Self-consistent simulations of nuclear cluster formation through globular cluster orbital decay and merging

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Accepted 2008 May 16. Received 2008 May 15; in original form 2008 April 24

ABSTRACT

We present results of fully self-consistent N-body simulations of the motion of four globular clusters moving in the inner region of their parent galaxy. With regard to previous simplified simulations, we confirm merging and formation of an almost steady nuclear cluster, in a slightly shorter time. The projected surface density profile shows strong similarity to that of resolved galactic nuclei. This similarity reflects also in the velocity dispersion profile which exhibits a central colder component as observed in many nucleated galaxies.

Key words: stellar dynamics – methods: numerical – galaxies: kinematics and dynamics – galaxies: star clusters.

1 INTRODUCTION

The motion of massive globular clusters (GCs) in a galaxy is determined by both the smooth general potential and the graininess of the stellar field. This latter, fluctuating, component acts as a decelerating mechanism: the so called dynamical friction (DFR). The role of DFR, which dissipates cluster orbital energy and angular momentum, has been found to be crucial in determining the time evolution of GC orbits in a galaxy, especially for orbits plunging in the inner, high-density galactic regions (e.g. Capuzzo-Dolcetta & Vicari 2005). The decay time may, indeed, be short enough for massive clusters to limit their motion to the inner galactic regions. However, any general astrophysical consideration regarding DFR cannot be based just on approximated evaluations based on Chandrasekhar-like formulas, even in their generalizations apt to treat axisymmetric or triaxial cases (Pesce, Capuzzo-Dolcetta & Vietri 1992; Capuzzo-Dolcetta 1993; Capuzzo-Dolcetta & Vicari 2005). Incidentally, note that limits and validity of the application of both Binney (1977) and Pesce et al. (1992) anisotropic expressions for DFR as well as of classic, isotropic Chandrasekhar (1943) formula have been carefully discussed in many papers, as for instance Penarrubia, Just & Kroupa (2004), Goerdt et al. (2006) and Read et al. (2006).

Several effects are indeed neglected by the analytical approach. For example, it is not considered the change in magnitude of the DFR due to the increase in the spatial extension of the cluster caused by the formation, and subsequent ‘expansion’, of its tidal tails. Also, the way the DFR acts on the different parts of the cluster (e.g. it could be stronger on its core than on the tails) is not taken into account. Recent numerical experiments have tried to shed light on this aspect finding that stars stripped from the cluster by the field, but still close enough to the system, continue to contribute to the mass of the decelerating system (Fellhauer & Lin 2007), and that, in general, the real DFR effect can be stronger than that estimated by the usual Chandrasekhar formula (probably because of the further friction due to tidal effects, see Fujii et al. 2007). Another unexplored question is how the gravitational feedback on the very inner part of the galaxy influences the DFR strength; this may be important when, during the final stages of orbital decay, the GC orbit gets very near to the centre so to enclose a galactic mass comparable with that of the cluster itself.

Clarifying the role of the above-mentioned dynamical effects is also important in the attempt to understand the mechanisms leading to the formation of Nuclear Clusters (NCs) and ultra compact dwarf galaxies. In fact, it can help in discriminating the various scenarios proposed for their formation (see e.g. Oh & Lin 2000; Oh, Lin & Richer 2000; Fellhauer & Kroupa 2002; Fellhauer et al. 2002; Bekki et al. 2004; Capuzzo-Dolcetta & Miocchi 2008, hereafter CM08; Goerdt et al. 2008). At this regard, we cite the recent observational evidence of the existence of a very young and massive star cluster in NGC 2139, located 2 arcsec offset from the kinematical centre of the host galaxy, suggesting a formation that was independent and non-coeval with that of the galactic bulge and, moreover, the observed environment is such that the system can decay to the centre in a time so short to keep intact its structure and become what is normally called NC (Andersen et al. 2008, see also Böker et al. 2002; Walcher et al. 2006).

Reliable indications would follow by straightforward, direct N-body integrations, which can be enormously time consuming when treating self-consistently the motion of a GC in a dense galactic environment. In this Letter, we present the preliminary results of a fully self-consistent N-body simulation concerning the close interaction of a sample of four massive GCs in the central region of a galaxy. Both the clusters and the galaxy are represented by mutually interacting particles, thus including self-consistently both DFR

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2 SIMULATIONS

Our N-body simulation has been carried out employing a parallel tree-code with a leap-frog time integrator using individual and variable time-steps (Miocchi & Capuzzo-Dolcetta 2002). The simulation is set in a way similar to that described in CM08, but for the role of the external galactic field which was, here, represented as a triaxial, analytical potential while, here, it is self-consistently (N-body) represented starting from initial conditions sampling a given equilibrium density profile, for the sake of simplicity chosen as spherical and such to resemble as much as possible the triaxial profile in CM08.

We resume briefly the main characteristics of our modelization. We choose to follow four massive GCs as templates of a multimergertime evolution among stellar systems decayed, conserving their initial conditions, in the inner galaxy region. A quick orbital decay induced by DFR is due to initial large values for the total mass of the clusters, whose resistance to external tidal disturbance was guaranteed by their sufficient initial compactness. The GC sample corresponds to the four densest clusters dealt with in CM08 and, moreover, every GC is composed by \( N = 2.5 \times 10^3 \) equal mass stars.

The stellar bulge where GCs move is here represented as another N-body system, with \( N_b = 512 \times 10^3 \) particles, sampling a Plummer model such to give the bodies initial positions and velocities according to a Monte Carlo representation of its equilibrium distribution function (\( \propto \rho^{-2} \) with \( \rho \) being the particle total energy per unit mass). This choice is not the most realistic for galaxies embedded in dark matter haloes; anyway, it was done with the scope to have the simplest possible equilibrium model for the central bulge of an elliptical galaxy of the type discussed in CM08, to sample N-body initial conditions from.

The Plummer density profile

\[
\rho_b(r) = \rho_0 \left[ 1 + \left( r/r_b \right)^2 \right]^{-5/2},
\]

where \( \rho_0 = 3\sqrt{\pi M_b/4\pi r_b^3} \) is the central density, has two scale parameters, the core mass \( (M_b) \) and the core radius \( (r_b) \) which are used, in the following, as mass and length units, respectively. Consequently, time, velocity and density will be measured in units of the galactic crossing time \( t_b = (r_b^2/GM_b)^{1/3} \), of \( t_b = (GM_b/r_b)^{1/2} \) and of the central density \( \rho_0 \), respectively. Due to the infinite extension of the Plummer sphere, it has to be truncated at a distance \( r_{cut} \) large enough to guarantee the stability of its N-body representation. We verified, at this scope, that the choice of \( r_{cut} = 12.2 r_b \) so as to contain 99 per cent of the total mass, is totally adequate, and agrees with results of Kazantzidis, Magorrian & Moore (2004) for finite mass density models. The stationarity of our N-body representation of the galactic bulge is guaranteed by the flat behaviour of the various lagrangian radii, as we checked. In order to have nearly the same galactic mean gravitational field of that in the CM08 model, we set the \( M_b \) and \( r_{bc} \) values as equal to those of the corresponding parameters of the galactic density distribution used in CM08, even though this gives a slightly larger \( \rho_0 \).

The time integration of the particles trajectories is performed by a second-order leap-frog algorithm, using an individual and a variable time-step (for more details, see Capuzzo-Dolcetta, Di Matteo & Miocchi 2005). To avoid instability in the time integration, we smoothed the \( 1/r_{ij} \) interaction potential by subtracting \( 1/r_{ij} \) with a continuous \( \beta \)-spline function that gives an exactly Newtonian potential for \( r_{ij} > \epsilon \). An optimal value is \( \epsilon = (\Delta r^2 G M)^{1/3} \sim 10^{-3} r_b \), where \( \Delta r_b \) is the minimum time-step allowed, \( m \) is the individual particle mass and \( r_c \) is the average value of the GC core radius (see Table 1). Note that the simulation results are scale-invariant: any quantity can be rescaled by fixing arbitrarily the values of \( M_b \) and \( r_{bc} \) in physical units. As an example, the choices \( M_b = 10^7 M_\odot \) and \( r_{bc} = 200 \) pc lead to \( M \approx 100 \) and \( M \approx 10^4 M_\odot \) for the GC and bulge particle masses, respectively; consequently, \( \epsilon \) results equal to 0.002 pc for the GC and 0.01 pc for the bulge. These values guarantee a good force resolution without introducing spurious collisional effects over the total integration time.

The four clusters [(a), (b), (c) and (d)], whose initial values of structural parameters are given in Table 1, start their evolution from the same initial conditions chosen in CM08. As clusters reference centres, we chose their centre-of-densities (CDs) as defined in Casertano & Hut (1985), for the sake of a more straightforward reference to observations.

3 RESULTS

The rapidity of the merger is evident in the upper panel of Fig. 2: the merger process is completed at about \( t_m \approx 17 \) when the Lagrangian radii of the four GCs, seen as a whole system, flatten to a quasi-stable configuration (see Fig. 1). In physical units:

\[
t_m \approx 0.5 \left( \frac{r_{bc}}{100 \text{pc}} \right)^{3/2} \left( \frac{M_b}{10^7 M_\odot} \right)^{-1/2} \text{Myr.}
\]

Table 1. Parameters list for the initial cluster models, expressed in galactic units. Reported are: the GC mass \( M \), the limiting radius \( r_l \), the King radius \( r_\text{K} \), the King concentration parameter \( c \), the half-mass radius \( r_h \), the central density \( \rho_0 \), the half-mass crossing time, \( t_\text{ch} \equiv \left[ \frac{r_l^2}{6GM_b} \right]^{1/2} \) and the King velocity parameter \( \sigma_K \). With the (example) choice \( M_b = 10^7 M_\odot \) and \( r_{bc} = 200 \) pc, a multiplication of the entries for \( \rho_0, t_m \) and \( \sigma_K \) in the table by factors of 84, 1.4 and 150, respectively, transforms them into physical units (M_\odot pc^{-1}, Myr and km s^{-1}).

| Clusters | \( M \)  | \( r_l \)  | \( r_\text{K} \) | \( c \) | \( r_h \)  | \( \rho_0 \)  | \( t_\text{ch} \)  | \( \sigma_K \) |
|----------|--------|--------|-----------|-----|--------|--------|--------|--------|
| (a)      | \( 6.7 \times 10^{-3} \) | 0.16   | 1.1 \times 10^{-2} | 1.2 | 2.3 \times 10^{-2} | 510    | 3.9 \times 10^{-2} | 0.24 |
| (b)      | \( 7.6 \times 10^{-3} \) | 0.16   | 1.5 \times 10^{-2} | 1.0 | 2.4 \times 10^{-2} | 270    | 4.2 \times 10^{-2} | 0.24 |
| (c)      | \( 8.1 \times 10^{-3} \) | 0.14   | 1.4 \times 10^{-2} | 0.99 | 2.2 \times 10^{-2} | 400    | 3.4 \times 10^{-2} | 0.27 |
| (d)      | \( 6.3 \times 10^{-3} \) | 0.14   | 1.8 \times 10^{-2} | 0.89 | 2.4 \times 10^{-2} | 160    | 4.9 \times 10^{-2} | 0.23 |
Of course, this ‘merging’ time depends much on the orbital initial conditions of the progenitor clusters and measures the time of the merger since the time in which the GCs are already confined within the galactic core region. Nevertheless, given that DFR has been convincingly shown to be an efficient mechanism to drag GCs in the very inner regions of a galaxy within a time much shorter than a Hubble time (see Capuzzo-Dolcetta 1993; Capuzzo-Dolcetta & Vicari 2005 and the discussion in Miocchi et al. 2006), this result supports the hypothesis stating that a GCs ‘sedimentation’ can take place at the galactic centre well within the galaxy lifetime.

It is interesting noting (see the upper panel of Fig. 2) that the CD of the merger remnant oscillates within 0.02$r_{bc}$ from the galactic CD. If, e.g. $r_{bc} \sim 200$ pc, this displacement corresponds to $\sim 4$ pc, i.e. a separation that would be hard to be resolved (corresponding, for instance, to $\sim 0.05$ arcsec at the Virgo cluster distance), so the NC would appear substantially centred. The off-centred NC position is due to the gravitational feedback between the very central part of the galaxy and the clusters, which naturally derives from the self-consistent nature of the model. Such an interaction reflects into the ‘perturbed’ behaviour of the inner Lagrangian radii (below $\sim 0.2r_{bc}$) of the galaxy.

The lower panel of Fig. 2 indicates that a first merging event between two clusters [(b) and (d)] occurs rather early (at $t < 5$), when their centres are still $\sim 0.2r_{bc}$ far from the galactic centre. The fact that such a binary coalescence takes place before the complete orbital decay, suggests that these events can occur even offset from the galactic centre, in spite of the strong tidal field. This ‘pre-decay’ coalescence was also found in the low-resolution self-consistent simulation by Oh & Lin (2000) (their model 1b), though in their case this phenomenon takes place much farther from the galactic centre.

By comparing the merger time with that of the CM08 simulation, it is found that here the orbital decay is $\sim 1.6$ times faster than in CM08 where the Pesce et al. (1992) generalization to the triaxial case of the Binney’s (Binney 1977) expression for DFR was used. This means that the DFR efficiency is greatly enhanced in the self-consistent model. Indeed, in Fig. 3, we see that, at least for

$t < 20$, the clusters CDs are always closer to the centre of the galaxy respect to the case of the CM08 simulation. For later times, the comparison is no longer reliable, because of the very small values of $r_{CD}$.

In Fig. 4, the total surface density profile is plotted for the last configuration. The galactic profile is reported for comparison, too. The final galactic profile is almost identical to the initial, confirming the good N-body representation of this collisionless component. In Fig. 4, the typical appearance of a nucleated galaxy central profile comes clearly out, as confirmed by the qualitative example comparison with the VCC 1871 profile in the Virgo cluster (Fig. 5).

In Fig. 4, the central ‘overdensity’ associated to the NC presence is less pronounced with respect to that obtained in CM08 and this is
An important result concerns the peculiar behaviour of the global velocity dispersion profile. Confirming the finding in CM08, the velocity dispersion of the whole system (galaxy plus NC) shows a clear decrease towards the centre (see Fig. 6). As discussed in CM08, this is a clear sign of the presence of two kinematically distinct systems that are relaxed into a different dynamical status. Such a peculiar feature has been actually found in most of the Virgo cluster nucleated dwarf ellipticals observed by Geha, Guhathakurta & van der Marel (2002, see their fig. 5). The decreasing trend to the centre of the velocity dispersion is also consistent with the solution of the Jeans equations for a sample of NCs observed in late-type spirals (Walcher et al. 2005). Finally, either a flattening or a slight central decrease is found and discussed in Oh & Lin (2000), too.

4 SUMMARY

Massive GCs suffer of DFR braking such to be limited to move in the inner part of the host galaxy. The interaction of decayed GCs among themselves and with the external tidal field may lead to subsequent merger events, whose modes are not easily understood.
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without detailed N-body simulations. In a previous paper (CM08), we followed numerically the interaction and merging of four GCs each represented as an $N = 250,000$ stars system moving in an analytical triaxial potential, taking DFR into account by means of the Pesce et al. (1992) formula. This Letter has the aim to check the CM08 results via a full self-consistent N-body modelization, i.e. sampling also the galactic environment by a large number ($= 512,000$) of interacting particles. All the main features of the merging event and of the ‘super cluster’ remnant found by CM08 are qualitatively confirmed by this, more detailed, simulation, but for a stronger orbital decay (two times faster) due to collective effects and for a less centrally concentrated merger product. This latter result, however, needs to be checked by higher resolution simulations which are also necessary to study reliably the long-term evolution and stability of the formed NC.

ACKNOWLEDGMENTS

The simulation was done thanks to the INAF–CINECA agreement (grant cne0in07).

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