Evolution of globular cluster systems in three galaxies of the Fornax cluster

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ABSTRACT
We studied and compared the radial profiles of globular clusters and of the stellar bulge component in three galaxies of the Fornax cluster observed with the WFPC2 of the HST. A careful comparative analysis of these distributions confirms that stars are more concentrated toward the galactic centres than globular clusters, in agreement with what was observed in many other galaxies. If the observed difference is the result of evolution of the globular cluster system starting from initial profiles similar to those of the halo–bulge stellar components, a relevant fraction of their mass (74%, 47%, 52% for NGC 1379, NGC 1399 and NGC 1404, respectively) is disappeared in the inner regions, likely contributing to the nuclear field population, local dynamics and high energy phenomena in the primeval life of the galaxy. An indication in favour of the evolutionary interpretation of the difference between the globular cluster system and stellar bulge radial profiles is given by the positive correlation we found between the value of the mass lost from the GCS and the central galactic black hole mass in the set of seven galaxies for which these data are available.

Key words: galaxies: globular clusters; galaxies: star distribution; galaxies: globular cluster evolution; galaxies: nuclei

1 INTRODUCTION
A lot of elliptical galaxies have globular cluster systems (hereafter GCSs) that are less concentrated to the galactic centre than the bulge-halo stars, thus showing radial distributions with larger core radii than those of the bulges. Two classical examples of this phenomenon are the two Virgo giants M87 and M49 (Grillmair et al., 1986, McLaughlin, 1995), to which our Galaxy and M31 have been added later (Capuzzo-Dolcetta & Vignola, 1997). The sample of galaxies that shows this particular feature has been recently enlarged thanks to 11 elliptical galaxies selected by Capuzzo-Dolcetta & Tesseri (1999) in a sample of 14 galaxies with kinematically distinct cores (Forbes et al., 1996) observed with the WFPC2 of the Hubble Space Telescope. Though we could not yet conclude that this phenomenon is common to all galaxies, we may say that there is no case where the halo stars are less concentrated than the GCS. Moreover there is a general agreement on that the difference between the two radial distributions is real and not due to a selective bias. Consequently, different hypotheses have been advanced with the purpose to explain this feature. Among these, two seem the most probable:

(i) the difference between the two distributions reflects different formation ages of the two systems, as suggested by Harris & Racine (1979) and Racine (1991); in their opinion globular clusters originated earlier, when the density distribution was less peaked. However, this hypothesis cannot explain why the two distributions are very similar in the outer galactic regions.

(ii) another explanation is based on the simple and reasonable assumption of coeval birth of globular clusters and halo stars (McLaughlin, 1995), with a further evolution of the GCS radial distribution, while the collisionless halo stands almost unchanged.

The GCS evolution is due to

(i) dynamical friction, that brings massive clusters very close to galactic centre,
(ii) tidal interaction with a compact nucleus (see for example Capuzzo-Dolcetta, 1993).

The combined effect of these dynamical mechanisms acts to deplete the GCSs in the central, denser regions, leaving almost unchanged the outer profile, that so remains similar to the halo stars’ one. The efficiency of the mentioned phenomena is higher in galactic triaxial potentials (see for example Ostriker et al., 1989, Pesce, Capuzzo-Dolcetta & Vietri, 1992), in which we find a family of orbits, the ‘box-like’, that do not conserve any component of their angular momentum.
and then well sample the central galactic regions. Pesce et al.
(1992) showed as globular clusters moving on box orbits lose
their orbital energy at a rate an order of magnitude larger
than on loop orbits of comparable size and energy. These
results showed as the previous evaluations of the dynamical
friction efficiency, based on very simplified hypotheses on
the globular cluster orbit distribution, led to an overestimate
of the dynamical braking time scales. On the contrary, it
has been ascertained that massive globular clusters in tri-
axial potentials could be braked during their motion so to
reach the inner regions in a relatively short time (Capuzzo-
Dolcetta, 1993). There they could have started a process of
merging, giving origin to a central massive nucleus (eventu-
ally a black hole) or fed a preexistent one (Ostriker, Binney
& Saha, 1989; Capuzzo-Dolcetta, 1993). Under the hypoth-
esis that the initial GCS and halo-bulge radial distributions
were the same, an accurate analysis of the observations al-

dows an estimate of the number of “missing clusters” and
therefore of the mass removed from the GCSs.

Actually, McLaughlin (1995), Capuzzo-Dolcetta & Vignola
(1997) and Capuzzo-Dolcetta & Tesseri (1999), scaling the radial surface profiles of the halo stars of a galaxy to that
its globular cluster system, estimated the number of missing
globular clusters as the integral of the difference between
the two radial profiles. A study like this led, for example,
Capuzzo-Dolcetta & Vignola (1997) and Capuzzo-Dolcetta
& Tesseri (1999) to suggest that the compact nuclei in our
galaxy, M31 and M87 as well as in many other galaxies could
have reasonably sucked a lot of decayed globular clusters in
the first few Gyrs of life. The aim of this paper is an ex-
tension of previous (McLaughlin 1995; Capuzzo-Dolcetta
& Vignola 1997; Capuzzo-Dolcetta & Tesseri, 1999) works
to the globular cluster data of a sample of three elliptical galax-
ies in the Fornax cluster (NGC 1379, NGC 1399 and NGC
1404) whose HST data were taken by Forbes et al. 1998a,b,
hereafter referred to F98a and F98b.

2 THE DATA AND THE RESULTS

In this Section we present and discuss our analysis of GCS
radial distribution in the overmentioned galaxies in the
Fornax cluster. The data come from recent HST WFPC2 ob-
servations (F98a, F98b) and, so, they take the advantage of
the HST excellent resolution, which allows an accurate analysis
of the crowded inner regions of galaxies at Virgo and Fornax
cluster distance. Moreover it allows the subtraction of most
of background galaxies. The available density data are, as
we will see later, at a high level of completeness.
We have approximated the observed density profiles with a
modified “core model”

\[
\Sigma(r) = \frac{\Sigma_0}{\left[1 + \left(\frac{r}{r_c}\right)^\gamma\right]^{\gamma}},
\]

(1)

where \(\Sigma_0\), \(\gamma\) and \(r_c\) are free parameters (\(r_c\) is called core
radius, but, to be precise, it corresponds to the usual defini-
tion of being the distance from the centre where the surface
distribution halves its central value just when \(\gamma = 1\). We have
chosen the free parameters in (1) minimizing the r.m.s
error, i.e.

\[
\sigma = \sum \frac{(f_i - f_{0i})^2 p_i}{\sum f_{0i}^2 p_i}
\]

(2)

where \(f_i\) and \(f_{0i}\) are, respectively, the fitted and the observed
values of the surface density. We have defined the weights \(p_i\)
as the inverse of the error bars of the surface density data.
The modified core model approximates very well the GCS
density data in the inner regions of the two galaxies NGC
1399 and NGC 1404 (\(\sigma \sim 10^{-4}\)), while the \(\sigma\) value results
a little higher (\(\sim 10^{-3}\)) for NGC 1379. As we will see in
the following, this is justified by the somewhat peculiar be-
avour of the light profile of the latter galaxy. By means
of fitting formula (1) we estimated the number of “missing”
clusters in a galaxy and the corresponding mass removed
from its GCS. In fact, an approximated value of the mass
fallen to the galactic centre is obtained through the two val-
ues, \(N_i\) and \(\langle m_i\rangle\), of the number and of the mean mass of
the missing (‘lost’) globular clusters. A priori, the determi-
nation of \(\langle m_i\rangle\) needs a detailed evaluation of the effects of
evolutionary processes on the mass spectrum of the
GCS. However, the most relevant phenomena (tidal shocking
and dynamical friction) act on opposite sides of the initial
mass function then – if the initial mass function is not too
asymmetric – we expect that the mean value of the glob-
ular cluster mass has not changed very much in time (see
Capuzzo-Dolcetta & Tesseri, 1997). Hence we can assume
the present mean value of the mass of globular clusters, \(m\),
as a good reference value for \(\langle m_i\rangle\). To estimate \(m\) it is thus
necessary to assume a mass function that satisfactorily rep-
resents the present distributions of globular clusters in the
three galaxies of our sample. On the basis of the observed
similarity among the mass spectra of elliptical galaxies (Ha-
riss & Pudritz 1994; McLaughlin 1994), we have obtained a
single mass spectrum for the Fornax galaxies normalizing
the mass spectrum adopted by McLaughlin (1995) for the
Virgo giant M87. We have made this normalization using a
mass to light ratio \(\beta \equiv (M/L)_{V,0}\) equal to 1.5 for the GCS.

The resulting mass spectrum is

\[
N(m) \propto m^{-s}
\]

(3)

with \(s\) defined as

\[
s = \begin{cases} 
  s_0 & \text{if } m \leq m_{min}, \\
  s_1 & \text{if } m_{min} < m \leq \frac{1}{2} \times 10^5 M_{\odot}, \\
  s_2 & \text{if } 1.2 \times 10^5 M_{\odot} \leq m \leq m_{max} \\
  s_3 & \text{if } m_{max} < m \leq 10^6 M_{\odot} 
\end{cases}
\]

(4)

where \(m_{min}\) and \(m_{max}\) depend explicitly on \(\beta\). Of course an
error in the value of \(s\) leads to an error in the evaluation of
the mean mass \(\langle m\rangle\). Then we think important to check the
degree of reliability of our method by estimating (in the way
described in the Appendix A) the mean error made using the
mass spectrum (3) to evaluate the mass.

2.1 NGC 1379

NGC 1379 is an EO galaxy in the Fornax cluster studied by,
e.g., Harris & Hanes (1987), Kissler-Patig et al. (1997) and
later F98b. Harris & Hanes (1987) compared the radial pro-
file of the GCS in NGC 1379 with the surface brightness of
the galaxy itself as given by Schombert (1986). Their study
was limited to the radial range 5-35 kpc, and they did not
detect any difference between the two profiles. This was con-
firmed by Kissler-Patig et al. (1997) that used ground-based
data over the 3-10 kpc range. The recent analysis of F98b, based on data of the HST WFPC2, confirms the similarity between the two surface profiles in the outer regions but, at the same time, show as the two differ in the inner regions. Thanks to these latter data, that cover a radial range larger than previously available, we managed to make a comparative study between the halo stars’ surface profile and the GCS one.

2.1.1 Observed data and the modified core model

In F98b detailed plots of the radial profile of the GCS of NGC 1379 are presented, thanks to the high resolution of HST. The profiles shown in the paper are two: one (containing GCs with B < 25.5) is complete and uncontaminated and the other (composed by objects with B > 25.5 and without correction for incompleteness) is expected to be composed mostly by background galaxies.

The radial profile of the brighter sample begins to decrease from ~ 10 to 80 arcsec (~ 1 - 7 kpc); at 80 arcsec from the centre the profile is lost in the background (see F98b).

Fig.1 shows the radial profile of clusters with B < 25.5 with a background of 2.7 objects per arcmin² subtracted. The superposed dotted line represents the luminosity profile of the underlying galaxy as provided by Kissler-Patig et al. (1997), scaled vertically to match the GCS profile in the outer regions. In this way the two profiles agree well at ~35-70 arcsec (3-6 kpc). The logarithmic slope of the GCS profile is ~ −2.4 at r > ~35 arcsec. Inwards of 30 arcsec it flattens out.

F98b estimated a core radius of 23 ± 6 arcsec (2.0 ± 0.5 kpc) assuming it as the distance from the centre where the surface density halves its central value. In its turn, the galaxy light seems to decline with a constant slope from ~ 10 to ~ 50 arcsec, where it seems to change slope slightly. To be sure of completeness, we have initially analysed only the brighter sample (B< 25.5): in a second analysis, we added the clusters of the fainter sample. Fitting the GCS density data with the law (1), we have the best fit with Σ₀ = 220.62 arcmin⁻², γ = 1 and r₀ = 23 arcsec (solid line in Fig.1). The modified core model approximates very well the density data in the outer regions, while it seems to be an overestimate in the inner regions. According to F98b the central dip of the observed GCS radial distribution is not an artefact of their analysis, but it represents a real drop in the volume density of clusters near the nucleus of galaxy. In fact they estimated a 97% completeness of the density data in the galactic region inwards of ~10 arcsec.

The observed decreasing behaviour toward the galactic centre of the GCS distribution of NGC 1379 seems to indicate that the dynamical depleting mechanisms are efficient, in this galaxy, up to significantly large radii.

2.1.2 The “missing clusters” in NGC 1379

As we said in the Introduction, the estimate of the (potentially) missing clusters can be obtained as the integral of the difference between the GCS and halo stars’ surface density distribution, after this latter has been normalized. For this reason we have considered only the radial range where the two profiles differ, i.e. 1.77-37.58 arcsec (see Fig.1). The bulge–halo radial profile has an almost constant slope, ~ -2.4, in the range 10 to 50 arcsec from the centre, but for our purpose it has been necessary to know the star profile also in the region within 10 arcsec. This has been made possible thanks to Grillmair, who gave us (1999, private communication) the model used to subtract the stellar light from globular clusters profile (99% complete for B < 25.5). We obtained a logarithmic slope of the stellar profile of about -1 in the radial range 1.77-10 arcsec (see Fig.1). In the annulus 1.77-37.58 arcsec, the number of stars is 512, on the other side, the modified core model fitting the globular cluster distribution gives 132 as number of clusters observed in the same annulus. Then, in the assumption that the normalized stellar profile gives the initial distribution of globular clusters, we find that the number of “missing clusters” is 380. Hence NGC 1379 could have lost about 74% of its initial population of globular clusters.

2.1.3 Data completeness and the mass fallen to the galactic centre

The relevant number of clusters possibly missing in the inner region of NGC 1379 corresponds to a great amount of mass supposedly fallen close to the galactic centre. Remembering that the value obtained of N_l is restricted to clusters with B < 25.5, we decided to provide two different evaluations of the mass removed from the GCS: one is the missing mass in the magnitude range of the observations, M_1, and another is the missing mass in the “whole” magnitude range, M_w. For this purpose it is useful to make some considerations on the GCS luminosity function.

F98b reported B and I photometry for ~ 300 globular clusters candidates in NGC 1379. This sample was detected with 4 WFPC2 chips covering a total area of 4.8
The sample with \( B \leq 26 \) is almost complete; at \( B > 26 \) the completeness begins to decrease very sharply. The principal source of contamination by foreground stars and background galaxies is due to compact, spherical galaxies and F98b provided a background-corrected luminosity function as a gaussian function with a peak magnitude of \( \langle B \rangle = 24.95 \pm 0.30 \) and a width \( \sigma_B = 1.55 \pm 0.21 \). This luminosity function is almost complete and uncontaminated in the range \( 21 < B < 25.5 \). Since we want to estimate the mass lost by the GCS, we had to convert the magnitude range \( 21 < B < 25.5 \) in a mass range. This was done assuming for the galaxy a distance modulus \( m - M = 31.32 \) for NGC 1379 (Madore, 1986) and, for the GCS, an average colour \( (B - V) = 0.7 \) and a mass to light ratio \( (M/L)_{V,\odot} = 1.5 \), thus obtaining \( (5.2 \times 10^6 M_\odot < m < 3.27 \times 10^6 M_\odot) \). Adopting the mass spectrum (3), the mean mass value of the clusters (over the told mass range) is \( \langle m \rangle = 3.5 \times 10^6 M_\odot \). This value, together with the number of the missing globular clusters (380), leads to \( M_l = 1.3 \times 10^8 M_\odot \) as estimate of the mass fallen to the galactic centre.

A discussion of the error in \( M_l \) induced by the error \( \Delta (m) \) for this agalaxy, as well for NGC 1399 and NGC 1404, is postponed to Sect. 3. With regard to the value of the mass lost, we remind it represents an underestimate of the mass removed from the GCS during its evolution because it is limited to the actual magnitude range of the observations. Hence to compute the "total" mass lost we set a minimum and a maximum mass, chosen as \( m_{\text{min}} = 10^5 M_\odot \) and \( m_{\text{max}} = 10^6 M_\odot \). Actually, normalizing the complete mass spectrum to reproduce the number (132) of clusters in the observed range \( (21 < B < 25.5) \), we obtain \( N_i,\text{tot} \) value of 179. Moreover, the averaged mass value over the whole magnitude range is \( 2.9 \times 10^5 M_\odot \) thus to give as estimate of the total missing mass \( M_i,\text{tot} = 1.5 \times 10^7 M_\odot \), i.e. \( \sim 15 \% \) greater than the value obtained in the magnitude range of the observations.

### 2.2 NGC 1399

NGC 1399 is a giant elliptical galaxy lying about at the centre of the Fornax cluster. Among the galaxies around the cluster, NGC 1399 is the most populous in globular clusters. Its GCS was deeply studied in the past through ground-based observations. Among these studies we mention that by Kissler-Patig et al. (1997), who deduced a total number of globular clusters of \( 5940 \pm 570 \), value that corresponds to the high specific frequency \( S_N = 11 \pm 4 \).

In F98a is presented the optical imaging of this galaxy obtained with the HST WFPC2 and the Cerro Tololo Inter-American Observatory 1.5m telescope. Combining these data they provided the spatial distribution of globular clusters used in the present study.

#### 2.2.1 The data and their fitting formulas

The imaging from HST led F98a to set as completeness limit \( B = 26.5 \). In order to avoid misleading revelations, they excluded also all the sources brighter than \( B = 21 \), since they would be more luminous than known normal globular clusters and so, probably, foreground stars. Moreover, these authors introduced a colour cut to the data:

\[
\gamma = 0.61
\]

where \( r \) and \( \Sigma(r) \) are expressed in arcmin and arcmin\(^{-2}\), respectively. It is clear from Fig.2 that the GCS surface density flattens out in the inner region. The estimate of the core radius given in F98a is 40 arcsec (3.4 kpc). We note that this value of the core radius lies in the scatter of the relation found by Forbes et al. (1996) between the GCS core radius and the galaxy luminosity. Assuming 40 arcsec as core radius, our modified-core model best fit for NGC 1399 GCS is that with \( \Sigma_0 = 234.42 \) arcmin\(^{-2}\) and \( \gamma = 0.61 \) (solid line in Fig.2). As done first by Hanes & Harris (1986) and later by F98a, we assumed 10 arcmin as limiting radius of the GCS. However it must be taken into account that an error on the limiting radius leads to an error in the evaluation of the globular cluster number. F98a estimated the error in the limiting radius \( \pm 1 \) arcmin; consequently, integrating our fit within 10 arcmin, we find that the total number of globular clusters in NGC 1399 is \( 6100 \pm 540 \). This value agrees well with the values found in previous studies (Kissler-Patig et al. 1997 gave \( 5940 \pm 570 \) and F98a obtained the value \( 5700 \pm 500 \), adopting the profile (6) completed by the inner available data).
2.2.2 Number of missing globular clusters in NGC 1399

The presumed flattening of the GCs distribution in NGC 1399 has been deeply discussed. While Bridges et al. (1991) stated that the GCS has the same slope of the halo stars, Wagner et al. (1991) and Kissler-Patig (1997), on the contrary, noticed a flattening of the GCS radial profile toward the galactic centre. A weighted average of the slopes provided by studies earlier than that of F98a brings to a value of $-1.47 \pm 0.09$ for the GCS and $-1.72 \pm 0.06$ for the halo stars. F98a found a difference of $0.4 \pm 0.22$ in the slopes between their fitted GCS distribution profile and that of the stellar halo, concluding that the flattening of the GCS density profile is a real feature. To provide an estimate of ‘missing’ GCs in NGC 1399, we adopted for the stellar light the following profile

$$\log I(r) = -1.6 \log r + 2.502,$$

obtained shifting the stellar halo density data (Forbes 1999, private communication) in the vertical direction, such to match the GCS profile in the outer regions. Extrapolating inward this profile to the galactic radius of 0.1 arcmin and integrating this surface density distribution in the galactic region where the GCS and the halo stars profiles differ, i.e. $\sim 0.1 - 8.5$ arcmin, we found a number of stars of about 9680. On the other side, in this radial range we find a number of GCs equal to 5165, which yields to an estimate of 4515 clusters lost, i.e. about 47% of the initial GC population.

2.2.3 Data completeness and evaluation of the mass lost

The previous results are limited to the magnitude range $21 < B < 26.5$ and to the colour range $1.2 < B-I < 2.5$. We now extend them to fainter magnitudes, obtaining two different evaluations of the mass lost in form of GCs. To this scope, it is necessary to make some considerations about the colour indices of the GCs in NGC 1399. Those in the outer region of the galaxy are bluer than those in the central region: $B-I = 1.70$ and 1.97, respectively (F98a). F98a made an estimate of the influence of the contamination of background galaxies to the globular cluster sample. In this way, they found $1.84$ as an average value of $B-I$. This allows us to find a value for $(B-V)$, which is needed to transform the magnitude interval in a mass range. We have adopted the relation $(B-V)_0 = 0.347(B-I)_0 + 0.163$ (Grillmair et al. 1999), obtaining $(B-V) \simeq 0.8$.

Adopting a distance modulus $m-M = 31.2$ (Jacoby et al. 1992) and a colour index $(B-V) \simeq 0.8$ for NGC 1399, and a mass-luminosity ratio, for its GCs, equal to 1.5, we obtain that the interval $21 < B < 26.5$ transforms into the mass range $2 \times 10^5 M_\odot < m < 3.2 \times 10^5 M_\odot$. The mean value of the GC mass is then $\langle m \rangle = 2.86 \times 10^5 M_\odot$. Since the number of lost globulars is 4515, the mass loss is $1.44 \times 10^8 M_\odot$, which differs of about 10% from that previously obtained.

2.3 NGC 1404

NGC 1404 is an E1 galaxy, about a magnitude fainter than NGC 1399, sited at about 10 arcmin east south of NGC 1399.

As for NGC 1399, much work has been done on the GCS of this galaxy. The estimates of the number of globular clusters of NGC 1404 are made difficult by its vicinity to NGC 1399. Grillmair et al. (1997) speculated that a great number of the NGC 1399 GCs (those of intermediate metallicity) have been tidally stripped by NGC 1404. The difficulties in distinguishing the two GCSs did not allow to obtain precise results from earlier studies, based on photographic plates (e.g., Hanes & Harris 1986 and Richtler et al. 1992). This problem seems to have been solved by the recent studies by F98a, based on data obtained by the HST WFPC2 and the 1.5 m CTIO telescope.

2.3.1 The data and their fitting formulas

As for NGC 1399, the magnitude and colour intervals of the GC sample are $21 < B < 26.5$ and $1.2 < B-I < 2.5$. About 90% of the observed clusters fall in these ranges. Since the number of background objects in the field is 14, F98a concluded that the completeness of the sample of clusters of NGC 1404 is $\geq 93\%$. The GCS surface density profile of NGC 1404 has been obtained by subtracting both the background density and the density of those clusters which are expected to belong to NGC 1399. Excluding the innermost data point, F98a fitted the resulting data with the following surface density profile:

$$\Sigma(r) = 36r^{-1.3 \pm 0.2},$$

where $r$ and $\Sigma(r)$ are in arcmin and arcmin$^{-2}$, respectively. Fig.3 shows a central flattening of the GCS distribution, which allows F98a to define, also in this case, a ‘core’ for the system. Their estimate of the core radius is of about 30 arcsec (2.5 kpc). As for NGC 1399, this core radius lies in the scatter of the correlation found by Forbes et al. (1996). We fitted the GCS density distribution data with a modified core model, as we have done for the two other galaxies. The best fit is that with $\Sigma_0 = 164.39$ arcmin$^{-2}$, $\gamma = 0.85$ and $r_c = 30$ arcsec (solid line in Fig.3). To obtain an estimate of the total number of globular clusters in this galaxy, we have integrated our density law in the galactic region within 250 arcsec (about 4 arcmin), which is the limiting radius of the observed data. F98a, in fact, showed that in the direction of NGC 1399, the GCS surface density is clearly dominated by this galaxy beyond 250 arcsec.

The modified core model gives a number of globular clusters of $744 \pm 120$ in this galactic region (the error in the GC number has been calculated adopting an error in the limiting radius equal to $\pm 1$ arcmin, as suggested by F98a). Our estimate of the GC total number is close to that of F98a; indeed, using the density profile (8) together with inner data points they obtained a number of GCs equal to 725$\pm 142$. Our value is between that estimated by Harris & Hanes (1986), 190$\pm 80$, and that by Richtler et al. (1992), 880$\pm 120$. 
Figure 3. Surface density profile for GCSs in NGC 1404 (black dots) from HST data in F98a. The modified core model fit adopted in our study is represented by the solid line, while the power law fit to the same data by F98a is shown by the dashed line. The underlying stellar light (dotted line) arbitrarily normalized in the vertical direction to match the globular cluster system is also shown. Radial distance is in arcsec (1 arcsec = 85 pc); surface density in arcmin$^{-2}$.

### 2.3.2 Number of missing clusters in NGC 1404

Also in this case, to compute the number of globular clusters lost to the galactic centre of NGC 1404 it is necessary to discuss the stellar halo profile. F98a determined a logarithmic slope of the star profile of $-1.9 \pm 0.1$. It is clear that the NGC 1404 GCS distribution is flatter than that of the halo. Thanks to data provided to us in private communication by Forbes (1999) we adopted the following star profile

$$\log I(r) = -1.9 \log r + 1.76$$  \hspace{1cm} (6)

where $r$ is in arcmin and $I(r)$ in arcmin$^{-2}$, which, as usual, was obtained by a vertical normalization so to match the GCS profile in the outer regions (see dotted line in Fig.3). Extrapolating this profile inward to the galactic radius of 0.1 arcmin and integrating this surface density distribution in the region of difference with the GCS profile ($\sim 0.1 - 2.32$ arcmin), we get 1061 as “initial” GC number. Integrating our GCS density data fit in the same annulus, we find 508 presently observed clusters, then we conclude that 553 GCS disappeared, i.e. $\sim 52\%$ of its initial clusters population.

### 2.3.3 Data completeness and evaluation of the number and mass of lost globular clusters

The data analysed are limited to the magnitude range $21 < B < 26.5$, transformed into a mass range in order to estimate the mass lost from the GCS of NGC 1404. For this aim let us do some considerations on the colour indices of the GCS. According to the analysis of F98a, the HST data show that NGC 1404 is dominated by red globular clusters, with a significant tail to the blue. Their colour distribution yields a mean value $\langle B-I \rangle = 1.96$, but F98a considered necessary to account for the background contamination. Using the CTIO data they found a bluer colour distribution, with a mean value $\langle B-I \rangle = 1.71$. Now, thanks to the relation between $B-V$ and $B-I$ given by Grillmair et al. (1999) we transformed $\langle B-I \rangle$ into $\langle B-V \rangle$, obtaining a $\langle B-V \rangle$ value of about 0.75. This value for $\langle B-V \rangle$ together with a distance modulus $m-M = 31.2$ maps the magnitude range $21 < B < 26.5$ onto the mass range $1.95 \times 10^4 M_\odot < m < 3 \times 10^5 M_\odot$. This allows to estimate a GC mean mass $\langle m \rangle = 2.48 \times 10^5 M_\odot$ and, being the number of missing clusters equal to 553, we deduce an amount of the mass lost by GCS of $1.37 \times 10^6 M_\odot$.

With regard to the total mass lost we have again adopted the mass range $10^4 M_\odot < m < 10^5 M_\odot$ as total mass range of globular clusters. Again, normalizing the mass spectrum (3) to reproduce the number of globular clusters actually observed in the magnitude range $21 < B < 26.5$, we find 556 as “total” number of GCs. This number, together with our estimate of the mean mass value in this range ($2.9 \times 10^5 M_\odot$), gives a total mass lost of $1.75 \times 10^6 M_\odot$, value $27\%$ greater than the previous one.

### 3 THE ERROR ON THE MEAN MASS VALUE

Using the expressions deduced in Appendix A we can give the error in the estimate of the average value of the mass, $\frac{\Delta(m)}{\langle m \rangle}$, of the GCs in the 3 galaxies studied.

We get

$$\frac{\Delta(m)}{\langle m \rangle} = -0.06 \frac{\Delta s_0}{s_0} - 1.48 \frac{\Delta s_1}{s_1} - 0.21 \frac{\Delta s_2}{s_2} + 0.45 \frac{\Delta \beta}{\beta}, \hspace{1cm} (7)$$

$$\frac{\Delta(m)}{\langle m \rangle} = -0.15 \frac{\Delta s_0}{s_0} - 1.63 \frac{\Delta s_1}{s_1} - 0.19 \frac{\Delta s_2}{s_2} + 0.37 \frac{\Delta \beta}{\beta}, \hspace{1cm} (8)$$

$$\frac{\Delta(m)}{\langle m \rangle} = -0.58 \frac{\Delta s_0}{s_0} - 1.95 \frac{\Delta s_1}{s_1} - 0.19 \frac{\Delta s_2}{s_2} + 0.36 \frac{\Delta \beta}{\beta}, \hspace{1cm} (9)$$

for NGC 1379, NGC 1399 and NGC 1404, respectively. From these expressions it is clear that the greatest source of indetermination is due to $s_1$, i.e. to the parameter of the mass spectrum that characterizes the intermediate mass range. However it is important to underline that the abundance of the GCs sample in these ranges allows an accurate determination of $s_1$. Assuming an error of $10\%$ in the parameters $s_0$, $s_2$ and $\beta \equiv (M/L)_V$, we obtain, as resulting errors in $\langle m \rangle$ $22\%$, $23\%$ and $30\%$, for NGC 1379, NGC 1399 and NGC 1404, respectively.

### Table 1. The presently observed number of clusters ($N$), its initial value ($N_i$), its fractional variation ($\Delta$), the mass lost in the magnitude range of the observations ($M_i$) and in the whole magnitude range ($M_{i,\text{tot}}$).

| Galaxy   | $N$  | $N_i$ | $\Delta$ | $M_i(M_\odot)$ | $M_{i,\text{tot}}(M_\odot)$ |
|----------|------|-------|----------|----------------|-----------------------------|
| NGC 1379 | 132  | 512   | 0.74     | $1.30 \times 10^6$ | $1.50 \times 10^6$ |
| NGC 1399 | 5165 | 9680  | 0.47     | $1.30 \times 10^6$ | $1.44 \times 10^6$ |
| NGC 1404 | 508  | 1061  | 0.52     | $1.37 \times 10^6$ | $1.75 \times 10^6$ |
4 THE CORRELATION BETWEEN THE MASS LOST BY GCS AND THE CENTRAL GALACTIC BLACK HOLE MASS

Even if theoretical arguments and observational data are clearly compatible with the explanation of the difference between the GCS and stellar bulge radial distributions as a result of dynamical evolution, we still cannot firmly state it. By the way it is interesting, and surely constitutes an argument in favour of this interpretation, to see how our results for the (supposed) mass loss in form of globular cluster correlates with the galactic central black hole mass, at least for the set of seven galaxies for which these data are available (our galaxy, M 31, M 87, NGC 1399, NGC 4365, NGC 4589, IC 1459).

Sources of data in Fig. 4 are: for $M_i$ this paper and Capuzzo–Dolcetta & Vignola, 1997, while the black hole masses are from Magorrian et al. (1998) except for our Galaxy and IC 1459 taken from Gebhardt et al. (2000). A recent estimate by Saglia et al. (2000) gives as compatible with kinematic data of the inner 5 arcsec of NGC 1399 a black hole mass $\sim 5 \times 10^6 M_{\odot}$, i.e. about a factor of 10 less than the value estimated by Magorrian et al. (1998) and reported in Fig. 4.

Fig. 4 shows, even in the paucity of data available, a clear increasing trend of $M_i$ as function of $M_{bh}$. Actually, the least square straight line fitting the data relative to galaxies with black hole masses heavier than $10^8 M_{\odot}$ has slope 0.99, i.e. the $M_i - M_{bh}$ relation is remarkably linear, while the straight line connecting the 2 low mass points has slope 0.08. The best simple fit to the whole set of data is given by $Log M_i = a + b exp(Log M_{bh})$ with $a = 7.158$ and $b = 1.194 \times 10^{-4}$, giving $r^2 = 0.76$ and standard error = 0.44 (the least square straight line fitting the whole data set yields $r^2 = 0.61$ and standard error = 0.56). Incidentally, we note that the steeper slope of the $M_i - M_{bh}$ relation for high values of the nucleus mass is what expected when the black hole is very massive and it acts as powerful engine of GCS evolution.

5 CONCLUSIONS

We used data taken with the WFPC2 of the Hubble Space Telescope to compare the globular cluster system distribution to that of bulge–halo stars in a sample of three elliptical galaxies in the Fornax cluster.

The first relevant outcome of this study is that the radial distributions of the globular cluster systems in NGC 1379, NGC 1399 and NGC 1404 confirm that the GCSs of NGC 1379, NGC 1399 and NGC 1404 could have lost the 74%, 47% and 53% of their initial populations, respectively. These results are, obviously, limited to the magnitude range of the observations within which the data reach a sufficiently high level of completeness.

The large number of ‘missing’ globular clusters obtained reveals that a significant amount of mass could have reached the galactic centre, too. An estimate of the mass fallen to the galactic centre needs the assumption of a value for the initial mean mass of globular clusters, ($\langle M \rangle$). It is reliable (see Capuzzo-Dolcetta & Tesseri 1997) to assume for ($\langle M \rangle$) the mean mass value of the presently observed globular clusters. This quantity can be estimated assuming a mass spectrum, that we took as a piece-wise power law for it seems to represent one of the best approximations for elliptical galaxies globular cluster systems (McLaughlin 1994; Harris & Pudritz 1994). In particular, we adopted as unique mass spectrum for the three galaxies of the Fornax cluster that obtained by normalization of the luminosity function adopted by McLaughlin (1995) for the Virgo elliptical giant M87, and assuming a mass to light ratio $(M/L)_{V,\odot} = 1.5$.

We provided two different estimates of the mass lost in form of globular clusters: the first is that due to clusters in the magnitude range of the observations and the other refers the “presumed” whole magnitude range. The first estimate, $M_i$, is simply obtained as the product of the mean mass and the number, $N_i$, of the missing globular clusters. With regard to the second estimate we made the, quite reasonable, assumption that the total number of missing globular clusters scales with the total number of the clusters present in the galaxy. Hence we computed this total number of globular clusters assuming $10^4 M_{\odot} < m < 10^7 M_{\odot}$ as whole mass range, so to include the contribution to $N_i$ coming from un-
observed clusters. The lower limit of the mass range has not a big influence on the total mass; with regard to the upper limit, the large decreasing slope ($-3$) of the MF at large masses ensures a high level of convergence of the total mass reached when assuming $10^7 M_\odot$ as maximum mass. The values of the total mass lost, $\tilde{M}_i$, obtained in this way for the three galaxies NGC 1379, NGC 1399 and NGC 1404 are not too different from those estimated in the mass ranges of the observations (the difference is about 15%, 10% and 27%, respectively; see Table 1). This is explained by that the range of magnitude covered by the observations is close enough to the whole magnitude range, thanks to the high power of HST.

It is relevant noting the positive correlation we found, for the available set of 7 galaxies in Fig. 4, between our evaluated mass lost from the GCS system and the central black hole mass of the parent galaxy: this is what expected on the basis of globular cluster-black hole tidal interaction because the more massive the central black hole the greater its influence on the GCS population.

To conclude, we remark how the values of the mass lost in form of decayed and destroyed globular clusters is significant and so it should have been played a role in the central region activity of their parent galaxies.

ACKNOWLEDGMENTS

We warmly thank D.A. Forbes for giving us some unpublished data useful for the determination of the stellar profile in NGC 1404. We are grateful to D.A. Forbes and C.J. Grillmair for important discussions and comments about the data used in this work.

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APPENDIX A:

A significant source of error on the evaluation of the mass removed from the GCS is due to the assumption of the exponent $s$ of the mass spectrum and of the value of the mass-light ratio $\langle M/L \rangle$ (hereafter $\beta$). Infact, an error on these parameters leads to the relative error on $\langle m \rangle$

$$\Delta \langle m \rangle = \frac{\langle m \rangle s \Delta s}{\langle m \rangle s} + \frac{\langle m \rangle \beta \Delta \beta}{\langle m \rangle \beta} \quad (A1)$$

Before giving an explicit expression of (A1), we note that, if we use the mass spectrum as in (3), $\langle m \rangle$ is so defined:

$$\langle m \rangle = \beta \langle L \rangle = \frac{\int_{L_{min}}^{L_{max}} k(L)L^{-s+1}dL}{\int_{L_{min}}^{L_{max}} k(L)L^{-s}dL} \quad (A2)$$

that is, in terms of mass

$$\langle m \rangle = \frac{\int_{m_{min}}^{m_{max}} k(m)m^{-s+1}dm}{\int_{m_{min}}^{m_{max}} k(m)m^{-s}dm} \quad (A3)$$

where $k(m)$ is obtained by the proper tranformation of the McLaughlin (1994) normalizing factor $k(L)$, i.e.

$$k(m) = \begin{cases} A & m_{min} \leq m \leq m_1 \\ Am_1^{-s} & m_1 \leq m \leq m_2 \\ Am_1^{-s}m_2^{-s+1} & m_2 \leq m \leq m_{max} \end{cases} \quad (A4)$$

where, of course, $m_{min}$, $m_{max}$, $m_1$ and $m_2$ depend linearly on $\beta$. To give (A1) a more compact form, we have put $m_0 \equiv m_{min}$ and $m_3 \equiv m_{max}$,

$$k_0 \equiv A, k_1 \equiv Am_1^{-s}m_2^{-s+1}, k_2 \equiv Am_1^{-s}m_2^{-s+1}, N_{tot} = \int_{m_{min}}^{m_{max}} k(m)m^{-s}dm.$$  

Remembering that $s = (s_0, s_1, s_2)$ (A1) becomes

$$\frac{\Delta \langle m \rangle}{\langle m \rangle} = \sum_{i=0}^{2} \frac{\partial \langle m \rangle}{\partial s_i} \frac{\Delta s_i}{s_i} + \frac{\partial \langle m \rangle}{\partial \beta} \frac{\Delta \beta}{\beta} \quad (A5)$$

where $\frac{\partial \langle m \rangle}{\partial s_i}$, $\frac{\partial \langle m \rangle}{\partial \beta}$ are so defined:

$$\frac{\partial \langle m \rangle}{\partial s_i} = \frac{1}{N_{tot}} \sum_{j=0}^{2} \left[ \left( \varphi_j^i (j+1, 2) - \varphi_j^i (j, 2) \right) + \left( \varphi_j^i (j+1, 1) - \varphi_j^i (j, 1) \right) \right] \quad (A6)$$

with

$$\varphi_j^i (r, s) = \frac{\partial k_j}{\partial s_i} m_j^{-s+1} \frac{m_j^{-s+1}}{s + s + 1} + \frac{\partial k_j}{\partial s_i} m_j^{-s+1} \frac{1}{s + s + 1} - \ln m_j$$

and

$$\frac{\partial \langle m \rangle}{\partial \beta} = \frac{1}{N_{tot}} \sum_{j=0}^{2} \frac{\partial k_j}{\partial \beta} \left[ \left( m_j^{-s+2} - m_j^{-s+2} \right) + \left( m_j^{-s+1} - m_j^{-s+1} \right) \right]. \quad (A7)$$

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