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Simulating the mass assembly history of nuclear star clusters through globular cluster mergers

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Abstract. Nuclear star clusters (NSCs) are dense, collisional, stellar systems observed in galactic nuclei, often hosting a central massive black hole (MBH). Although there is a close connection between their evolution and that of their host galaxies, the formation mechanism of NSCs is still unknown. Here we explore the merger scenario, in which GCs inspiral to the galactic nucleus building-up the NSC, by means of constrained *N*-body simulations, using parameters appropriate for the Milky Way. When intermediate mass black holes (IMBHs) are present inside the infalling clusters, once decayed to the galactic center, they act as massive-perturbers that boost the stellar tidal disruption event (TDE) rate. For the first time, we generate 2D mock stellar mass and kinematic maps that can be directly compared to observed NSCs. Our simulated cluster exhibits many of the features of the Galactic NSC, including its rotation (especially in runs with no IMBHs), suggesting that the merger scenario could have a significative role in the formation of NSCs.

Key words. galaxies: bulges – galaxies: kinematics and dynamics – galaxies: nuclei – galaxies: center – Galaxy: evolution – Galaxy: formation – methods: numerical

1. Introduction

Nuclear star clusters (NSCs) are extremely dense and compact stellar systems, with typically $\sim 10^6 - 10^7$ stars, effective radii of a few pc and central luminosities up to $\sim 10^7$ $L_\odot$. They are observed at the center of a significant fraction of galactic nuclei and they often coexist with a central massive black hole (MBH, see Böker 2010, for an overview). Although their evolution is strictly connected to that of their host galaxy, their formation mechanism is not known. Two main hypotheses have been suggested: (i) in the in-situ star formation scenario gas infalls into the nucleus and forms stars (Schödel et al. 2008), (ii) in the merger scenario massive clusters, like globular clusters (GCs) decay to the galactic center via dynamical friction and merge to form a dense nucleus (Tremaine et al. 1975; Capuzzo-Dolcetta 1993). These processes are not in competition and both could contribute to the formation of NSCs. Here we explore and test the merger scenario using detailed *N*-body simulations of consecutive decay of GCs into a Milky Way (MW) like nuclear bulge and compare the results of the simulations to observations, using the MW NSC as a benchmark. Additionally, we study the effect of the presence of intermediate mass black holes (IMBHs) at the center of the constituent clusters (Madau & Rees 2001; Bromm et al. 2003) on the evolution and final structure of NSCs.

In Section 2 we describe the initial conditions and the simulations, in Sections 3 and 4 we show and discuss the results obtained.

2. Initial conditions and simulations

We followed the decay and the merging of twelve massive dense clusters inside the galactic central region by means of detailed and self-consistent *N*-body simulations (see Antonini et al. 2012; Mastrobuono-Battisti et al. 2014, for a detailed description of the initial conditions). Recent observations (Launhardt et al. 2002) of the MW central region have been used to model the nuclear bulge of the simulated galaxy. Our model includes a central MBH as massive as Sgr A* ($4\times10^6 M_\odot$, Ghez et al. 2008; Gillessen et al. 2009). The GCs, whose *N*-body representations have been built starting from a tidally limited, massive and compact King model were allowed to decay inside the live nuclear bulge one after the other, starting on randomly inclined circular orbits with 20pc radii. We ran two different realisations of these initial conditions, and three additional ones where each GC hosts a central IMBH of $10^4 M_\odot$. After the end of all the merger events we followed the relaxation process of the final system. The total simulation time, rescaled with the relaxation time of the system, as described in Mastrobuono-Battisti & Perets (2013), extends to $\sim$ 12 Gyr. The simulations were ran on the GPU partition of the Tamnun cluster at the Technion using $\phi GRAPE$ (Harfst et al. 2007), a direct-summation code optimized for computer clusters accelerated by GRAPE boards (Makino 1998) and recently adapted to run on graphic processing units (GPUs, Gaburov et al. 2009).

3. Results

3.1. NSC properties: the effect of IMBHs

The NSC density grows with time as more GCs decay and accumulate their mass at the galactic center (see left panel of Fig. 1). In the IMBH-free case, at the end of the last merging event, the core radius of the NSC is $\sim$ 1pc (see right panel of Fig. 1). The merging phase is followed by a two body relaxation, which is predicted to shrink the initial core with time toward the Bahcall & Wolf (1976) cusp steady state, that will be eventually achieved in a time scale of the order of the relaxation time at the influence radius of the central MBH (Merritt 2010).

After the end of the mergings, the system indeed evolves in a self-similar way, with the external radial slope nearly unaltered (~ -1.8, comparable to what found for the MW NSC), while its core shrinks up to a final size essentially identical to the size of the core observed at the center of the MW ($\sim$ 0.5 pc, see Fig. 2).

The NSC evolution changes significantly when IMBHs objects are introduced inside the decaying GCs (Mastrobuono-Battisti et al. 2014). After the host GC is destroyed, each IMBH inspirals to the center, leading to a fast relaxation of the NSC stellar population and building a central cusp early during the NSC formation. At the end of the last infall the inner slope of the radial density profile for the whole system is steeper than what found in the IMBHs-free case (see right panel of Fig. 1), and after $\sim$ 12 Gyr of evolution the system has developed a full cusp (see Fig. 2). Indeed, the IMBHs act as massive perturbers, significantly decreasing the relaxation time of the host system (Perets et al. 2007). The loss cone, that in the absence of IMBHs was empty inside the influence radius of the MBH, is now full at any radius. The integrated tidal disruption event (TDE) rate is 1.6×10^{-5} yr^{-1} accounting only for stars, while the presence of IMBHs enhance the rate to 10^{-3} yr^{-1}. The comparison of these values with the observationally constrained rate ($10^{-5} - 10^{-4}$ yr^{-1}, see e.g. Khabibullin & Sazonov 2014) suggests that typical NSCs should not contain IMBHs. The morphology and kinematic of the NSC evolves during the course of the infalls toward an oblate/axisymmetric shape and a slightly tangentially anisotropic configuration. In the IMBH-free case, the flattening parameter of the NSC after 12 Gyr of evolution is $q \sim 0.67$, close to what observed for the MW NSC (Schödel et al. 2014).

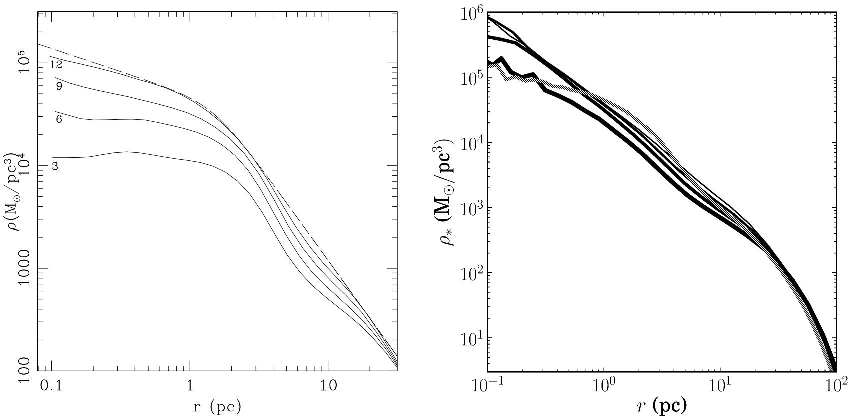

Fig. 1. Left panel: Spatial profile of the central NSC after 3, 6, 9 and 12 mergers. The dashed line is the broken power-law best fit to the NSC profile obtained at the end of the last merging event. Right panel: The same but for the simulation with IMBHs. The thickness of lines decreases with time. The grey solid line represents the density profile of the NSC after 12 merging events in the IMBHs-free case. From Antonini et al. (2012); Mastrobuono-Battisti & Capuzzo-Dolcetta (2012); Mastrobuono-Battisti et al. (2014).

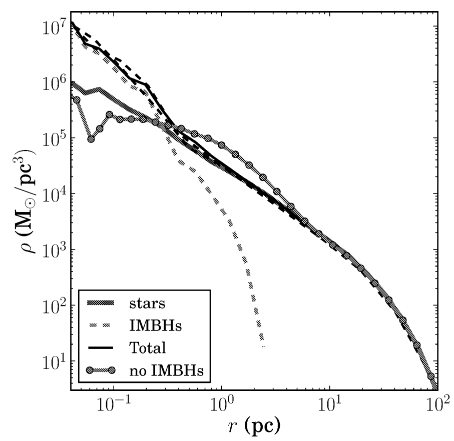

Fig. 2. The black thin solid line is density profiles of the NSC at the end of the simulation run with an IMBH at the center of each cluster. The two thin dashed black lines are the same density profiles obtained from two additional simulations. The thick dark grey solid line shows the spatial profile of the stellar component, while the grey dashed line is the final density profile of the IMBHs. The grey solid line with bullets shows the density profile of the NSC without IMBHs. From Mastrobuono-Battisti et al. (2014).

3.2. Comparison with observations

Mock kinematic maps of the simulated cluster were created using the final snapshot of both of the IMBH-free simulations, allowing for a direct comparison with the observed properties of the MW NSC (Tsatsi & Mastrobuono-Battisti, in prep.). In both the realisations the radial kinematic profiles as well as the large amount of rotation found for the simulated NSC, are in remarkable agreement with what is found for the Galactic NSC (Feldmeier et al.

2014). Moreover, the simulated NSC kinematic maps show the presence of a kinematic substructure, left behind by the ninth GC, similar to the one found by Feldmeier et al. (2014) in the MW NSC.

4. Discussion and conclusions

Using detailed *N*-body simulations we found that the consecutive merging of several dense GCs can produce a NSC whose properties match those observed for the Milky Way NSC. The simulated cluster, after $\sim$ 12 Gyr of evolution, shows a density profile with a central and almost flat core and an external slope of -1.8, as actually observed in the MW NSC. Moreover the slight tangential anisotropy and flattening of the simulated NSC is comparable to what was recently found for the MW NSC (Schödel et al. 2014). Despite the random distribution of the GCs orbits, the resulting NSC shows a significant amount of rotation and a kinematic structure in agreement with that of the Galactic NSC. Kinematic substructures, like the one found in the simulated and Galactic NSCs could be the observable signature of recent cluster mergers (Feldmeier et al. 2014). These results suggest that the merger scenario can explain the formation of the old stellar component of the MW NSC. If present inside the infalling clusters, once in the center, IMBHs are found to scatter each other and the NSC stars, with the latter reaching high eccentricities. The NSC is strongly mass-segregated (Alexander & Hopman 2009), it develops a cusp already in its early evolutionary stages and the system is in the full loss cone regime. As a consequence, the TDE rates, in the simulations with IMBHs, are two orders of magnitude larger than TDE rate estimates from observations, suggesting that typical NSCs, and hence dense stellar clusters, which in the merger scenario are the NSC building blocks, may not contain IMBHs.

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