 10.5$ discussed in the text. The seven curves shown correspond, from the upper to the lower one, to host galaxies with decreasing values of M_e (in panel (a) the curves cross each other, and we refer to the order of the seven curves on the right-hand side of the plot).

Figure 4a shows $\overline{\log M}_f$ as a function of $\overline{\log M}_i$ for the seven fiducial host galaxies considered. The range of values spanned by $\overline{\log M}_f$ is larger for low and high values of $\overline{\log M}_i$ while for intermediate values of $\overline{\log M}_i$ ($4.7 \lesssim \overline{\log M}_i \lesssim 5.5$), in spite of the significant spread of values of N_f/N_i (see figure 4b) the range of values of $\overline{\log M}_f$ is very small.

The dependence of $\overline{\log M}_f$ on M_e varies with $\overline{\log M}_i$: for low values of $\overline{\log M}_i$, $\overline{\log M}_f$ decreases as M_e increases while $\overline{\log M}_f$ increases with M_e for high values of $\overline{\log M}_i$. Since here we have restricted our attention to galaxies with $\log M_e > 10.5$, for which observational analyses show that $\overline{\log M}$ spans a narrow range of values, our results seem to exclude the possibility that the initial GCMF was a log-normal function with low ($\overline{\log M}_i \lesssim 4.7$) or high ($\overline{\log M}_i \gtrsim 5.5$) values of the mean mass. Moreover the values of $\overline{\log M}_f$ obtained for $\overline{\log M}_i \lesssim 4.7$ and for $\overline{\log M}_i \gtrsim 5.5$ do not fall in the range of observed values.

Power-law initial GCMF

The motivation for considering a power-law initial GCMF comes both from some theoretical investigations of globular clusters formation (see e.g. Elemgreen & Efremov 1997, Harris & Pudritz 1994) which predict a power-law initial GCMF and from several observational studies of young clusters in interacting and merging galaxies (see e.g. Whitmore 1999 for a review and references

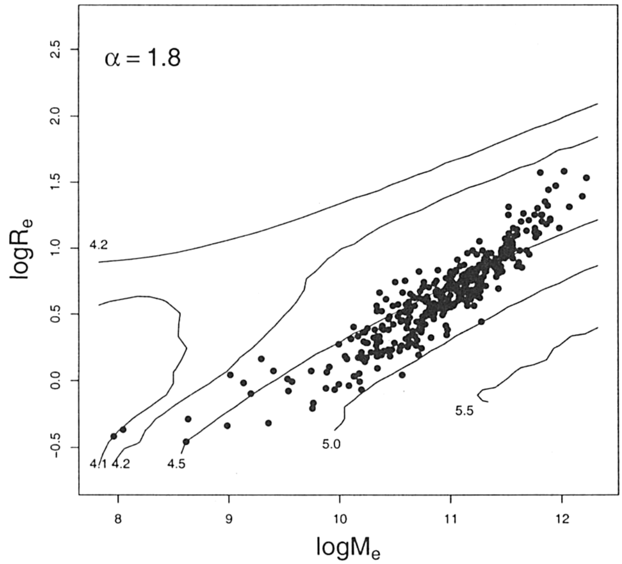

Figure 5. Contour plot of $\overline{\log M_f}$ in the plane $\log M_e - \log R_e$ with observational values of $\log M_e$ and $\log R_e$ for elliptical galaxies (data from Burstein et al. 1997) superimposed as filled dots. The initial GCMF adopted is a power-law function with $\alpha = 1.8$.

therein) showing that these systems are characterized by a power-law GCLF. As far as the evolution of the shape of the GCMF is concerned, several theoretical investigations (see e.g. Vesperini 1994, 1997, 1998, Okazaki & Tosa 1995, Elmegreen & Efremov 1997, Baumgardt 1998) have shown that a power-law initial GCMF can be turned by evolutionary processes into a bell-shaped GCMF similar to a log-normal; on the other hand it is not clear whether evolutionary processes, acting with different efficiency in galaxies with different structures, can turn an initial power-law into a log-normal GCMF with similar values of the parameters in different galaxies as found in most current observational studies.

Figure 5 shows the contour plot of $\overline{\log M_f}$ in the $\log M_e - \log R_e$ plane obtained from simulations of the evolution of GCS with a power-law initial GCMF, $f(M) \propto M^{-\alpha}$, for $10^4\ M_\odot < M < 10^7\ M_\odot$ with $\alpha = 1.8$. The values of $\log M_e$ and $\log R_e$ determined by Burstein et al. (1997) for a sample of elliptical galaxies are superimposed in this figure. While both for a log-normal and a power-law initial GCMF, the evolutionary processes considered in this investigation are very important and lead to the disruption of a significant fraction of the initial population of clusters, the dependence of their efficiency on the structure of the host galaxy manifests itself in the final GCMF parameters only for the power-law initial GCMF (or as discussed above, for log-normal initial GCMF with either low, $\overline{\log M_i} \lesssim 4.7$, or large, $\overline{\log M_i} \gtrsim 5.5$, values of $\overline{\log M_i}$).

https://doi.org/10.1017/S0074180900224509 Published online by Cambridge University Press

It is evident that the range of values of $\overline{\log M_f}$ obtained starting with a power-law initial GCMF is much broader than that found above for a log-normal initial GCMF (compare figure 5 with figure 2a) and it is not consistent with the approximate universality of the turnover of the GCLF found in observational investigations (see e.g. Harris 2001). Moreover for most galaxies the values of $\overline{\log M_f}$ obtained are smaller than those observed.

As for the radial variation of $\overline{\log M_f}$ within individual galaxies, we find that the differences between the mean mass of inner and outer clusters is larger than that found for a log-normal initial GCMF and not consistent with observations (see e.g. figure 4 in Vesperini 2001).

A complete understanding of the relation between young cluster systems in merging galaxies, which are characterized by a power-law GCLF similar to that considered here, and old cluster systems in elliptical galaxies requires further exploration and work on this issue is currently in progress.

References

Ashman K.M., Zepf S.E., 1998, Globular Cluster Systems, Cambridge University Press

Baumgardt H., 1998, A&A, 330, 480

Binney J., Tremaine S., 1987, Galactic Dynamics, Princeton University Press, Princeton, New Jersey

Burstein D. , Bender R., Faber S., Nolthenius R., 1997, AJ, 114, 1365

Elmegreen B.G., Efremov Y.N., 1997, ApJ, 480, 235

Faber S.M., Dressler A., Davies R., Burstein D., Lynden-Bell D., 1987, in Nearly Normal Galaxies, ed. S.M.Faber (New York Springer) 175

Gnedin O.Y., 1997, ApJ, 474, 223

Harris W.E., Pudritz R.E., 1994, ApJ, 429, 177

Harris W.E., 2001,in Star Clusters, Lectures for 1998 Saas-Fee Advanced School on Star Clusters, ed. L. Labhardt, B. Binngeli, (New York Springer)

McLaughlin D., Harris W.E. & Hanes D.A., 1994,ApJ, 422, 486

Murali C., Weinberg M.D., 1997, MNRAS, 288, 767

Okazaki T., Tosa, M., 1995, MNRAS, 274, 48

Secker J., 1992, AJ, 104, 1472

Vesperini E., 1994, Ph.D. Thesis, Scuola Normale Superiore, Pisa

Vesperini E., 1997, MNRAS, 287, 915

Vesperini E., 1998, MNRAS, 299, 1019

Vesperini E., 2000, MNRAS, 318, 841

Vesperini E., 2001, MNRAS, 322, 247

Vesperini E., Heggie D.C., 1997, MNRAS, 289, 898

Whitmore B.C., 1999, in Galaxy interactions at low and high redshift, IAU Symp. 186, Barnes J.E. & Sanders D.B. editors, Kluwer Academic Publishers, p.251