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Dynamical evolution of globular cluster systems in clusters of galaxies: I. The case of NGC 1404 in the Fornax cluster

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ABSTRACT

We investigate, via numerical simulations, the tidal stripping and accretion of globular clusters (GCs). In particular, we focus on creating models that simulate the situation for the GC systems of NGC 1404 and NGC 1399 in the Fornax cluster, which have poor (specific frequency $S_{\rm N} \sim 2$) and rich ($S_{\rm N} \sim 10$) GC systems respectively. We initially assign NGC 1404 in our simulation a typical $S_{\rm N}$ (~ 5) for cluster ellipticals, and find that its GC system can only be reduced through stripping to the presently observed value, if its orbit is highly eccentric (with orbital eccentricity of > 0.5) and if the initial scale length of the GCs system is about twice as large as the effective radius of NGC 1404 itself. These stripped GCs can be said to have formed a 'tidal stream' of intracluster globular clusters (ICGCs) orbiting the centre of Fornax cluster (many of which would be assigned to NGC 1399 in an imaging study). The physical properties of these GCs (e.g., number, radial distribution, and kinematics) depend on the orbit and initial distribution of GCs in NGC 1404. Our simulations also predict a trend for $S_{\rm N}$ to rise with increasing clustercentric distance - a trend for which there is some observational support in the Fornax cluster. We demonstrate that since the kinematical properties of ICGCs formed by tidal stripping in the cluster tidal field depend strongly on the orbits of their previous host galaxies, observations of ICGC kinematics provides a new method for probing galaxy dynamics in a cluster.

Key words: globular clusters:general – galaxies:elliptical and lenticular, cD – galaxies:formation – galaxies:interaction.

1 INTRODUCTION

Studies of Globular Cluster (GC) systems have provided increasingly useful constraints on the formation and evolution of their host galaxies (for recent reviews see Harris 2001; Forbes 2002). In the case of cD and central cluster galaxies a variety of processes may have contributed to their rich GC systems. This variety has meant that the origin of the rich GC systems in these galaxies is still poorly understood. Ideas to explain the rich GC systems in such galaxies have included cooling flows (Fabian, Nulsen & Canizares 1984), biased GC formation (West et al. 1995), mergers (e.g. Ashman & Zepf 1992; Bekki et al. 2002), tidal stripping and accretion (e.g. Muzzio et al. 1984; Forbes et al. 1997; Côte et al. 1998), *in situ* formation (e.g. Harris 1991; Forbes, Brodie & Grillmair 1997; Harris, Harris & McLaughlin 1998). Alternatively the galaxies themselves may be 'underluminous' for their GC richness (Blakeslee, Tonry & Metzger 1997; McLaughlin 1999; Beasley et al. 2002). It is perhaps the latter three ideas (i.e. accretion, *in situ* formation and missing light) that are considered the current 'best bets' to explain the excess of GCs.

In this paper we further explore the scenario of a central cluster galaxy accreting GCs via tidal stripping (as opposed to the accretion of dwarf galaxies and their GCs as advocated by Côte et al. 1998). In recent years, a number of new observational facts have lent support to the stripping and accretion scenario. These include: the correlation of relative richness of the GC system (called specific frequency S_N) with velocity dispersion (e.g. Blakeslee et al. 1997) - more stripping should occur in the higher velocity dispersion clusters; that high S_N galaxies have relatively more metal-poor GCs (Forbes et al. 1997) - as metal-poor GCs have a shallower density profile they are more likely to be stripped from a donor galaxy; that S_N values may correlate with projected clustercentric distance (Forbes et al. 1997) - galaxies near the cluster core should experience more stripping; that the high S_N values in the literature are generally being revised downwards (see e.g. Forte et al. 2002) - this makes the high S_N systems less extreme and hence less accretion is required.

Although there have been developments on the observational front, there has been little modelling work carried out since the initial simulations by J. C. Muzzio and colleagues in the 1980s (Forte et al. 1982; Muzzio et al. 1984; Muzzio 1986a,b; Muzzio et al. 1987; Muzzio 1987). They found that the GCs accreted by the most cluster galaxies do not come from dwarf galaxies but rather galaxies of similar mass. All cluster galaxies gain and lose GCs due to tidal stripping, and for many galaxies the net outcome was a loss of GCs to the ICM. When the galaxies represented a small fraction of the total cluster mass, both the GC gains and losses were smaller.

In the twenty years since the initial models of Muzzio, computing power has advanced significantly. This combined with further observational evidence means that the time is ripe to revisit this issue of GC accretion with a N-body simulation. It is however still a formidable task to perform a fully self-consistent simulation encompassing the dynamical evolution of galaxies with vastly different masses (from small dwarfs to central massive cDs) and that of GC systems. Here we focus exclusively on perhaps the best case for tidal stripping and accretion, i.e. the GC systems of NGC 1399 and NGC 1404 in the Fornax cluster.

Several lines of evidence suggest that NGC 1399 is currently in a non-equilibrium state, and possibly undergoing a dynamical interaction with its nearby partner NGC 1404. ROSAT HRI and Chandra data analysed by Paolillo et al. (2001) indicates that the hot gas centroid of NGC 1399 is offset by $\sim$ 5 kpc to the SW of its optical counterpart. These authors also find that NGC 1399 has an extended and asymmetric gas distribution on cluster scales (r $>$ 90kpc), which exhibits prominent structures ('holes' and filamentary features) expected from N-body numerical simulations (e.g. Barnes 2000).

Independent evidence comes from discrete dynamical tracers such as GCs (Grillmair etal. 1994; Minniti etal. 1998; Kissler-Patig etal. 1999) and planetary nebulae (PNe, Arnaboldi etal. 1994; Napolitano et al. 2002). In particular, Napolitani et al. (2002) find evidence for a disturbed velocity structure after re-analysing the PNe data of Arnaboldi etal. Their non-equilibrium dynamical analysis shows a peak rotation of 250 km s^{-1} for the PNe at $\sim$ 12.6 kpc from the optical centre of NGC 1399, coincident with a velocity dispersion minimum at this point, which subsequently rises at larger radii. A viable analytical explanation for this kinematical behavior is that NGC 1404 has undergone a "flyby" of NGC 1399, whose stellar halo is currently attempting to return to equilibrium (Napolitani et al. 2002).

Thus the purpose of this paper is to investigate numerically whether tidal stripping of the NGC 1404 GC system by the global gravitational field of the Fornax cluster (and thus NGC 1399) can explain physical properties of its GC system. In particular, we investigate (1) whether the observed relatively low S_N value of 2 in NGC 1404 can be explained by the tidal stripping of GCs and (2) how the density profile of the GC system can change after GC stripping. We also try to identify observational signatures of the GC stripping and accretion process. White (1987) suggested that intracluster GCs can be formed owing to tidal stripping of GCs from cluster member galaxies and Bassino et al. (2002) have recently found GC candidates in the Fornax cluster. In light of these results, we discuss the origin of intracluster GCs in the Fornax cluster in the context of GC stripping from NGC 1404. This paper is the first in a series of papers in which we seek a self-consistent understanding of dynamical evolution of GC systems in cluster environments. Here we focus on the limited case of the interaction between NGC 1399 and NGC 1404, and its effect on their GC systems. The distance of the Fornax cluster is assumed to be 18.6 Mpc throughout this paper.

2 THE MODEL

We consider a collisionless stellar system of an elliptical galaxy with a mass and size similar to those of NGC 1404, orbiting the centre of Fornax cluster of galaxies (i.e., NGC 1399). Since the gravitational field around NGC 1399 at distances greater than 40 kpc is observed to be dominated by the global cluster rather than by luminous components of NGC 1399 itself (e.g., Kissler-Patig et al. 1999; Napolitano et al. 2002), we consider that the gravitational field of the dark matter halo of the cluster has the strongest influence on the dynamical evolution of the globular cluster system in NGC 1404. Accordingly, we model only the cluster tidal field and do not include any tidal effects of other cluster member galaxies in the present simulations. Although these simulations are idealized in some aspects, we believe that our model still contains the essential ingredients for the dynamical evolution of NGC 1404's globular cluster system in Fornax cluster.

To give our model a realistic radial density profile for the dark matter halo, we base it on both the X-ray observational results of Jones et al. (1997) and the predictions from the standard cold dark matter cosmogony (Navarro, Frenk, & White 1996, hereafter NFW). The NFW profile is described as,

$$\rho(r) = \frac{\rho_0}{(r/r_{\rm s})(1+r/r_{\rm s})^2}, \qquad (1)$$

where ρ_0 and $r_{\rm s}$ are the central density and the scale length of a dark halo, respectively. ρ_0 is chosen such that the total mass of Fornax cluster within 125 kpc is the same as the observed one ($8.1\times10^{12}{\rm M}_{\odot}$) estimated from X-ray observations (Jones et al. 1997). We adopt 55 kpc for $r_{\rm s}$ which is reasonable value for a CDM halo with the mass similar to that of Fornax cluster.

NGC 1404 is modeled as a fully self-gravitating system and assumed to consist of dark matter halo, stellar component, and GCs. The density profile of the dark matter halo of the elliptical is also represented by NFW profile with the scale length the same as the effective radius of the stellar component of NGC 1404 (i.e. 2.5 kpc). The mass ratio of the dark matter halo to the stellar component is set to be 5. The effective radius and the total mass of the stellar components is 2.5 kpc and 4.4 $\times$ 10^{10} $M_{\odot}$, respectively, which are consistent with observational properties of NGC 1404. The projected density profile of the stellar component is represented by $R^{1/4}$ law and the density profile is cut off at R $= 5R_{\rm e}$. We estimate both the velocities of the dark matter halo particles and those of stellar ones from the gravitational potential at the positions where they are located. In detail, we first calculate the one-dimensional isotropic dispersion according to the (local) virial theorem:

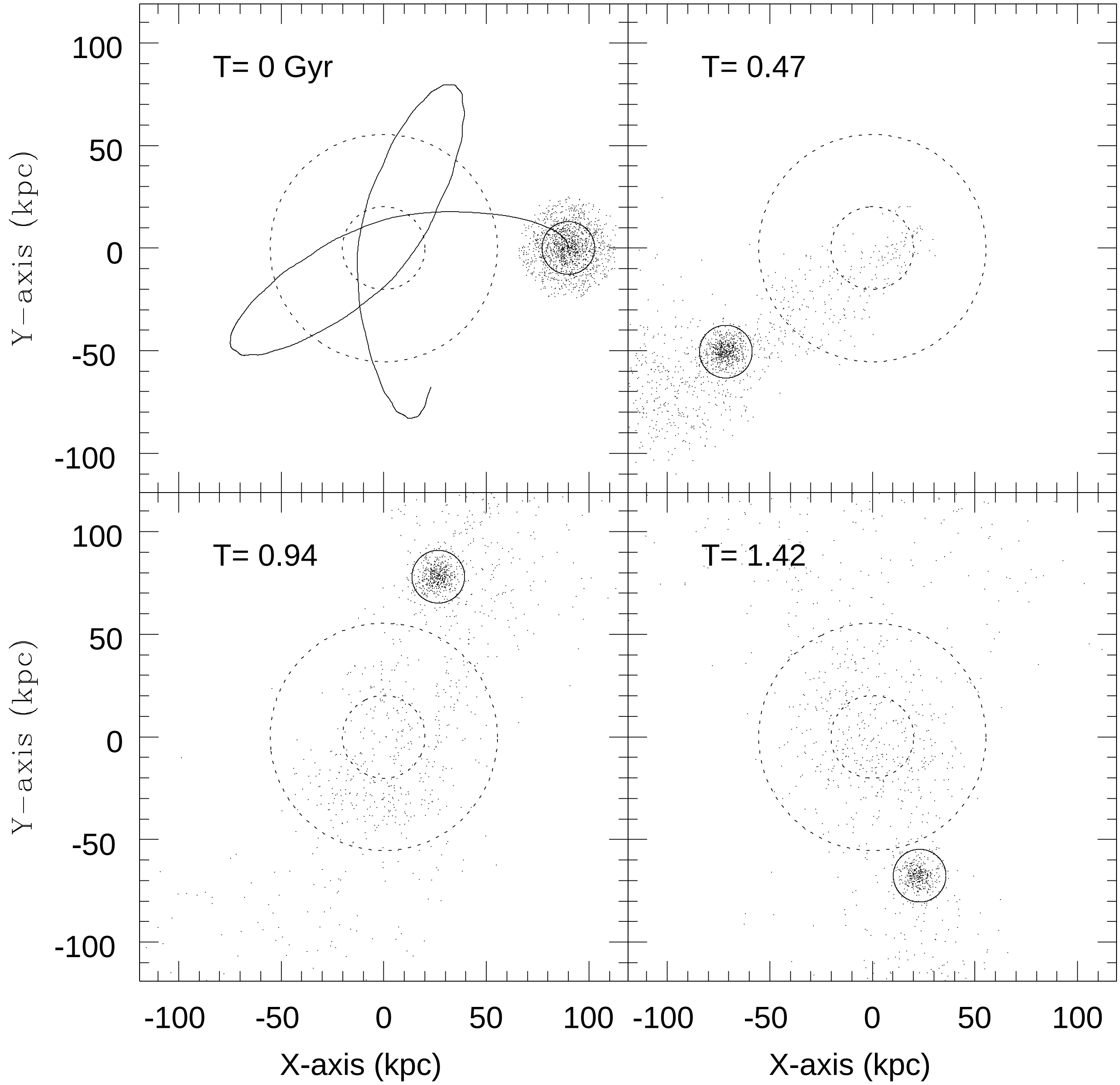

Figure 1. Morphological evolution of the globular cluster system of NGC 1404 orbiting within the Fornax cluster. here we show the fiducial model (Model 3) with $e_{\rm p} = 0.76$ and $a_{\rm gc} = 2.0$ projected onto the x-y plane. The time T (in Gyr) represents the time that has elapsed since the simulation started. The larger and smaller dotted circles represent the cluster scale radius $r_{\rm s}$ of the adopted NFW mass profile and 5 $R_{\rm e}$ (where $R_{\rm e}$ is effective radius) of the central NGC 1399, respectively. Solid lines represent the orbit of NGC 1404 (for 0 $\leq T \leq$ 1.42 Gyr) and 5 $R_{\rm e}$ of NGC 1404.

$$\sigma^2(r) = -\frac{U(r)}{3}, \tag{2}$$

where $U(r)$ is the gravitational potential at the position r. Then we allocate a velocity to each collisionless particle (dark matter halo and stellar particles) so that the distribution of velocities of these particles can have a Gaussian form with a dispersion equal to $\sigma^2(r)$.

It should be noted here that we use the above $U(r) - \sigma^2(r)$ relation rather than the Jeans equation for a spherically symmetric system (Binney & Tremaine 1987);

$$\frac{d(\rho(r)\sigma^2(r))}{dr} = -\rho(r)\frac{d\Phi(r)}{dr}. \tag{3}$$

This is firstly because the self-gravitating systems modeled in the present study are composed of three different stellar components (dark matter halo, $R^{1/4}$-law elliptical stellar component, and GCs) with non-analytical radial density distributions and secondly because we introduce the cut off radius for each component. The derived $\sigma^2(r)$ at each location of a particle can be consistent with those derived in the Jeans equation.

In the present study, we introduce the cut off radius ($R_{\rm c}$) beyond which no dark matter (stellar) particles are initially allocated ($R_{\rm c} = 5R_{\rm e}$). Because of this somewhat artificial boundary condition, the very outer part of the NGC

1404 system is initially not in a dynamical equilibrium in a strict sense. Therefore we need to make the dark matter component dynamically relaxed after giving $\sigma(r)$ to each dark matter particle and then use the relaxed system as an initial model for each simulation. We ran an isolated elliptical model for five dynamical time scales until the dark matter component reaches the new dynamical state (during this dynamical relaxation, the outer part of the system expands only slightly). For all simulations, this dynamically relaxed model is used as an initial NGC 1404 system.

The globular cluster distribution is assumed to follow $\rho(R) \propto (R_{\rm c} + R)^{\alpha}$, where R, $R_{\rm c}$, and α are the radius from the centre of NGC 1404, the core radius of the GC distribution, and the slope of the GC profile. There are only a few papers which have attempted to derive the slope of the GC distribution both for metal-poor GCs and for metal-rich GCs (e.g. Geisler et al. 1996), though a number of observational studies have estimated the profiles for the *whole* GC populations and their correlations with other global properties of GC's host galaxies (e.g., Forbes et al. 1997). In the present paper, we do not distinguish blue metal-poor GCs and red metal-rich ones. Therefore we use the observed mean value of α (= -1.9) derived for the whole GC system for the projected density profile of the GC system of NGC 1404. However we note that the metal-poor GCs have a shallower distribution (Forbes et al. 1998).

The ratio of $R_{\rm c}$ to $R_{\rm e}$ is considered to be an important free parameter and represented by $a_{\rm gc}$. The total number of GCs is set to be 1350, which corresponds to initial $S_{\rm N}$ of 5.0 (i.e. a typical cluster elliptical value). Each GC has a mass of 10^6 $M_{\odot}$ and its velocity is given in the same way as each stellar (dark matter) particle is given its velocity. The present numerical results do not depend strongly on the mass of each GC particle ($M_{\rm gc}$), and the dependences on $M_{\rm gc}$ are briefly summarized in the Appendix A for 10^5 $M_{\odot} \le M_{\rm gc} \le 10^6$ $M_{\odot}$.

The orbit of NGC 1404 is assumed to be influenced only by the gravitational potential resulting from the dark halo component of the Fornax cluster. Since the adopted cluster potential is spherical symmetry (not triaxial), the orbit of NGC 1404 forms a rosette within a plane. This orbital plane is set to be x-y in all models. The centre of the cluster is always set to be (x,y,z) = (0,0,0) whereas the initial position of NGC 1404 is set to be (x,y,z) = ($R_{\rm ini}$, 0, 0). The projected distance between NGC 1399 (or the centre of Fornax cluster) and NGC 1404 (hereafter $R_{\rm obs}$) and the relative radial velocity of the two galaxies are observed to be $\sim$ 45 kpc and 525 km s^{-1}, respectively (Forbes et al. 1997). Since these observational values can not give any strong constraints on the orbit of NGC 1404, we consider any reasonable values of $R_{\rm ini}$ larger than $R_{\rm obs}$. We show the results of the models with $R_{\rm ini} = 2$ $R_{\rm obs}$ (90 kpc) in which the projected distance between the two galaxies can be the same as the observed one (depending on the line of sight) during orbital evolution of these models.

The initial velocity of NGC 1404 ($v_{\rm x}$,$v_{\rm y}$,$v_{\rm z}$) is set to be (0, $f_{\rm v}V_{\rm c}$, 0), where $f_{\rm v}$ and $V_{\rm c}$ are the parameters controlling the orbital eccentricity (i.e, the larger $f_{\rm v}$ is, the more circular the orbit becomes) and the circular velocity of the cluster at $R = R_{\rm ini}$, respectively. We investigate three representative values of $f_{\rm v}$ = 0.25, 0.5, and 1, which corresponds to NGC 1404's orbital eccentricity (hereafter $e_{\rm p}$) of 0.76, 0.5, and 0.0 (circular), respectively.

Two parameters $a_{\rm gc}$ and $e_{\rm p}$ (or $f_{\rm v}$) are considered to be the most important parameters for the dynamical evolution of NGC 1404's GCs in the present study: These determine the effectiveness of tidal stripping of GCs in a cluster environment. In total, we show the results of the following 6 models: Model 1 with $e_{\rm p}$ = 0.0 and $a_{\rm gc}$ = 2.0, 2 with $e_{\rm p}$ = 0.50 and $a_{\rm gc}$ = 2.0, 3 with $e_{\rm p}$ = 0.76 and $a_{\rm gc}$ = 2.0, 4 with $e_{\rm p}$ = 0.00 and $a_{\rm gc}$ = 1.0, 5 with $e_{\rm p}$ = 0.50 and $a_{\rm gc}$ = 1.0, and 6 with $e_{\rm p}$ = 0.76 and $a_{\rm gc}$ = 1.0. We describe the results of model 3 (hereafter referred to as a fiducial model) in more detail, because this model shows behaviours typical of dynamical evolution of the GC system in our models. All the simulations have been carried out on the GRAPE board (Sugimoto et al. 1990) with the total particle number of 11350 (10000 for dark matter and stellar particles and 1350 for GC particles) and the gravitational softening length of each component equal to the mean particle separation at the half mass radius of each component (i.e., 0.71, 0.55, and 2.95 kpc for dark matter, stars, and GCs, respectively).

3 RESULTS

3.1 Fiducial model

Fig. 1 summarises the dynamical evolution of GCs in NGC 1404 orbiting the central dominant galaxy (NGC 1399) of Fornax cluster. As the galaxy passes through the cluster core for the first time, GCs in NGC 1404 are efficiently stripped owing to the strong cluster tidal field. About 46 % of the GCs are located outside 10 R_e, where R_e is the effective radius of NGC 1404, and we regard them as being tidally stripped after this first pericenter passage (T = 0.47 Gyr), whereas only $\sim$ 6 % of field stars are stripped owing to its their more compact configuration. The stripped GCs are distributed along the orbit of NGC 1404 and some fraction of them can be clearly seen within the NGC 1399's optical radius (defined as 5 $R_{\rm e}$ of NGC 1399 in this paper). Since the orbit of NGC 1404 in the adopted spherical gravitational potential forms a rosette, the stripped GCs can be finally distributed widely throughout the cluster scale radius $r_{\rm s}$ ($\sim$ 55 kpc). The overall (projected) distribution of the stripped GCs within the central 100 kpc of the cluster can be regarded as rather elongated, which reflects the fact that the NGC 1404's orbit is highly eccentric (orbital eccentricity e_p = 0.76). The overall distributions also show appreciable inhomogeneity, in particular, for the regions with $R > 50$ kpc.

During dynamical evolution of NGC 1404 within the cluster, the GCs are more strongly influenced by the cluster tidal field than the main stellar component of NGC 1404, because the GC system is initially less compact. Fig. 2 shows how this difference in the effectiveness of tidal stripping between the stellar component and GCs can cause the decrease of $S_{\rm N}$ in NGC 1404. After the first pericenter passage, the $S_{\rm N}$ is reduced from 5 to 2.86 (T = 0.47), and the reduction rate is nearly proportional to the number of the stripped GCs. GCs can be successively stripped everytime NGC 1404 passes through the cluster core, though the total number of the stripped ones become smaller in the second and the third pericenter passages compared with those stripped in the first

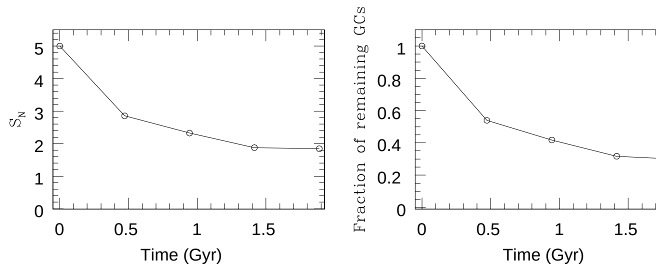

Figure 2. Time evolution of $S_{\rm N}$ (left) and number of GCs remaining within NGC 1404 (right) in the fiducial model. NGC 1404 is assumed to have 1350 GCs initially within 10 $R_{\rm e}$.

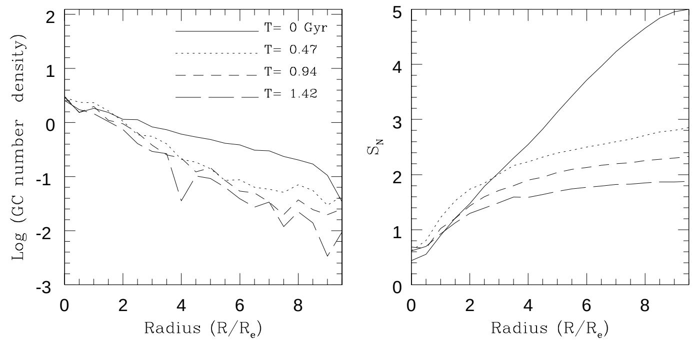

Figure 3. Time evolution of projected surface number density of NGC 1404 GCs (left) and the radial dependence of $S_{\rm N}$ (right) in the fiducial model. It should be noted that the decrease of $S_{\rm N}$ is more significant in the outer parts of the galaxy.

pericenter passage ($S_N = 2.32$ and 1.88 for $T = 0.94$ and 1.42, respectively). These results clearly suggest that the origin of the observed smaller S_N (~ 2) of NGC 1404 GCs may be closely associated with tidal stripping of GCs by the cluster tidal field. Finally, the dynamical evolution of these stripped GCs becomes gravitationally influenced by the cluster potential rather than by NGC 1404 and therefore can be identified as drifting intracluster GCs.

The NGC 1404's tidal radius ($R_{\rm t}$), within which collisionless components (dark matter, stellar components, and GCs) do not suffer so severely from tidal stripping by the cluster, can be analytically estimated to be 3.7 $R_{\rm e}$ for the fiducial model with $e_{\rm p} = 0.76$ and the total mass of NGC 1404 equal to 2.64×10^{11} $M_{\odot}$. The initial total number of GCs within $R_{\rm t}$ is 288 for the fiducial model, and accordingly 1062 GCs are expected to be tidally stripped from NGC 1404. The final number of GCs within $R_{\rm t}$ is 253 ($T =$ 1.42 Gyr) in the simulation, and accordingly 1097 GCs are tidally stripped from NGC 1404. Therefore, the simulated number of GCs stripped from NGC 1404 differs from the analytical estimation only by 3 %. The probable reason for the larger number of the stripped GCs in the simulation is that the NGC 1404 system becomes less strongly self-gravitating (thus more susceptible to tidal stripping) after stripping of dark matter and stellar components during its dynamical evolution. The possibility of the present model's overestimation of the number of stripped GCs (due to numerical relaxation effects) is discussed in the Appendix B.

Fig. 3 shows that as NGC 1404 orbits the centre of the Fornax cluster, the radial distribution of GCs in NGC 1404 becomes steeper and the radial S_N distribution becomes flatter. This is essentially because GCs initially outside the galaxy are more likely to be tidally stripped. The S_N within $5R_{\rm e}$ is changed from 2.83 to 1.64 (a factor of 1.73 smaller) at $T = 1.42$ Gyr whereas the S_N within $10R_{\rm e}$ is changed from 5 to 1.88 (a factor of 2.66 smaller). These results suggest that tidal stripping of GCs causes the steepening of radial distributions of GCs. Furthermore, they imply that if a cluster elliptical galaxy with lower S_N has a typical S_N estimated for its halo region within a few times $R_{\rm e}$ and a significantly smaller S_N within $5 - 10$ $R_{\rm e}$, the lower S_N of this elliptical can be caused by the strong cluster tidal field. Thus, we suggest that the ratio of the inner S_N and the outer S_N in a cluster elliptical is one observable test for the tidal stripping of GCs in cluster elliptical galaxies.

The derived radial density profile with the power-law slope of ~ -2.6 for $0 \leq R/R_{\rm e} \leq 10$ is steeper than the observed value of -1.3 (Forbes et al. 1997). This disagreement between the present simulations and the observation is due partly to the adopted initially steep slope (-1.9), which is chosen such that the value is similar to the typical value of the power-law slope of globular cluster systems in elliptical galaxies. As the simulations demonstrate, the density profile of the GC system of an elliptical in a cluster is more likely to become steeper as it orbits the cluster because of the more efficient tidal stripping in the outer part of the galaxy. We therefore suggest that if the origin of the observed low $S_{\rm N}$ of NGC 1404 is due to tidal stripping, the power-law slope of the GCs radial density profile should have been initially flatter (i.e. before interaction with Fornax cluster).

The radial number density profile of the GCS around NGC 1404 can be influenced by later tidal disruption of GCs by NGC 1404. We can roughly estimate the effect of tidal disruption of GCs on the number density profile by using early numerical results by Aguilar et al. (1988). They demonstrated that if the Galactic GCs are within ~ 2 kpc from the Galactic centre, the GCs can be destroyed by the strong tidal field of the bulge. The radius within which GCs can be destroyed is referred to as $R_{\rm des}$ from now on for convenience ($R_{\rm des} \sim 2$ kpc for the Galactic bulge). By assuming that $R_{\rm des}$ is simply scaled to ${M_{\rm gal}}^{1/3}$ for a galaxy, (where $M_{\rm gal}$ is the total luminous mass of the galaxy), $R_{\rm des}$ for NGC 1404 can be estimated to be 3.3 kpc (or 1.3 $R_{\rm e}$). In this estimation, we consider that GCs can be destroyed by the more compact luminous component rather than by the diffuse dark matter halo in the central region of NGC 1404. Therefore, we suggest that since GCs within 1.3 $R_{\rm e}$ can be all destroyed by the NGC 1404's tidal field, the radial density profile of the NGC 1404's GCS can become more flattened for $R/R_{\rm e} < 1.3$ (compared with the simulated distribution). The outer density distribution of GCs ($R/R_{\rm e} > 2$) could not be influenced by the GC disruption.

Fig. 4 shows projected number density profiles of "stripped" GCs *with respect to the centre of the cluster* at $T =$1.42 Gyr. Here the "stripped" GCs are defined as those that have a projected distance (from NGC 1404) of larger than 10 $R_{\rm e}$ (where $R_{\rm e}$ is the effective radius of NGC 1404). It should be stressed here that the adopted radius of 10 $R_{\rm e}$ just corresponds to the initial size of the GC system and thus some of GCs outside this radius could be still orbiting NGC 1404 (i.e., not all of GCs outside this radius are really stripped from NGC 1404 gravitational field). Since

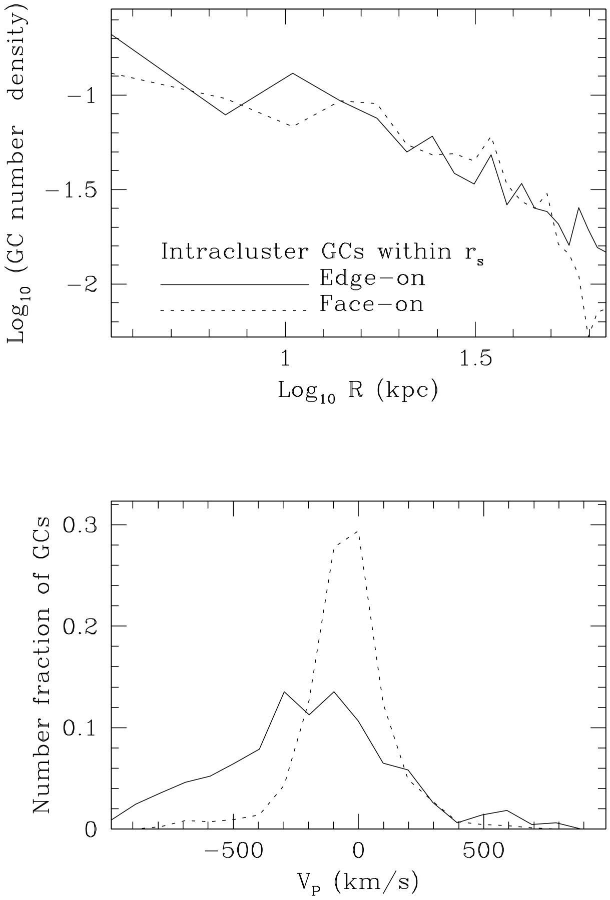

Figure 4. *Upper*: Final (projected) surface number distribution of intracluster globular clusters (ICGCs) that are within r_s of the Fornax cluster model and were stripped from NGC 1404 for the fiducial model (Model 3) at $T = 1.9$ Gyr. Here the distance (R) of each ICGC is that from the centre of the cluster (not from the centre of NGC 1404). Both vertical and horizontal scales are given in log scales and solid and dotted lines represent the result for the edge-on view (seen from the orbital plane of NGC 1404) and for the face-on one (from the above of the orbital plane), respectively. *Lower*: Final histogram of projected velocity dispersion of the ICGCs for the edge-on view (solid) and the face-one one (dotted).

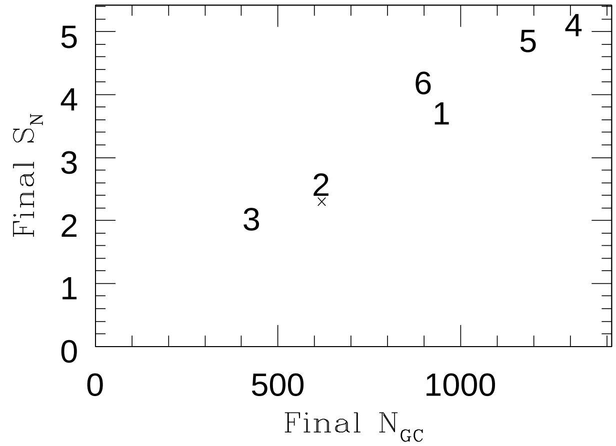

Figure 5. Final distribution of the six models (Model 1 - 6) with different orbital configurations and initial GC distributions in the $S_{\rm N}$-$N_{\rm GC}$ plane. Model 1 ($e_{\rm p} = 0.00$ and $a_{\rm gc} = 2.0$), 2 ($e_{\rm p} = 0.50$ and $a_{\rm gc} = 2.0$), 3 ($e_{\rm p} = 0.76$ and $a_{\rm gc} = 2.0$), 4 ($e_{\rm p} = 0.00$ and $a_{\rm gc} = 1.0$), 5 ($e_{\rm p} = 0.50$ and $a_{\rm gc} = 1.0$), and 6 ($e_{\rm p} = 0.76$ and $a_{\rm gc} = 1.0$) are represented by their numbers. For comparison, the observed values of $S_{\rm N}$ and $N_{\rm GC}$ of NGC 1404 is plotted by cross.

it is very difficult to determine, only from *projected radius and kinematics* in the simulations, whether a GC is really stripped from NGC1404, we consider that this adopted 10 $R_{\rm e}$ is a plausible value which gives a boundary between GCs trapped in NGC 1404 and those stripped. We suggest that these stripped GCs (far from their previous host galaxies) could be identified as “intracluster globular clusters” (defined by West 1990) in future observations studies. These intracluster globular clusters are referred to as ICGCs in the present study, however we emphasize that they did not form in the ICM but now reside there.

The derived number density profiles of ICGCs within the cluster scale radius r_s clearly show negative gradients both in edge-on and face-on views. The power-law slopes of these can be estimated to be ~ -0.85 within r_s, which is similar to the observed slope (-1.0 ± 0.2) of the central metal-poor GCs in NGC 1399 (e.g., Forbes et al. 1997; Also see the Fig.2 in Hilker et al. 2000) and rather shallower than that of the metal-rich ones (-1.7 ± 0.2; See Dirsch et al. 2003 for the latest value). One possible reason for the negative gradient in the ICGC distribution is that GCs are more likely to be stripped in the inner regions of the cluster. The derived value of the slope implies that only the blue GCs in the central region of Fornax cluster (equally, GCs of NGC 1399) were previously NGC 1404's GCs. Blue GCs in elliptical galaxies show more extended distributions or shallower density profiles than red GCs (e.g., Geisler et al 1996; Forbes, Brodie & Huchra 1997). Our simulations demonstrate that the outer GCs are more likely to be stripped during the dynamical evolution than inner ones. Thus, although GCs stripped from NGC 1404 consists of only some fraction of GCs in the central region of Fornax cluster, it is reasonable to claim that the tidal stripping processes of *outer blue* GCs from NGC 1404 can contribute partly to the observed power-law slope of blue GCs in the central region of Fornax cluster.

Fig. 4 furthermore demonstrates that the ICGCs show wider wings of the (projected) velocity ($V_{\rm p}$) distribution in the edge-on view whereas they have the sharp distribution in the face-one one. This result just reflects that the edge-on view is nearly coincident with the orbital planes for most of drifting ICGCs. A larger fraction of large projected velocity of ICGCs with respect to the cluster centre (> 400 km s^{-1}) can be found in the edge-on distribution, in particular, in its negative velocity side. The velocity dispersion for ICGCs within r_s (and with the absolute magnitude of projected velocity $V_{\rm p}$ less than 1000 km s^{-1}) can be estimated to be 340 km s^{-1} for the edge-on view and 174 km s^{-1} for face-one one. Some of ICGCs with $|V_{\rm p}| > 400$ km s^{-1} are located close to the central NGC 1399 (i.e. within 5 times the effective radius of NGC 1399) so that these can be identified as NGC 1399's GCs (not as ICGCs) with an unusually large projected velocity.

The derived velocity dispersion of 340 km s^{-1} of ICGCs, some fraction of which are close to the centre of the cluster (i.e., NGC 1399), is significantly larger than the observed outer stellar velocity dispersion (~ 200 km s^{-1} for the region 1 - 8 kpc from the centre) in NGC 1399 (e.g., Bicknell et al.

1989). Based on the radial velocity measurement of 74 GCs around NGC 1399, Kissler-Patig et al. (1999) found that the velocity dispersion for the whole sample is 373 ± 35 km s^{-1} and the velocity dispersion depends on radius in such a way that it *increases* with radius from the NGC 1399 centre between 10 - 30 kpc (e.g., 263 ± 92 at 2 ′ and 408 ± 107 km s^{-1} at 5 ′). This outer increase of velocity dispersion has also been found in the kinematical analysis of planetary nebulae (e.g., Napolitano, Arnaboldi, and Capaccioli 2002). The observed velocity dispersion of GCs (and PNe) is larger than the (outer) stars of NGC 1399, which is considered to be a possible evidence that GCs (PNe) are orbiting in a gravitational potential of the Fornax cluster rather than in NGC 1399 itself (Grillmair et al. 1994; Kissler-Patig et al. 1999).

Our results on the larger velocity dispersion of ICGCs strongly suggests that if they originated from tidal stripping of GCs initially in NGC 1404 and observationally identified as GCs in NGC 1399, these GCs can have a velocity dispersion as large as the observed one for GCs in the very outer part of NGC 1399. These results furthermore imply that if outer GCs in NGC 1399 are composed mostly of ICGCs stripped from other cluster member galaxies, GCs in NGC 1399 as a whole can show a clear difference in velocity dispersion between the inner "intrinsic" GCs that are closely associated with the NGC 1399 formation itself and the outer accreted/stripped ones from other cluster member galaxies. Our numerical simulations have been carried out *only* for the dynamical evolution of NGC 1404 with plausible orbits. The (projected) radial velocity dispersion profile of ICGCs depends on from which galaxy these are stripped, because the projected velocity of each stripped GC depends on the orbit of its previous host galaxy (i.e., the orbit of each GC follows the orbit of its host). We thus suggest that the observed radial velocity dispersion profile of GCs in NGC 1399 may be "a fossil record" of the histories of GC stripping from other cluster member galaxies around NGC 1399. However it may be difficult in practice to disentangle kinematically any stripping signature from other (formation) mechanisms that give rise to the rich GC systems of cD galaxies.

3.2 Parameter Dependences

Although our general results on the stripping of GCs from NGC 1404 due to the strong tidal field of the Fornax cluster do not depend on the model parameters, the final $S_{\rm N}$ and $N_{\rm GC}$ do depend on (1) orbital eccentricity ($e_{\rm p}$) of the host galaxy NGC 1404 and (2) initial ratio of the scale length of GC system to the effective radius of NGC 1404 (a_{gc}). The final $S_{\rm N}$ and $N_{\rm GC}$ of GCs around NGC 1400 are estimated at $T = 1.89$ Gyr when time evolution of $S_{\rm N}$ and $N_{\rm GC}$ becomes insignificant for all models (Model 1 - 6). We can only discuss the final structural and kinematical properties of ICGCs for the models 2 and 3, in which total number of GCs are large enough. (Total number of stripped GCs in Model 1, 4, 5, and 6 are too small for us to derive velocity dispersion of ICGCs at a given radius). Therefore, we only briefly describe the dependences of ICGC properties on model parameters. In Figs. 5 and 6, we illustrate the derived dependences on the above two parameters. We find the following:

(i) Both $S_{\rm N}$ and $N_{\rm GC}$ are smaller for the models with larger $e_{\rm p}$, because in the models with larger $e_{\rm p}$ (i.e., with smaller pericenter distance), galaxies can pass through the inner region of the cluster, where the cluster tidal field is sufficiently strong such that a larger number of GCs can be stripped. This dependence does not depend on $a_{\rm gc}$.

(ii) Irrespective of $e_{\rm p}$ and $a_{\rm gc}$, the model with smaller $N_{\rm GC}$ shows smaller $S_{\rm N}$. This means that the stripping of stars in NGC 1404, which can increase $S_{\rm N}$ if stripping of GCs does not happen, is much less efficient compared with GC stripping, so that the decrement of $S_{\rm N}$ depends strongly on that of $N_{\rm GC}$.

(iii) Final $S_{\rm N}$ depends on $a_{\rm gc}$ such that models with smaller $a_{\rm gc}$ have larger final $S_{\rm N}$ because of its less efficient tidal stripping of GCs. Comparison of our results and the observations suggests that in order to explain both the observed $N_{\rm GC}$ and $S_{\rm N}$, *both* $e_{\rm p}$ *and* $a_{\rm gc}$ *should be large.* (Either Model 2 or 3 can best reproduce the observed properties of NGC 1404 in the present study).

(iv) Our models predict that $S_{\rm N}$ correlates with the distance of GCs' host galaxy from the centre of Fornax cluster (equivalently, from NGC 1399) in such a way that a galaxy with the larger distance shows larger $S_{\rm N}$. In Fig 7 we plot the observed SN of Fornax ellipticals as a function of clustercentric radius. These data suggest that galaxies at larger radii have higher SN. The location of NGC 1404 GCs in Fig. 6 also suggests that if the observed lower $S_{\rm N}$ and $N_{\rm GC}$ in NGC 1404 are due to tidal stripping by the cluster tidal field, $e_{\rm p}$ should be as large as (or larger than) 0.5 and $a_{\rm gc}$ is ~ 2.

(v) Projected surface number density profiles and velocity dispersion of ICGCs (around NGC 1399) are likely to be shallower and smaller, respectively, in the model with smaller $e_{\rm p}$, though we could investigate these only for the models with $a_{\rm gc} = 2.0$ because of the very smaller number of ICGCs in other models. These results indicate that physical properties of ICGCs in a cluster depends on the orbital populations (e.g., the mean orbital eccentricity) of galaxies in the cluster.

4 DISCUSSION

4.1 Observable evidence for the tidal stripping scenario for low $S_{\rm N}$ cluster ellipticals

So far, we have focused on just one elliptical galaxy (NGC 1404) in Fornax cluster and the origin of its relatively low $S_{\rm N}$. Based on these results, we propose that we can assess the importance of tidal stripping by strong cluster gravitational fields in the formation of low $S_{\rm N}$ elliptical galaxies *in general* by checking the following three observable physical properties of GC systems of cluster ellipticals. The foremost is *the ratio of* $S_{\rm N}$ *within* $1 - 2R_{\rm e}$ *to that within 5–10* $R_{\rm e}$, where $R_{\rm e}$ is the effective radius of a cluster elliptical galaxy. From now on, we refer to this $S_{\rm N}$ ratio as $r_{\rm sn}$ just for convenience. As our simulations have demonstrated, the outer GCs are much more efficiently stripped than the inner GCs in an elliptical galaxy. As a natural result of this, for example, the ratio of $S_{\rm N}$ within $R_{\rm e}$ to that within 10 $R_{\rm e}$ in NGC 1404 is changed from 0.18 into 0.49 during 2 Gyr of dynamical evolution (for an orbital eccentricity of 0.76). We can therefore distinguish the tidal stripping scenario of low $S_{\rm N}$ E formation from that in which NGC 1404 has initially

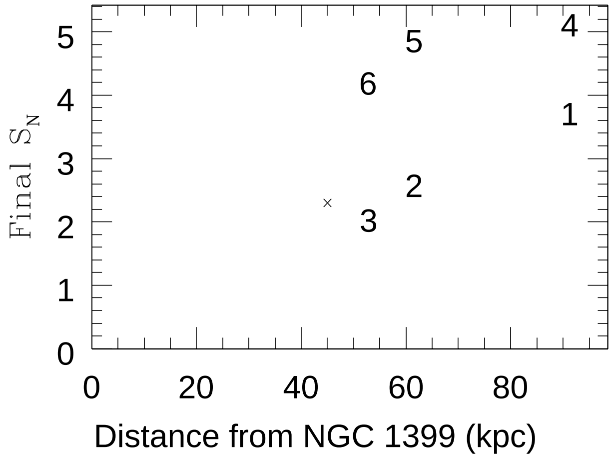

Figure 6. Variation of $S_{\rm N}$ with projected distance. Final distribution of the six models (Model 1 - 6) with different orbital configurations and initial GC distributions on a plane defined by $S_{\rm N}$ and the projected distance from the cluster centre. Models 1, 2, 3, 4, 5, and 6 are represented by their numbers. The distance is defined as $(r_{\rm apo}+r_{\rm peri})/2$, where $r_{\rm apo}$ and $r_{\rm peri}$ are the apocenter and pericenter of NGC 1404's orbit in each model, respectively. For comparison, the observed values of $S_{\rm N}$ and the projected distance of the NGC 1404 from NGC 1399 is plotted by a cross.

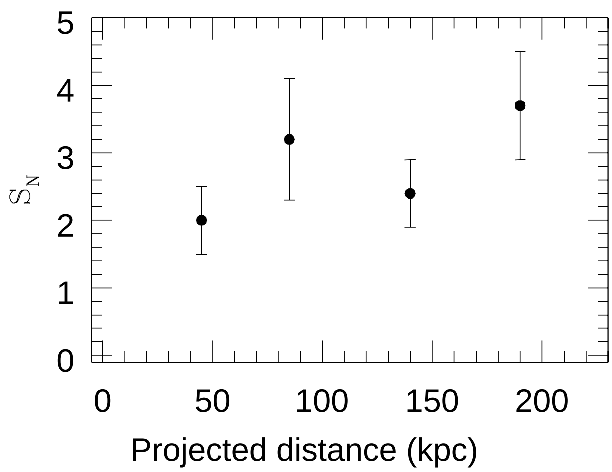

Figure 7. The observed variation of $S_{\rm N}$ with projected distance for ellipticals in the Fornax cluster (Forbes et al. 1997). Here the projected distance is measured from the central cD galaxy NGC 1399. The results are shown for NGC 1374, 1379, 1387, and 1404.

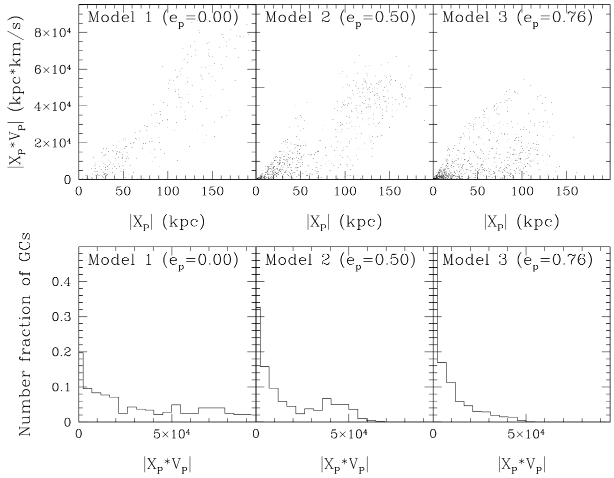

Figure 8. *Upper three*: Distributions of ICGCs on the $|X_{\rm p}|$-$|X_{\rm p}|\times|V_{\rm p}|$ planes, where $|X_{\rm p}|$ and $|V_{\rm p}|$ represents the projected distance from the centre of Fornax cluster and velocity, respectively, for the three representative models with different orbital eccentricity ($e_{\rm p}$) of NGC 1404. The properties $|X_{\rm p}|\times|V_{\rm p}|$ can be considered to correspond to the "projected orbital angular momentum" of ICGCs. *Lower three*: Number histogram of $|X_{\rm p}|\times|V_{\rm p}|$ of ICGCs in the three models. For clarity, the number fraction of ICGCs in each bin is shown.

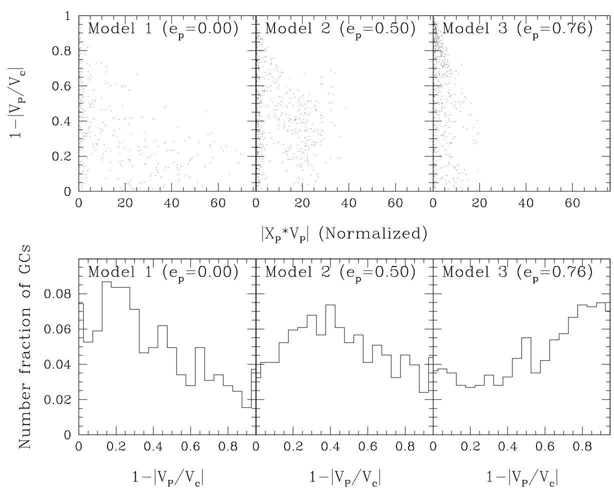

Figure 9. *Upper three*: Distributions of ICGCs on the $|X_{\rm p}|\times|V_{\rm p}|$-$(1-|V_{\rm p}/V_{\rm c}|)$ planes, where $|X_{\rm p}|$, $|V_{\rm p}|$, and $|V_{\rm c}|$ represent the projected distance from the centre of Fornax cluster, and the projected velocity, and the circular velocity estimated from the adopted NFW mass model for Fornax cluster at $|X_{\rm p}|$, respectively, for the three representative models with different orbital eccentricity ($e_{\rm p}$) of NGC 1404. The properties $1-|V_{\rm p}/V_{\rm c}|$ can be considered to correspond to the "projected orbital eccentricity" of ICGCs. *Lower three*: Number histogram of $1-|V_{\rm p}/V_{\rm c}|$ of ICGCs in the three models. For clarity, the number fraction of ICGCs in each bin is shown.

a small $S_{\rm N}$ of ~ 2, because only the former scenario predicts a larger $r_{\rm sn}$ (>0.2). NGC 1404 has a local $S_{\rm N}$ of 0.5 at $R = 1R_{\rm e}$ and 2.0 at $R = 9R_{\rm e}$ and thus a larger $r_{\rm sn}$ of 0.25, which implies that tidal stripping can be responsible for the observed low $S_{\rm N}$ of 2 in NGC 1404.

The second observable characteristic of the tidal stripping scenario is the formation of an elongated or flattened distribution (or "tidal stream") of ICGCs along the orbit of their previous host galaxy. We do, however, point out that it is formidable task to determine which cluster member galaxy previously hosted each "ICGC stream". Kinematic and metallicity information of ICGCs may help up to identify each individual stream, only if the ICGCs have not been affected by scattering and dynamical relaxation via interaction between these ICGCs and other cluster member galaxies since they were stripped from their host galaxies. The central region of a cluster is a place where many galaxies mutually interact with one another, and much larger number of metal-poor GCs could be stripped from numerous dwarf galaxies surrounding the central cluster cD, which hampers the identification of the possible ICGC streams formed by GC stripping from cluster ellipticals. Thus we conclude that it is very hard to demonstrate that the process of GC stripping is taking place from the projected distributions alone.

The third is the statistical correlation between the distance of an elliptical galaxy from the centre of a cluster and the $S_{\rm N}$ of the galaxy. The present numerical results predict that if the orbital eccentricities of galaxies does not depend on the location of these with respect to the centre of a cluster, $S_{\rm N}$ of a galaxy can correlate with the distance from the cluster centre such that $S_{\rm N}$ is smaller for a galaxy close to the cluster core. Some evidence of this trend can be seen in the Fornax cluster. We expect the proposed correlation to be more obvious in the more dynamically relaxed/older galaxy clusters, because elliptical galaxies in these clusters have already experienced pericenter passages several times and lost their GCs by tidal stripping. In our future work we will generalise our simulations to more galaxies within a cluster, and to clusters of varying properties.

4.2 Kinematics of intracluster globular clusters as a new clue to galaxy evolution in clusters.

Various different physical mechanisms are considered to play a role in galaxy evolution in clusters: e.g., Ram pressure stripping (Gunn & Gott 1972), tidal encounters (Iche 1985; Moore et al. 1996), tidal compression by the gravitational field of a cluster (Byrd & Valtonen 1990), minor or unequal-mass mergers (Bekki 1998). One of the most important parameters which determine the effectiveness of the each physical mechanism is suggested to be the pericenter distance of the orbit of a galaxy. For example, ram pressure stripping is efficient only when a gas-rich cluster galaxy can pass through the cluster core where there is plenty of hot gas (e.g., Abadi et al. 1999). Equally, morphological transformation via a cluster tidal field can be significant only when the pericenter of a cluster galaxy is small enough to approach the core radius (it should be noted here that the latest high-resolution simulations on dynamical evolution of galaxies in hierarchically forming clusters by Gnedin (2003) demonstrate that the tidal effects can be important throughout the cluster). Therefore it is important to give some observational constraints on the orbital properties (e.g., mean eccentricity of galaxy orbits and its dispersion) of galaxies in clusters.

Based on the present numerical results, we propose that the *kinematical properties of intracluster globular clusters (ICGCs) can provide some constraints on orbital populations of cluster galaxies and thus new clues to the origin of galaxy evolution in clusters of galaxies*. Figs. 8 and 9 illustrate which kinematical properties can be useful for this purpose. In these two figures, we first choose GCs that are outside 10 $R_{\rm e}$ of NGC 1404 in each model and then investigated kinematical properties of these stripped GCs that are regarded as as ICGCs drifting Fornax cluster. The upper panel of Fig. 8 shows that the distribution of ICGCs on $|X_{\rm p}|$-$|X_{\rm p}|\times|V_{\rm p}|$ plane, where $|X_{\rm p}|$ and $|V_{\rm p}|$ are projected distance and velocity of a GC, respectively, can provide some information on the orbital eccentricity ($e_{\rm p}$) of the previous host galaxy of ICGCs. ICGCs can be distributed in the upper right region with larger $|X_{\rm p}|\times|V_{\rm p}|$ and larger $|X_{\rm p}|$ in the low $e_{\rm p}$ model. The lower panel of Fig. 8 can provide a clearer difference, and demonstrates that the high $e_{\rm p}$ model has the narrower distribution in the histogram of $|X_{\rm p}|\times|V_{\rm p}|$ and a larger number of GCs in the smaller $|X_{\rm p}|\times|V_{\rm p}|$ bins. From these results, we expect that if a cluster consists mostly of galaxies with higher orbital eccentricities, it shows narrower $|X_{\rm p}|\times|V_{\rm p}|$ histogram of ICGCs and their ICGCs are located preferentially in the lower region of the $|X_{\rm p}|$-$|X_{\rm p}|\times|V_{\rm p}|$ plane of ICGCs. We can investigate the above just based on the projected distance and radial velocity of each ICGC in a cluster.

Fig. 9 suggests that if we know the mass profile of a cluster and thus its rotation curve through X-ray hot gas observations and kinematical properties of cluster member galaxies, we can provide even clearer evidence on orbital properties of cluster galaxies by combining the ICGC kinematics and the cluster mass profile. This figure demonstrates that if the orbits of cluster galaxies are more eccentric as a whole, ICGCs (stripped from these) populate mostly in the upper left region on the $|X_{\rm p}|\times|V_{\rm p}|$-$(1-|V_{\rm p}/V_{\rm c}|)$ plane, where $V_{\rm c}$ is the circular velocity of a ICGC at $|X_{\rm p}|$ and estimated from the adopted mass profile of a cluster. This is essentially because these ICGCs also have highly eccentric orbits and thus smaller projected velocity $|V_{\rm p}|$ for the $V_{\rm c}$ at their positions. Furthermore we can more clearly see the difference between the models with different orbital eccentricities in the histogram of $1-|V_{\rm p}/V_{\rm c}|$. This difference suggests that if the orbits of cluster galaxies are more eccentric as a whole, such a cluster may show the peak at high values of $1-|V_{\rm p}/V_{\rm c}|$. It should be noted here that the observed difference in the above properties of ICGCs may not be clearly distinguished as proposed because of the mixture of different orbits of galaxies in a cluster. However future observations on ICGCs in different nearby clusters of galaxies can still provide valuable constraints on galaxy evolution in clusters.

5 CONCLUSIONS

We have numerically investigated the roles of the cluster tidal field in dynamical evolution of the GC system of NGC 1404. We summarise our principle results as follows.

(1) Final $S_{\rm N}$ depends both on $e_{\rm p}$ (orbital eccentricity of NGC 1404) and on $a_{\rm gc}$ (the ratio of the scale length of the GC system to the effective radius of stellar component of NGC 1404) in such a way that $S_{\rm N}$ is smaller in the models with larger $e_{\rm p}$ and larger $a_{\rm gc}$. $S_{\rm N}$ can be significantly reduced by tidal stripping of GCs to become as low as the observed value (~ 2), only if the orbit of NGC 1404 is highly eccentric (with orbital eccentricity of > 0.5) and if the initial scale length of the GCs distribution is about twice as large as the effective radius of NGC 1404.

(2) The radial number density profile of the GC system becomes steeper after the stripping of GCs, because the outer GCs are more easily stripped during tidal interaction. This result implies that since the observed slope of the power-law density profile of the GC system in NGC 1404 is shallower (~ -1.3) compared with the typical value for cluster ellipticals (-1.9), the initial slope (before tidal interaction) was rather shallow (i.e. larger than -1.3), if the observed low $S_{\rm N}$ is due to tidal stripping of GCs.

(3) One of the observable characteristics of a cluster elliptical with a low $S_{\rm N}$ (< 2) resulting from tidal stripping is the larger ratio of $S_{\rm N}$ within $1-2R_{\rm e}$ to that within 5–10

R_e, where R_e is the effective radius of a cluster elliptical galaxy. We also suggest that if tidal stripping of GCs via a cluster tidal field is a main cause for the evolution of S_N of cluster ellipticals, there should be a positive correlation between the distance of a cluster elliptical from the centre of a cluster and S_N of the galaxy (as may be present in the Fornax cluster).

(4) Stripped GCs are found to become intracluster GCs (ICGCs) orbiting the centre of Fornax cluster (i.e., NGC 1399) and their physical properties (e.g., number, radial distribution, and kinematics with respect to the cluster centre) depend on the orbit of NGC 1404 and the initial distribution of the GCs in NGC 1404. For example, the ICGCs within the cluster core have a projected number density profile with the power-law slope of ~ -0.9 and rather large velocity dispersion (~ 340 km s^{-1}) for the highly eccentric orbit model of NGC 1404.

(5) Our numerical results suggest that not only structural properties but the kinematical properties of ICGCs formed from tidal stripping can depend strongly on the orbits of their previous host galaxies. This implies that the detailed investigation of ICGC kinematics by multi-object spectrographs on 8-10m-class telescopes can shed new insight into galaxy dynamics in the cluster as a whole.

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APPENDIX A: DEPENDENCES ON GC MASS

Although the main purpose of this paper is not to discuss the dependences of tidal stripping processes on GC mass M_{gc}, it is important to confirm whether the present numerical results depend on M_{gc}. We thus investigate the model with $M_{gc} = 10^5\ M_\odot$ (and $5 \times 10^5\ M_\odot$). In these models with smaller M_{gc}, the globular cluster system (GCS) is more weakly self-gravitating and the dynamical friction of each GC in the inner part of NGC 1404 is less efficient (though the present simulations can not precisely treat the dynamical friction between GCs and the stellar and the dark matter components of NGC 1404 because of the resolution of the simulations). Therefore, large numbers of GCs can be stripped from NGC 1404 during the tidal interaction between NGC 1404 and the Fornax cluster in the model with smaller M_{gc}.

The derived differences in final structural properties of the NGC 1404's GCS between the two models with $M_{gc} = 10^6\ M_\odot$ (the fiducial model) and $M_{gc} = 10^5\ M_\odot$ are summarized as follows. Firstly, $R_{0.1}$, which is the radius (from the centre of NGC 1404) within which 10 % of initial GCs in number (i.e., 135) can be located, is larger by 21 (23) % in

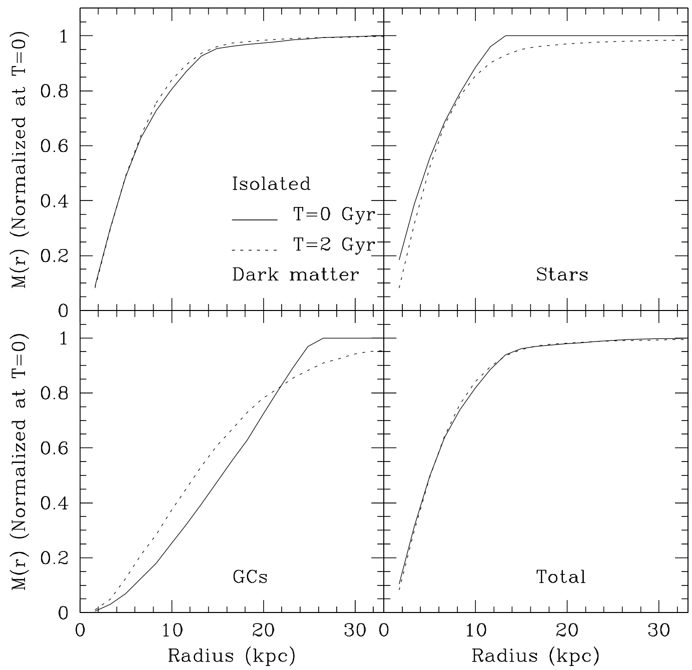

Figure 10. Cumulative mass distributions ($M(r)$) in the isolated model for dark matter (upper left), stars (upper right), GCs (lower left), and total (lower right) at $T = 0$ Gyr (solid) and 2 Gyr (dotted). $M(r)$ represents the total mass within r (from the center of the model) divided by the total mass of the model at $T = 0$ Gyr for each component (e.g, dark matter and GCs). This normalized $M(r)$ in the isolated model enables us to estimate numerical relaxation effects on the radial distribution of each component.

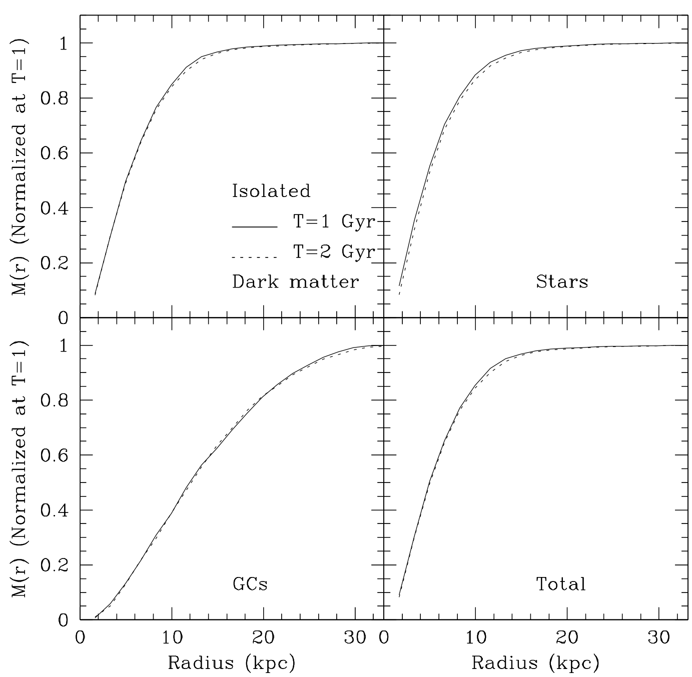

Figure 11. The same as Figure 10 but normalized at $T = 1$ Gyr.

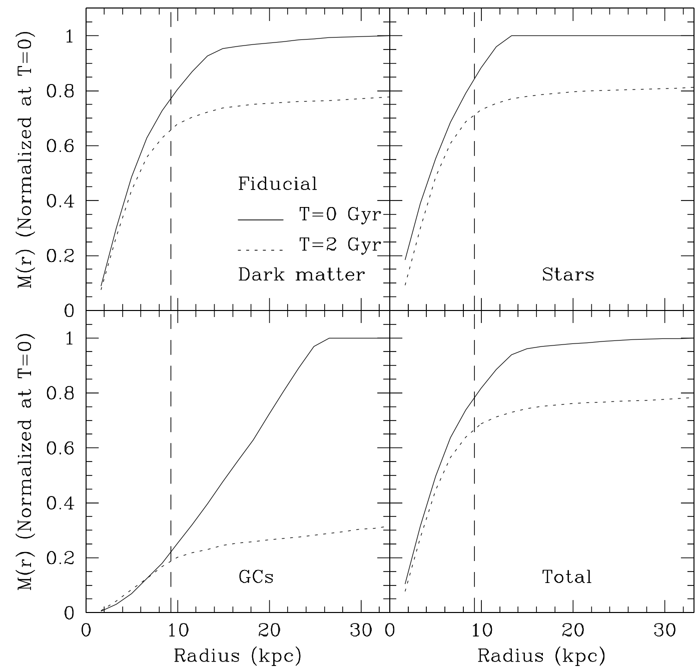

Figure 12. The same as Figure 10 but for the fiducial model. For comparison, the tidal radius of this model is shown by a dashed line in each panel.

the model with $M_{\rm gc} = 10^5\ M_{\odot}$ than in the fiducial model at $T = 0.47$ (0.94) Gyr. This suggests that the final GCS has the lower number density in the central region of NGC 1404 for the model with smaller $M_{\rm gc}$. Secondly, the total number of stripped GCs (estimated for $R/R_{\rm e} < 10$) is larger by 19 % (22 %) in the model with $M_{\rm gc} = 10^5\ M_{\odot}$ than in the fiducial model at $T = 0.47$ (0.97) Gyr. This means that a larger number of GCs from NGC 1404 can form the ICGC population in the Fornax cluster for the model with smaller $M_{\rm gc}$. From these two results, we can conclude that time evolution of $S_{\rm N}$, final structural properties of the GCS in NGC 1404, and the total number of ICGC originated from NGC 1404 in the Fornax cluster does not depend so strongly on $M_{\rm gc}$.

APPENDIX B: LONG-TERM EVOLUTION OF AN ISOLATED MODEL AND NUMERICAL RELAXATION EFFECTS

It is possible that our numerical simulations overestimate the total number of stripped GCs in a cluster owing to the undesirable numerical relaxation effects from the limited particle number used in the simulations. Our numerical results could be influenced by (1) the somewhat abrupt truncation of mass distribution for each component and (2) the difference in masses between different components. In order to estimate these purely numerical effects (and to discriminate these effects with those from a cluster tidal force), we investigate the long-term dynamical evolution (~ 2 Gyr corresponding to 4000 time steps) of an isolated galaxy model with no external tidal force. Figs. 10 and 11 show the mass distribution for each collisionless component at $T = 0$ and 2 Gyr in the isolated model. Although the entire mass distribution of the isolated model does not change so significantly during 2 Gyr evolution, the mass distributions of stars and GCs change slightly. The stellar component shows a small degree of expansion (i.e., lower density in the inner and the outer regions), which may be caused by mass segregation between less massive stellar particles and more massive dark matter ones (in particular, for the first 1 Gyr evolution). Also the initial abrupt truncation of the stellar mass distribution may be responsible for the appreciable expansion.

The GC component at $T = 2$ Gyr shows the higher density in its inner region and the more diffuse outer one compared with the initial distributions ($T = 0$ Gyr). This implies that owing to (1) the low GC number density in the inner part and (2) the adopted large softening length of the GC particle, the mass segregation between less massive GC particles and the more massive dark matter ones does not proceed significantly within a time scale of 2 Gyr (compared with the case of the stellar component). This also implies that the initial abrupt truncation of the GC (and stellar) distribution(s) can cause a more serious numerical effect on dynamical evolution of the GC component compared with the stellar component. The GC component is more widely distributed than the stellar one and the initial velocity dispersion of the GC component is determined by the local potential energy at the positions of GC particles. Accordingly, the velocity dispersions of the outer GCs ($R > 5r_{\rm e} \sim$ 12.5 kpc), which constitute the majority of GCs (~ 70 %) in the isolated model, must be determined by much smaller number of particles at $R > 5r_{\rm e}$ (where there are initially no stellar particles because of the adopted abrupt truncation of the stellar distribution). This less precise estimation of initial velocity dispersions of the outer GCs (thus initially less stable dynamical state of the GCs) can be responsible for the dynamical relaxation that leads to the formation of the "core-halo" structure (i.e., higher density inner region and the lower density outer one) seen in the mass distribution of the GC component at $T = 1$ and 2 Gyrs.

The derived "apparent" decrease of GCs in the isolated model is at most $5 - 10\%$ in the outer region of the model. Therefore, it is less likely that we overestimate significantly the number of GCs stripped by the tidal force of a cluster because of the purely numerical effects described above in the isolated model. Fig. 12 describes the mass distribution of each component in the fiducial model for the long-term (2 Gyr) dynamical evolution. It is clear from this figure that about 70 % of GCs are stripped by the clusters global tidal field during 2 Gyr. The derived number of 70 % is much higher than that of $5 - 10\%$ which is derived for the isolated model and could be due to purely numerical relaxation effects of the present simulations. Therefore, it can be concluded that numerical relaxation effects do not significantly alter the present results described in the main text. Fig. 12 also clearly demonstrates that the total number of stripped GCs becomes suddenly larger beyond the tidal radius that is analytically estimated for the NGC 1404 model (see the main text).