FORMATION AND EVOLUTION OF NUCLEAR STAR CLUSTERS WITH IN SITU STAR FORMATION: NUCLEAR CORES AND AGE SEGREGATION

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ABSTRACT

Nuclear stellar clusters (NSCs) are known to exist around massive black holes (MBHs) in galactic nuclei. Two formation scenarios were suggested for their origin: (1) buildup of NSCs from consecutive infall of stellar clusters and (2) continuous in situ star formation. Though the cluster infall scenario has been extensively studied, the in situ formation scenario has been hardly explored. Here we use Fokker–Planck (FP) calculations to study the effects of star formation on the buildup of NSCs and its implications for their long-term evolution and their resulting structure. We use the FP equation to describe the evolution of stellar populations and add appropriate source terms to account for the effects of newly formed stars. We show that continuous star formation even 1–2 pc away from the MBH can lead to the buildup of an NSC with properties similar to those of the Milky Way NSC. We find that the structure of the old stellar population in the NSC with in situ star formation could be very similar to the steady-state Bahcall–Wolf cuspy structure. However, its younger populations do not yet achieve a steady state. In particular, formed/evolved NSCs with in situ star formation contain differential age-segregated stellar populations that are not yet fully mixed. Younger stellar populations formed in the outer regions of the NSC have a cuspy structure toward the NSC outskirts, while showing a core-like distribution inward, with younger populations having larger core sizes. In principal, such a structure can give rise to an apparent core-like radial distribution of younger stars, as observed in the Galactic center.

Key words: Galaxy: center – Galaxy: formation – Galaxy: nucleus – stars: formation – stars: kinematics and dynamics

1. INTRODUCTION

Nuclear stellar clusters (NSCs) hosting massive black holes (MBHs) are thought to exist in a significant fraction of all galactic nuclei. Their origin is still not well understood. Two main scenarios were suggested for their origin: (1) the cluster infall scenario, in which stellar clusters inspiral to the galactic nucleus, disrupted, and thereby build up the nuclear cluster (Tremaine et al. 1975; Capuzzo-Dolcetta 1993; Agarwal & Milosavljević 2011; Antonini 2013); and (2) the nuclear star formation (SF) scenario, in which gas infalls into the nucleus and then transforms into stars through SF processes (Loose et al. 1982). Here we focus on the latter process and study the long-term effects of SF on the formation and evolution of NSCs.

The structure, evolution, and dynamics of NSCs have been extensively studied in recent years. These explored the general dynamics of NSCs, and in particular NSCs similar to the well-observed NSC in the Milky Way Galactic center (GC). The presence of a young stellar disk in the central parsec of the GC, as well as the dense concentration of \( H\alpha \) regions and young stars throughout the central 100 pc of the Milky Way (Figer et al. 2004), provide evidence for a continuous SF in this region, both today and in the past (Genzel et al. 2010). The majority of the observed stars in the GC are either late-type main-sequence stars or red giants, suggesting that most of the stars in the GC likely formed at least a few gigayears ago (Genzel et al. 2010). Pfuhl et al. (2011) argued that the SF rate in the central pc of the GC has decreased since then, dropping to a deep minimum 1–2 Gyr ago and increasing again during the past few hundred megayears, suggesting that there are a number of epochs of SF. Evidence for SF exists in other extragalactic NSCs (e.g., Seth et al. 2006; Georgiev & Böker 2014, and references therein). Walcher et al. (2005) argued that NSCs are protobulges that grow by repeated accretion of gas and subsequent SF; McLaughlin et al. (2006) suggested an NSC in situ SF model regulated by momentum feedback.

These various studies provide further motivation and suggest that SF has an important role in shaping NSCs and their evolution. Nevertheless, very few studies systematically explored its role, while most studies focused on the cluster infall scenario. Here we focus on the role of in situ SF in NSCs and explore its implications for both the buildup of the NSC and the long-term evolution and structure of NSCs. Our work makes use of the Fokker–Planck (FP) diffusion equations, first used by Bahcall & Wolf (1976) in this context, to describe the dynamics of stellar populations in dense clusters around MBHs.

In the following we begin with a brief description of the original FP method used to study MBH-hosting clusters, and then we describe our approach of adding an additional source term and multiple populations to account for the effects of SF. We then present the resulting NSC structure arising from the SF-included evolution, as characterized by the number density and age distribution of its constituent stellar populations. We explore various possible models for the NSC SF history and study their outcomes. Finally, we discuss our results and their implications for the formation of NSC, nuclear cores, and age-segregated populations and summarize.

2. RELAXATION AND EVOLUTION OF NSCs AROUND MBHs

NSCs are complex interacting systems. Their evolution and dynamics are mainly affected by two-body relaxation (see Section 2.1.1). Theoretical studies of NSCs based on two-body relaxation include simulations of many-particle systems under a potential generated by a massive body (MBH). One method to obtain a realistic model of NSCs is through a full \( N\)-body simulation. However, running these simulations to describe the
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The evolution of realistic NSCs is currently still too computationally expensive, and only a few studies involving N-body simulations of relatively small NSCs have been done (e.g., Preto et al. 2004; Antonini et al. 2012 and references therein). Other, more efficient methods, though more limited in their application and dependence on specific assumptions, make use of the FP diffusion equation approach (Bahcall & Wolf 1976; Cohn & Kulsrud 1978) (also solved through Monte Carlo simulations Shapiro & Marchant 1978; Freitag et al. 2006). Here we follow the latter and study the evolution of NSCs by numerically solving the FP equations following the approach first used by Bahcall & Wolf (1976, 1977, hereafter BW77) in this context. However, we supplement the basic equations, for the first time, with a source term accounting for SF, as well as use a large number of distinct stellar populations to account for different SF epochs. We also parallelized the FP code to allow us to easily explore the NSC with both high resolution and a large number of stellar populations. With these tools in hand we obtain a model for the long-term evolution of SF in NSCs with in situ SF. In the following we provide a brief discussion of the original FP approach and then present the additional SF source term, as well as discuss the model assumptions and limitations.

2.1. FP Analysis

2.1.1. The Basic Model

Following the model introduced by Bahcall & Wolf (1976, 1977), we simulate the evolution in time, t, of the energy, E, distribution function (DF)—\( f(E, t) \) and the number density of stars in a spherical system around an MBH, with a mass of \( M_\odot = 4 \times 10^6 M_\odot \) (the latter is chosen to be similar to the MBH mass in the GC). We focus on the distribution of stars in the central few parsecs, and in particular in the range between the tidal radius, \( r_t \approx r_c (M_\odot / M_\bullet)^{1/3} \), below which regular stars are disrupted by the MBH, and the radius of influence, where the stellar motions are dominated by the MBH potential, defined by \( r_h = G M_\odot / \sigma_\star^2 \), where \( r_c \) and \( M_\odot \) are the typical radius and mass of stars in the NSC, respectively, and \( \sigma_\star \) is the velocity dispersion of stars just outside the NSC. The velocity dispersion in our model is \( \sigma \approx 75 \text{ km s}^{-1} \) (consistent with the \( M-\sigma \) relation; Ferrarese & Merritt (2000)). For \( r > r_h \) the original BW model assumes the existence of a “thermal bath” that supplies stars to the inner region of the galactic nucleus. The stellar orbits are assumed to be Keplerian in this range. The model timescale is dominated by the relaxation time, which is defined for a single mass system as

\[
T_r \approx \frac{\sigma^3}{G^2 M_\odot \rho \ln(\Lambda)},
\]

where \( \rho \) is the stellar density and \( \ln(\Lambda) \) is the Coulomb logarithm, a factor that is related to the scale of the system (\( \ln(\Lambda) \approx 10 \)). The simulation is done by solving the time- and energy-dependent, angular-momentum-averaged particle conservation equation. This FP equation describes the two-body diffusion of stars in energy phase space within the boundary conditions, i.e., between the fixed thermal bath reservoir of stars outside the radius of influence and the MBH sink, where the distribution is null on the tidal radius. The stars in the reservoir (\( r > r_h \)) are assumed to have a Maxwellian distribution, with the energy-dependent distribution

\[
f(E, t) = n_0 (2\pi \sigma^2)^{-1/2} e^{-E/2},
\]

where \( n_0 \) is the number density of stars in the reservoir. Inside the radius of influence (\( r < r_h \)) the DF is evaluated using the FP diffusion equation with a loss-cone term (which will be discussed in the following):

\[
\frac{\partial f(E, t)}{\partial t} = -AE^{-\frac{1}{2}} \frac{\partial f}{\partial E} - F_{\text{LC}}(E, T),
\]

where

\[
A = \frac{32\pi^2}{3} G^2 M_\odot^2 \ln(\Lambda).
\]

The term \( F = F[f(E, E)] \) is related to the stellar flow and plays an important role in the evolution of the stellar cluster. It presents the flow of stars in energy space due to two-body relaxation and is defined by

\[
F = \int dE' \left( f(E, t) \frac{\partial f(E', t)}{\partial E'} - f(E', t) \frac{\partial f(E, t)}{\partial E} \right) \times (\max(E, E'))^{-\frac{1}{2}}.
\]

The sink term \( F_{\text{LC}}(E, T) \) is the rate at which stars, with energies in the interval \((E, E + dE)\), flow into the MBH and are therefore lost from the system (hence the term loss cone) through disruption by the MBH at the tidal radius, and it is approximated by

\[
F_{\text{LC}}(E, T) \propto \frac{f(E, t)}{T_r}.
\]

The added \( F_{\text{LC}}(E, T) \) term corresponds to the empty loss-cone regime; once the rate of angular momentum diffusion exceeds the “pinhole” regime limit, the full loss-cone regime dominates the tidal disruption dynamics and the tidal disruption rate saturates. We therefore take \( F_{\text{LC}}(E, T) = \min(F_{\text{LC}}^{\text{Empty}}, F_{\text{LC}}^{\text{Full}}(E, T)) \), as a simple approximation accounting for the transition between the empty and full loss-cone regimes (see Lightman & Shapiro 1977; Young 1977; Perets et al. 2007). Note that the BW 1D FP equation allows stars to diffuse only in energy phase space and does not account for stars with small angular momentum that may be disrupted as they approach the MBH through highly eccentric orbits, whose pericenter becomes smaller than the tidal radius. The above loss-cone term is an added term that effectively accounts for the loss through angular momentum (Frank & Rees 1976; Bahcall & Wolf 1977), which is not properly accounted for in the 1D FP equation in energy phase space.

2.1.2. The Star Formation Source Term

In our model we simulate the SF in the GC through adding an extra source term component to the FP equation. Hamers & Portegies Zwart (2015) also used a source term with FP equation for modeling inflow of planetesimals. The term’s value and range in our model are determined according to the number of new stars added in the appropriate region. We simulate multiple stellar populations forming at different epochs and follow the evolution of their distribution. The initial conditions of the simulated NSCs include a background stellar population that either evolves from an initial steady-state BW distribution or is initially zero and is then entirely built up from the in situ SF.

The modified FP equation with the addition of the source term (and the loss-cone term) has the form

\[
\frac{\partial f(E, t)}{\partial t} = -AE^{-\frac{1}{2}} \frac{\partial f}{\partial E} - F_{\text{LC}}(E, T) + F_{\text{SF}} \]

where

\[
F_{\text{SF}} = \frac{\partial}{\partial t} (\Pi(E) E^\alpha) .
\]
\( \Pi(E) \) is a rectangular function, whose boundaries correspond to the region where new stars are assumed to form; \( E_0 \) is the source term amplitude; and \( F_{SF} \) is a power-law function with a slope \( \alpha \), defining the SF distribution in phase space. We simulated a number of NSC evolutionary scenarios, taking different models for the SF function (rate and spatial structure) and for the background population (see Section 3). The chosen slope of the SF function was motivated by the observed power-law (Do et al. 2009; Bartko et al. 2009) distribution of young stars observed in the young stellar disk in the GC.

2.2. Methods

In order to calculate the distribution and the number density profile of stellar populations in the modeled NSCs, we numerically integrate the differential equations presented in BW77 (including an effective tidal disruption loss-cone sink term), supplemented with the additional source, in order to follow the long-term evolution of the NSC stellar populations. Our code is based on the original code written by Hopman & Alexander (2006b), which was significantly modified, as follows: (1) it includes the added SF source term as discussed above; (2) it now includes both empty and full loss-cone dynamics, which were not consistently included before; (3) we use the simple moving window average method to deal with numerical instabilities, which lead to fluctuations in the numerical solution in previous treatments; and (4) to improve the numerical resolution and reduce computation time, our algorithm was parallelized using the OpenMP library, allowing for efficient calculation of higher-resolution grids and the modeling of a large number of stellar populations.

3. MODELS

3.1. Basic Assumptions and Limitations

In our work we use a simplified 1D FP model and consider only a single mass for all stars. Multimass populations can affect the dynamical evolution of the NSC both through the potentially faster relaxation induced by more massive stars and through mass segregation processes, which may induce different distributions for different-mass stars (e.g., Bahcall & Wolf 1977; Alexander & Hopman 2009). The first effect can be effectively studied to some extent even in single-mass populations by changing the mass of all stars, treating it as the mean mass; we therefore use models with stellar masses of either 0.6 \( M_\odot \) or 0.8 \( M_\odot \). The latter effect of mass segregation requires more complex models. Note that the typical present-day mass function has a very steep power law; therefore, the low frequency of more massive stars has relatively little effect on the relaxation processes, even given the relaxation time dependence on the stellar masses. Moreover, the vast majority of stars are of comparable mass to the mean masses used in the single-mass approximation (massive stars become low-mass compact objects on timescales typically much shorter than the relaxation time), and therefore mass segregation effects are weak. The most significant effect is for stellar black holes, whose mass is considerably larger than the typical stellar mass. These objects are therefore likely to segregate to the inner regions, potentially contributing to production of extreme mass ratio gravitational wave inspirals, and slightly accelerate relaxation processes in the innermost region of the cusp (e.g., Freitag et al. 2006; Hopman & Alexander 2006b). We do not model the latter effects; multimass populations and mass changes due to stellar evolution (e.g., Murphy et al. 1991) are beyond the scope of this study and will be explored elsewhere. We consider only NSCs hosting MBHs of \( 4 \times 10^6 \ M_\odot \), similar to the GC MBH, and assume no growth of the MBH during the evolution.

Similar to previous studies (Bahcall & Wolf 1976; Hopman & Alexander 2006b), it is assumed that the gravitational potential is always dominated by the MBH, and the contribution of the NSC stellar mass to the gravitational potential is neglected. This assumption is reasonable as long as the NSC mass is smaller, or comparable to that of the MBH. This is generally true for our simulated NSC, as we consider regions of up to a few parsecs away from the MBH, typically comparable to the MBH radius of influence. We do note that in the simulations with the highest stellar densities this assumption becomes somewhat weaker for the outskirts of the NSC, a few parsecs away from the MBH. Nevertheless, the range at which our analysis exceeds the \( r_h \) is not more than twice of it, and the difference in the typical parameters (i.e., \( T_R, r_h, \sigma \)) is expected to be small. Moreover, the relaxation times in these regions are very long, and very little evolution, if any, is expected to occur there such as to significantly affect the NSC bulk population.

Newly formed stars are assumed to form isotropically. Hence, we do not self-consistently take into account the possibility of SF in a disk-like configuration (e.g., the GC stellar disk; Levin & Beloborodov 2003; Bartko et al. 2009; Lu et al. 2009; Hobbs & Nayakshin 2009; Gualandris et al. 2012; and stellar disks in extragalactic NSCs; Seth et al. 2006). In principle, other source terms of stars can exist, such as stars captured following a binary disruption (e.g., Hills 1988; Gould & Quillen 2003; Perets et al. 2007), which could have a very different distribution and affect the NSC dynamics (Perets et al. 2009; Perets & Gualandris 2010). We postpone treatment of such qualitatively different source terms to future studies.

Finally, our models only include two-body scattering relaxation processes by stars and do not include effects of coherent resonant relaxation (Rauch & Tremaine 1996; Hopman & Alexander 2006a) or two-body relaxation by massive perturbers (Perets et al. 2007).

We consider two general types of models. In the first we study the buildup of an NSC around an MBH, in which all stars originate from long-term in situ SF processes, modeled through the FP SF source term. In the second, we consider a preexisting NSC with an initial steady-state BW structure and study the effect of adding SF to the cluster, to explore the distribution and evolution of stellar populations that form at different epochs.

3.2. Model Parameters: Initial NSC Structure, Stellar Components, and Star Formation Histories

We simulated various scenarios that describe the evolution of NSCs and the stellar populations that compose them. We consider a variety of different scenarios, summarized in Tables 1 and 2. The specific initial conditions and the characteristics of SF in NSCs are not known, and therefore we study a variety of possible cases. These differ in their SF rates and history, the regions where SF occurs, the typical masses of stars in the NSCs, and whether they include a preexisting NSC or not. Naturally, the different scenarios are not exhaustive, but they provide a basic characterization of a range of plausible, though simplified, scenarios for NSC evolution. The regions where SF occurs are motivated by the observed young stars in the young stellar disk (for models with SF in the inner 0.5 pc) and the circumnuclear disk in the GC, as well as evidence for long-term SF in the central 100 pc of the Milky Way (for models with SF in the inner 1.5–5 pc region; e.g., Figer et al. 2004; Oka et al. 2011).

We consider only single-mass models; in particular, we study
cases where the mean mass of stars is assumed to be either 0.8 or 0.6 \(M_\odot\). The stellar radii are also changed, assuming a mass-radius relation of \(R = (M/M_\odot)^{0.8} R_\odot\). The corresponding tidal radii used are then changed accordingly; see Table 1.

All the models are evolved for a Hubble time. In most models one population represents the background initial stellar population of the cusp (or the stellar population that formed at an early stage of the NSC evolution), and 10 additional populations are later introduced consecutively to study the evolution of stars formed at different epochs, up to 1 (or 3) Gyr ago. Each population represents stars forming over a continuous range of 100 (or 300) Myr and introduced continuously after the end of the previous SF epoch (besides model 8, where we consider 100 Myr SF bursts once every 1 Gyr, i.e., separated by long quiescent times). Stellar populations formed much earlier typically have sufficient time to achieve an almost steady-state solution, very similar to the BW solution, and are not studied in detail by themselves, but only considered together (as part of the first/background population), while younger populations are not relaxed and show a differential behavior (see below).

### 4. RESULTS

#### 4.1. Dynamical Evolution of Star-forming NSCs

As described in the previous sections, we have followed the evolution of multiple stellar populations formed at different epochs. Figure 1 demonstrates (model 7 in Table 1) the buildup and structure evolution of an NSC that grows through a continuous long-term in situ SF. The final configuration of this NSC is very similar to that of a steady-state BW cusp, and the number densities are comparable to those observed in the GC. However, in the BW77 scenario stars flow from the external region of the NSC (i.e., from the background “thermal bath”) into the central regions; in the SF scenario, the stars are formed in the star-forming region and slowly diffuse away to produce a flow that can be reversed in direction compared with the flow in the BW77 model. The flow direction is important when discussing populations formed at different ages; since older stars had more time to diffuse, they could be observed farther away from the SF region compared with younger stars, and the general direction of the stellar flow would determine the differential distribution of older versus younger stars (e.g., an inflow would lead to older stars dominating the inner regions, while an outflow will lead to older stars dominating the outer region).

The rate at which stars diffuse in phase space and attain a steady state depends on the relaxation time of the system. Systems with shorter relaxation times will attain a relaxed configuration, while those with slower relaxation times might still preserve signatures of their initial conditions (e.g., the distribution of an unrelaxed population of stars might be closer to that of their initial post-SF distribution). In Figure 2 we
show the dependence of the relaxation time on the distance from the MBH for the different evolutionary scenarios. We see that the behavior of the relaxation time hardly changes with time in the case where a preexisting BW cusp is set in place prior to the initial evolution. In this case the background population dominates the relaxation rate. However, in models where the NSC is built completely by SF, the initial number densities are small, and they slowly increase as more stars are formed. This is reflected by the relaxation time evolution, which becomes systematically shorter as the NSC is built and becomes denser. The relaxation times converge to those seen in the case of the initial BW cusp, once the NSC grows to comparable masses. The in situ built NSCs therefore have longer relaxation times during most of their evolution and would better preserve signatures of the SF history and structure, and differential structures of stellar populations formed at different epochs.

### 4.2. The Structure of Star-forming NSCs

As summarized in Tables 1 and 2, we have explored various models for NSCs and their SF histories. The final structures of these NSCs after 10 Gyr of evolution are summarized in Table 2 and in Figures 3 and 4, and 5. The four right-hand columns of Table 2 summarize some of the mean properties of the clusters, including the range of core sizes observed (i.e., where power-law number density profiles break to become significantly shallower) for the young stellar populations, the total number...
of stars in the NSC (up to 2 pc from the MBH), and the NSC relaxation time (at 2 pc from the MBH). The relaxation time is calculated according to Equation (1). Figures 4 and 5 show the detailed number density profile of the stellar populations in each cluster. Many of these models show the existence of a core-like structure for the young stellar populations, where the cores vary in size and are systematically bigger for younger populations. This can be seen in detail in Figure 3; similar plots are shown for the other models in Figures 4–5.

5. DISCUSSION

In this work we studied the formation and evolution of NSCs, while taking into account the effects of in situ SF using FP modeling. We explored two types of scenarios: (1) preexisting NSCs with a BW-like structure that experience later SF, and (2) NSCs built up completely from in situ SF. Both type of models assume that several epochs of gas infall into the nuclear region triggered SF, transforming the infalling gas into newly born stars (e.g., following Loose et al. 1982). The specific properties of such a SF epoch are unknown, and various models for SF histories, rates, and spatial characteristics have been explored. In the following we discuss the outcomes of the evolution of such NSCs.

5.1. The Buildup of Nuclear Stellar Clusters through In Situ Star Formation

As can be seen in Figure 5, NSCs built up from in situ SF (models 7, 10, and 12) give rise to NSCs dominated by the stellar population formed at earlier stages (first few gigayears). The structure of the older population is very similar to a steady-state BW cusp, and the total number of stars is comparable to that inferred for the GC NSC. Models with significantly lower rates of SF (not shown) cannot, by themselves, reproduce number densities comparable to the NSC and can only form a low-mass NSC with a large core (for SF inside the central 2 pc) or a very compact low-mass NSC (for SF inside the central 2 pc; model 2b). Conversely, models with high SF rates (\( > 10^{-3} \) yr\(^{-1} \)) give rise to high stellar densities, and the resulting shortening of the relaxation times leads to the formation of an NSC and its fast relaxation into a steady-state BW-like configuration, very similar to that obtained in the absence of SF. However, a significant negative feedback takes place in this case, and the typical inflow of stars in the BW-like models is replaced by an outflow, and though the number densities of such NSCs are higher than BW-like models, they only grow by a factor of a few, even where extreme (likely unrealistic) models of high SF rates (\( 10^{-2} \) yr\(^{-1} \)) are tested (not shown).

We also note that when lower-mass stellar populations (models 11–12) are assumed (e.g., if different initial mass functions are considered), the relaxation times become longer, as expected, and late-formed younger populations are far from achieving a steady-state structure, producing larger core-like structures, as discussed in more detail below.

5.2. Age Segregation

The study of multiple stellar populations formed at different epochs allows us to study the distribution of stellar ages in NSCs. In particular, many of the models studied here show a differential structure of different age populations. Older stellar populations are more relaxed than younger ones and therefore present qualitatively and quantitatively different number density profiles. Older populations of ages comparable with the cluster relaxation time achieve a BW-like cuspy steady state, while younger populations behave differently. Young populations in models with SF at the outer regions of the NSCs present large cores in their inner number density profile, with younger populations...
showing larger cores (see Figures 3, 4, and 5. Given the long relaxation times in some of the NSC models, the relaxation and slow diffusion of stars from the outer regions to the inner ones can take longer than the age of these stellar populations, leading to low stellar densities in the inner regions and the core structure. Conversely, scenarios in which SF occurs in the inner regions show, in some cases, a significant differentiation of stellar population in the outer regions, effectively producing an age-segregated structure; different regions in the NSC outskirts are dominated by populations of different ages, with the oldest populations outside and younger populations closer in. These different behaviors are well demonstrated by Figure 3. A closer examination of the age segregation in the NSCs is shown in Figure 6, where the mean age of the newly formed stars (the 1–3 Gyr old population, depending on the model and not including the older background population) is shown as a function of the distance from the MBH. The evaluated standard deviation from the mean age for these scenarios is approximately constant, $\Delta_{\text{age}} \sim 200 \text{ Myr}$. The observed age difference as a function of the separation from the center can be potentially observable.

As can be seen in Figure 6, some of the different models show distinct age segregation behavior (especially scenarios 1–6), with both positive and negative age gradients. This suggests that detailed modeling of the observed age distribution of the stellar populations in the GC can provide a handle on the relevant SF models. It should be noted that younger stellar populations are more massive (higher turnoff mass), and therefore there could be a degeneracy between interpretations of observations as arising from mass segregation and from age segregation. Indeed, there are clues for the existence of extreme mass segregation in the GC that could be difficult to explain in the context of mass segregation processes Alexander (2007); age segregation processes may therefore help to better understand this issue.

It is interesting to note that the cluster infall scenario can also lead to age-segregated NSCs, as discussed in detail by Perets and Mastrobuono-Battisti (2014), and the age distribution of stellar populations in NSCs can help us study not only their SF history but potentially the impact of both the in situ SF and the cluster infall scenario roles in the buildup of NSC. However, the contribution of both processes may also give rise to a complex...
Figure 5. Number density profiles of NSCs with different SF histories, (similar to Figure 3, now shown for scenarios 7–12). Models 8, 9, and 11 show cases of NSC evolution with a preexisting BW cusp (similar to models 1–6 in Figure 4, but with different SF histories). Models 7, 10, and 12 show models of NSCs built completely from in situ SF (no background population). Detailed model descriptions can be found in Tables 1 and 2.

5.3. Core-cusp Structure

As discussed above, we find that after \( \sim 10 \) Gyr of NSC evolution, the younger stellar populations in NSCs may evolve to a core-like distribution, while older populations already become progressively cuspier. These results are of great interest in light of the recent findings about the structure of the GC NSC.

Findings by several different groups have provided strong evidence for a core-like density profile for red giants observed in the GC (Buchholz et al. 2009; Do et al. 2009; Bartko et al. 2010; Genzel et al. 2010). Though the exact size of this core is still debated, it extends throughout the central few 0.1 pc, with some 3D modeling suggesting a core as large as 1 pc (Do et al. 2013). As noted by Merritt (2010), cores are ubiquitous components of galaxies with MBHs, at least in galaxies that are bright enough or near enough for parsec-scale features to be resolved (Ferrarese et al. 2006). In the GC, observational biases limit the study of number density profiles only to the most luminous stars, and therefore the number density profile of main-sequence low-mass stars is still unknown. Whether the core-like structure represents the overall distribution of stars in the GC or only that of evolved red giant stars is therefore still an open question, with some important implications. Such core-like density profiles in the central part of the GC would give rise to long relaxation times and slow dynamical evolution. The combined effect of slow relaxation and low stellar densities would be a low rate of tidal disruption events, as well as a low rate of extreme mass ratio gravitational-wave inspirals (EMRIs). In particular, if the GC is representative of the structure of typical NSCs around low-mass MBHs, the total event rates from such MBH-star strong interactions could be significantly lower than that expected from NSCs with a BW-cusp distribution.

Several models were suggested to explain the origin of the GC core. Some suggest that it only represents the distribution of
red giants, which were preferentially destroyed through stellar collisions (Genzel et al. 1996; Alexander 1999; Bailey & Davies 1999; Dale et al. 2009; Davies et al. 2011), and/or interaction with clumps in a gaseous disk (Amaro-Seoane & Chen 2014). However, the expected realistic collision rates are far too low to explain a core distribution much larger than $\sim 0.01$ pc (Dale et al. 2009; Merritt 2010). The model for collisions with clumps in gaseous disks (Amaro-Seoane & Chen 2014) is extremely dependent on the distance from the MBH and assumptions on the radial number density profile of the gas and may therefore potentially explain only small cores ($<0.1$ pc, compared with the 0.5–1 pc cores inferred from 3D modeling of the observations) under specific assumptions.

Another possibility is that the observed core distribution represents all stars, not only the red giants. Antonini et al. (2012) and Perets & Mastrobuono-Battisti (2014) have shown that the cluster infall scenario could lead to the formation of NSCs with significant cores. Such cores are not limited to a specific type of stars (such as red giants), as in the other models discussed above, but represent all the stellar populations (though age segregation could show different distributions for stars coming from clusters infalling at different times; nevertheless, a large difference in the core distribution of stars from different clusters is not expected; Perets & Mastrobuono-Battisti 2014).

Merritt (2010) suggested that a binary merger, or a triaxial potential, could deplete the inner regions of an NSC producing a large core, and they have shown that the long relaxation times would not be sufficient to regrow a cusp. A similar behavior is seen in our models, where progressively younger populations of stars formed in the outer regions of the NSC do not relax and grow an inner cusp. Though in both cases slow relaxation explains the nongrowth of the inner cusp, the origins of the initial core in both models differ, and the outcomes could significantly differ as well. In particular, the SF models studied here suggest that cores of different sizes could exist for different stellar populations, and in particular an NSC can have both a cusp distribution of old stars and a core distribution for young and intermediate-age stars.

We note that younger, more massive red giants could be more luminous and more easily detected in observations (Maness et al. 2007; Pfuhl et al. 2011). We therefore hypothesize that if such younger red giants (up to 2–3 Gyr old) are overly represented in observations, then the observed core could be limited to these younger populations, while the underlying population of older stars might still have a cusp distribution. This can be well demonstrated both in Figure 5 and in more detail in Figure 7, where the model results are compared with the 3D modeled number density profiles determined by Do et al. (2013) based on observations. As can be seen, in some models a large, parsec-sized core of up to a few Gyr old stellar populations can exist. Such a core might be consistent with the density profiles inferred from observations, while the old stellar population preserves a typical BW-like cusp profile. An interesting basic prediction
of such models would therefore be for stars of different ages to show a different position for the break in their distribution, between an inner cusp and an outer core. A deeper study of the observational properties and stellar evolution of populations in such models of SF origin for the core is to be done elsewhere.

6. SUMMARY

In this work we explore the formation and evolution of NSCs arising from in situ SF. We solve the FP equation with an additional source term accounting for the in situ SF, and we explore the dynamics and structure evolution of the modeled star-forming NSCs. Our models follow the dynamics of several stellar populations near an MBH of $4 \times 10^6 M_\odot$ driven by two-body relaxation processes. We find, by comparing with observations, that the scenario of NSCs arising from in situ SF can be proposed as a realistic model of galactic nuclei formation. We show that the old stellar populations have a cuspy distribution near an MBH (which corresponds to the classical Bahcall & Wolf model), while the younger populations behave differently, depending on the regions where SF occurs. Stars formed in the NSC outskirts tend to distribute in a core-like distribution, where the size of the core decreases with time, with different stellar populations potentially showing different number density profiles. In particular, younger stellar populations may have larger cores. We explore such age segregation in NSCs and present the age gradient produced through the evolution of several populations arising from SF at different epochs. We find that our results might explain the origin of the core-like distribution of red giants in the GC, and we suggest that it might be limited to intermediate-age stellar populations ($<3$ Gyr old), while the underlying old stellar population might have a cuspy structure.

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