SPIRAL ARMS, WARPING, AND CLUMPS FORMATION IN THE GALACTIC CENTER YOUNG STELLAR DISK

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Abstract

The Galactic center of the Milky-Way harbors a massive black hole (BH) orbited by a diverse population of young and old stars. A significant fraction of the youngest stars (∼ 4 − 7 Myr) reside in a thin stellar disk with puzzling properties; the disk appears to be warped, shows asymmetries, and contains one or more clumpy structures (e.g. IRS 13). Models explaining the clumping invoked the existence of an intermediate mass BH of 10^{3} − 10^{4} M_{\odot}, but no kinematic evidence for such a BH has been found. Here we use extended N-body simulations and hybrid self-consistent field method models to show that naturally formed residual temporal asphericity of the hosting nuclear star cluster gives rise to torques on the disk, which lead to changes in its orientation over time, and to recurrent formation and dissolution of single spiral arm (m = 1 modes) structures. The changing orientation leads to a flapping-like behavior of the disk and to the formation of a warped disk structure. The spiral arms may explain the over-densities in the disk (clumping) and its observed asymmetry, without invoking the existence of an intermediate mass BH. The spiral arms are also important for the overall disk evolution, and can be used to constrain the structure and composition of the nuclear stellar cluster.

1. INTRODUCTION

Based on detailed kinematic data of stars in the Galactic nucleus, a massive black hole (MBH; measured at ∼ 4.3 × 10^{6} solar masses, M_{\odot}), is inferred to exist in its center (Genzel et al. 1997; Ghez et al. 1998; Genzel et al. 2010). Similar data have been used to reveal the existence of a disk of young, 4-7 Myrs massive stars orbiting the MBH (Levin & Beloborodov 2003; Paumard et al. 2006; Lu et al. 2009; Bartko et al. 2009; Genzel et al. 2010), embedded in a massive few-pc sized, Gyr old, nuclear stellar cluster (NSC). Extensive studies of the disk over the last decade have characterized its unique structure and composition. The disk appears to be warped (Genzel et al. 2010), and a significant over-density (clump) was identified in the disk (the IRS 13 structure; Maillard et al. 2004).

The existence of a very young stellar disk close to the massive black hole (MBH) in the Galactic center (GC) has been suggested to originate from the infall of a gas cloud forming a gaseous disk which then fragments and gives rise to the observed stellar disk (Levin & Beloborodov 2003). Detailed hydrodynamical simulations of nuclear-disk star-formation have been able to produce stellar disks with similar global properties as those observed in the GC in terms of mass, stellar mass function and radial density profile (Nayakshin et al. 2007; Bonnell & Rice 2008). However, any initial inhomogeneities in the disk were found to be rapidly erased after a few orbits, leaving behind a smooth disk. The later evolution of the disk is affected by two-body relaxation processes due to stars in the disk and in the host NSC. Such processes kinematically heat the disk (i.e. increase the velocity dispersion of the disk stars), leading to higher eccentricities and disk thickening (Alexander et al. 2007; Mikhaloff & Perets 2017; Naoz et al. 2018), but are not expected to produce any of the aforementioned peculiar kinetic features (clumping, warping, asymmetries). The clump has been suggested to result from an IMBH residing in the disk; however, detailed kinematic studies of IRS13 ruled out the existence of such object (Maillard et al. 2004; Genzel et al. 2010). The origins of the clump, as well as the disk warping, therefore remained open questions. Here we show that collective processes operate in such an environment and give rise to such properties, potentially explaining their origin in the GC disk.

In order to study the evolution of the nuclear disk, we simulated the evolution of both the stellar disk as well as the background stellar population of the nuclear stellar cluster (NSC) in which the disk is embedded, us-
ing full (i.e. direct) $N$-body simulations. Due to the computational cost of such simulations, they can not follow the large number of stars in the NSC, and we therefore complemented these simulations with a hybrid self-consistent field (SCF) modeling (Meiron et al. 2014) to validate and extend our results, for a realistic NSC accounting for all the stars. Together our models show that collective processes robustly determine the evolution of the disk and may give rise to its peculiar properties.

We begin by describing the disk models we considered and the methods/codes used to simulate the disk evolution (section 2). We then describe our results (section 2), followed by the discussion (section 3) and summary (section 4).

2. SIMULATION MODELS

2.1. Disk and cusp models

Observations show the existence of a stellar cusp of typically low-mass, old, stellar population, in which the disk is embedded; theoretical studies suggest that it includes a significant population of compact objects, most importantly stellar black holes (SBHs; e.g. (Miralda-Escudé & Gould 2000; Hopman & Alexander 2006; Freitag et al. 2006; Aharon & Perets 2016)). Our initial conditions were chosen as to best realize the initial properties of the disk and the NSC, given their observed, inferred and modeled characteristics. The considered a disk extending between 0.03 and 0.3pc (we also considered 0.01pc inner cutoffs with no qualitative differences observed), with a power-law surface density profile ($\propto r^{-\gamma}$; $1.5 \leq \gamma \leq 2$) and a total disk mass of a few $10^5 M_\odot$ up to $\sim 10^4 M_\odot$ (Genzel et al. 2010). We assumed that the initial disk was thin following its formation (Nayakshin et al. 2007), taking the initial disk height to be 0.025pc (5% of the disk length). The masses of disk stars were sampled from a Salpeter mass function, between 0.6 and 60$M_\odot$ (though as we later show, the masses of the disk stars play a negligible role). The MBH position was kept constant as in a realistic NSC, only little Brownian motion of the MBH is expected (Merritt 2005). Nevertheless we also modeled cases with freely moving MBH (not discussed here; which showed qualitatively similar behaviors).

Following the evolution of all stars in a realistic NSC is computationally prohibitive, and we therefore first modeled only the population of SBHs in the spherical cusp, which is the dynamically dominant population in this region. The rest of the NSC mass was initially modeled as an external smooth potential, not following the evolution of the individual stars in the NSC. As we discuss later on, we also used a hybrid model consisting of a self-consistent field (SCF) method to model the NSC coupled with an $N$-body code for modeling the disk itself (Meiron et al. 2014). The hybrid modeling allowed us to explore a more realistic NSC (on the expense of neglecting 2-body relaxation processes in the NSC). We have explored several modifications of the initial conditions and models (as described in Table 1). We explored the cases where the disk is evolved in an NSC modeled as a smooth external potential (or with no NSC at all), i.e. not including the stochastic effects introduced by individual stars; we considered the effects of changing the SBHs masses (while keeping the total mass of the SBH population constant); and we explored the case when the disk stars are treated as test-particles as to exclude disk self-gravity effects. The full details of all the models studies can be found in Table 1, where we also list the specific codes used (see below).

2.2. $N$-body and hybrid self-self-consistent field method simulations

In our study we made use of the $\phi$GRAPE (Hartf et al. 2007) $N$-body code (modified to allow the addition of an external potential), using a GPU-based GRAPE emulation library. In addition, we also employed the self-developed NBSymple code (Capuzzo-Dolcetta et al. 2011) to better verify and check that our results are not numerical artifacts arising from the use of a specific code. Finally we complemented the $N$-body simulations using a hybrid code coupling $\phi$GRAPE with the self-consistent field method ETICS (Meiron et al. 2014) code. The hybrid code works by dividing the stellar system into a collisional (C) and collisionless (S, for soft) parts, in this case C is comprised only of the disk particles, while S is comprised of the SBHs and NSC stars. The full force calculation has four components designated CC, CS, SC, and SS. The first represents the force exerted by collisional (disk) particles on other collisional particles, the second represents the force exerted by the collisional particles on the collisionless particles, and so on. Of those four components, CC is calculated by direct summation by employing a GRAPE call from an emulation library, while the three other components are calculated with the SCF method by calling ETICS subroutines. The forces are then combined in a proper way and returned to $\phi$GRAPE to perform the time integration in the normal way. In all cases, the codes produced similar outcomes when similar initial conditions had been used, and therefore in the following we describe only qualitatively different simulations done using the $\phi$GRAPE $N$-body code and the hybrid code. The energy conservation in our simulations was in the range of $10^{-3} - 10^{-2}$ after 6 Myrs of evolution. We simulated both disks that evolve around the MBH in isolation without a hosting NSC, as well as disks coupled to a NSC. The properties of the disks and NSCs explored in our simulations are described in the following, and a
Figure 1. The evolution of a nuclear stellar disk embedded in a live NSC over a few Myrs of evolution (model 9). The NSC contains both stellar and SBH components, and the system hosts a $4.3 \times 10^6 \, M_\odot$ MBH as observed in the Galactic center. Shown are four edge-on and face-on snapshot views of the disk at several times. The formation and evolution of spiral arm structure and warping are clearly seen. The detailed properties of disk and the hosting NSC are given in Table 1.
The models for the disk and nuclear cluster explored with the N-body (GRAPE code) and SCF-hybrid (ETICS code) simulations. Live refers to full N-body modeling of the stars; Test particles refer to the N-body modeling of the stars as mass-less test particles. Hybrid refers to the case where each of the stars is fully represented on a one to one level, but the overall potential from the NSC stars is calculated only through the SCF method, while the disk stars are fully modeled through N-body evolution. Smooth potential refers to spherically symmetric external potential representing the overall smoothed mass distribution of the stars without the effect of their discrete representation.

| #  | Model                  | Disk stars     | NSC stars     | NSC SBHs | Code    | Result                                      |
|----|------------------------|----------------|---------------|----------|---------|---------------------------------------------|
| 1  | Isolated disk          | Salpeter       | —             | No SBHs  | N-body  | stable, smooth non-warped disk              |
| 2  | Disk+smooth NSC        | Salpeter       | Smooth potential | No SBHs | N-body  | stable, smooth non-warped disk              |
| 3  | Disk+live SBHs         | Salpeter       | —             | 10M⊙     | N-body  | unstable, spiral arm, clumping, warping     |
| 4  | Test disk+live SBHs    | Mass-less      | —             | 10M⊙     | N-body  | unstable, spiral arm, clumping, warping     |
| 5  | Disk+live SBHs +smooth NSC | Salpeter | Smooth potential | 10M⊙     | N-body  | unstable, spiral arm, clumping, warping     |
| 6  | Disk+live SBHs +smooth NSC | Salpeter | Smooth potential | 20M⊙     | N-body  | unstable, spiral arm, clumping, warping     |
| 7  | Disk+live SBHs +smooth NSC | Salpeter | Smooth potential | 40M⊙     | N-body  | unstable, spiral arm, clumping, warping     |
| 8  | Disk+live SBHs +NSC    | Salpeter       | SCF(160k stars; m=4M⊙) | 40M⊙     | hybrid  | unstable, spiral arm, clumping, warping     |
| 9  | Disk+live SBHs +NSC    | Salpeter       | SCF(640k stars; m=1M⊙) | 10M⊙     | hybrid  | unstable, spiral arm, clumping, warping     |
| 10 | Disk+live SBHs +NSC    | Salpeter       | SCF(640k stars; m=1M⊙) | 20M⊙     | hybrid  | unstable, spiral arm, clumping, warping     |
| 11 | Disk+live SBHs +NSC    | Salpeter       | SCF(640k stars; m=1M⊙) | 40M⊙     | hybrid  | unstable, spiral arm, clumping, warping     |
| 12 | Disk+NSC               | Salpeter       | SCF(640k stars; m=1M⊙) | No SBHs  | hybrid  | unstable, spiral arm, clumping, warping     |

Table 1.
summary of our main models is shown in Table 1.

Disk: We explored several models for the evolution of a stellar disk with global properties comparable to that observed/inferred for the stellar disk in the GC (Genzel et al. 2010). All our disks included 5000 stars, which masses are sampled from a Salpeter mass function in the range $0.6 - 60 M_\odot$ with a total disk mass of $\sim 9500 M_\odot$. In order to explore the role played by the self-gravity of the disk we also considered a disk composed of mass-less test-particles. The latter mass-less disk evolved qualitatively the same as the realistic massive disk. Our simulated disks extend between 0.05 and 0.5 pc, comparable to the GC disk. We also considered a model with a lower inner cutoff (0.03 pc), for which results showed no qualitative differences from our other models. We considered a power-law surface density profile for all simulated disk ($\propto r^{-\gamma}$; $1.5 \leq \gamma \leq 2$). We assumed the initial disk was thin following its formation (Nayakshin et al. 2007), taking the initial disk height to be 0.025 pc (5% of the disk length).

NSC: Several qualitatively different types of NSC models were considered.

1. Live-NSCs composed only of SBHs: These were run with the $N$-body simulation and included 16k/8k/4k point-mass particles of 10, 20 and 40 $M_\odot$, respectively, where the total mass in SBHs ($1.6 \times 10^9 M_\odot$) had been kept constant. The SBHs were distributed isotropically around the MBH with a $r^{-2}$ radial density profile between 0.03 – 0.8 pc from the MBH (we also considered lower, 0.01 pc, and higher 0.04pc cutoffs, showing similar qualitative behavior). Such BH cusps are expected to exist in GC-like nuclei, following the formation and evolution through mass-segregation processes (e.g. Hopman & Alexander 2006; Freitag et al. 2006; Alexander & Hopman 2009; Preto & Amaro-Seoane 2010; Aharon & Perets 2016).

2. Smooth potential and hybrid live-NSCs: In order to disentangle the overall effects of the NSC smooth background potential from the emergent asphericity effects, arising from the discreteness of the NSC background stellar population, we also ran models with the NSC modeled as a smooth spherical gravitational potential. Such models produced no instabilities. In our $N$-body models we included a smooth potential for the large stellar NSC, and a live, full $N$-body model of the SBHs-only cases.

3. Realistic live-NSCs: These included both the SBHs (as in the SBHs-only models), as well as a realistic live stellar NSC, composed of $6.4 \times 10^5$ ($1 M_\odot$ stars), distributed isotropically with a $r^{-7/4}$ density profile over the same 0.03 – 0.8 pc range as the SBHs. We also considered a case of a live NSC with no SBHs, composed only of the stellar component. Since full $N$-body simulations of such realistic NSCs are too computationally expensive to run with direct $N$-body simulations, the realistic NSC models were all run using our hybrid code.

3. RESULTS

Our simulations confirm the results of previous models in the case of the evolution of an isolated (no NSC) stellar disk (e.g. (Alexander et al. 2007; Šubr & Haas 2014; Mikhaloff & Perets 2017) and references therein), showing only a steady disk-height increase over its 6 Myrs evolution, consistent with 2-body relaxation models. Such models produce a smooth (no clumps or asymmetries), aligned (no warping) structure which does not change its orientation. Adding a constant smooth potential to model the NSC shows very similar results. However, once we include the effects of individual SBHs in the NSC (a “live” NSC) the picture changes dramatically (see Figures 1-2). The collective variable contribution of the stars in the NSC gives rise to naturally emerging residual asphericity in the NSC (which effects were first studied in the context of resonant relaxation (Rauch & Tremaine 1996)) producing torques on the disk stars. Since the direction of the global torque evolves randomly in time, the torque direction evolves, and in turn, the disk orientation changes with time, leading to a flapping like behavior, and warping of the disk (see Figure 2). It should be noted that Kocsis & Tremaine (2011) studied a resonant relaxation origin of warping, though without self-consistent and realistic treatment of the NSC; in particular they did not follow individual particles, and therefore could not observe the important processes described in the following.

Besides the warping, a different process can be seen. The disk shows a recurrent growth and destruction of a global $m = 1$ unstable mode, as it manifests itself in a single spiral arm structure in the disk, thereby giving rise to large scale asymmetries in the distribution of stars in the disk and significant over-densities (clumping) of the stars.

4. DISCUSSION

The spiral arm and asymmetry produced in the disk, together with warping may help explain the origin of the puzzling properties of the nuclear stellar disk in the Galactic center (see Figures 1-2). In particular, these processes give rise to the possible existence of a spiral arm structure and/or asymmetries and correlated clumping to be searched for in current and future data.

We suggest that the disk evolution is driven by the
Figure 2. The structure of a nuclear stellar disk after 6 Myrs of evolution (distance shown in pc). Left: A disk evolved in isolation with no NSC, showing a smooth symmetric structure. Right: A disk evolved with an NSC composed of live SBHs and a smooth potential for the contribution of regular stars (model 7). In this model, a significant spiral arm formed already at 1.5 Myrs, dissipated and then reformed at $\sim 5.5$ Myrs, and the disk changed its orientation over time and became warped.

development of a difference between the position of the central mass component (such as the MBH in our case) and the center of mass of the system (such as the NSC in our case), even irrespective of the disk. Such effects were shown to play a role in the formation of $m = 1$ unstable modes in other astrophysical systems of different scales (such as galactic disks on large scales, and protoplanetary systems on small scales; see Jog & Combes (2009) for an overview and references therein), but they have been only little explored in the context of NSCs (Tremaine 2005). Such processes can not be captured by considering a smooth external potential, explaining the different evolution in models where the NSC were only realized through such potentials.

In the system explored here, the randomly changing potential from the cusp SBHs and stars provides a changing environment. Such changes may explain the recurrent formation and destruction of the spiral structures and the random-walk-like behavior of the disk inclination, compared with the coherent process occurring in the galactic-scale and protoplanetary scale systems. Indeed, our simulations further verify and pinpoint the collective nature of the process in even more realistic models which account for all stars in the cusp. Our hybrid modeling (models 8-12) realistically represents not only the live SBHs, but also allows us to realistically model the contribution of a live NSC, which computational cost in regular $N$-body simulations would have been too prohibitive. The reproduction of the same behavior in this case confirms that it is not the result of the more artificial conditions used in the $N$-body simulations, and further supports the robust nature of our results. Moreover, besides realizing a large number of stars, the SCF modeling allows us to remove any effects due to two-body relaxation, and consider only collective effects due to the randomly induced overall change in the NSC potential over time. In all cases where a discrete NSC is introduced we find a qualitatively similar behavior, namely the recurrent formation and dissipation of spiral arms, accompanied by a random walk of the disk inclination and the development of disk warping. Such behavior is seen even when the disk stars are treated as mass-less test particles (model 4), i.e. the self-gravity of the disk does not play a major role in these processes.

Increasing the SBHs mass (e.g. taking 40 $M_\odot$ instead of 10 $M_\odot$, e.g. motivated by Aharon & Perets 2016) increases the randomly produced aspherical component of the NSC and leads to a more pronounced and rapidly varying spiral arm structure. Nevertheless, though the role of the SBHs is important, the same qualitatively-similar behavior (spiral arms, warping and clumping) could be seen even in a model in which only the stellar
(live) component of NSC was considered and no SBHs were included (model 12).

Currently, only the few tens brightest OB stars can be directly observed in the GC stellar disk. Unfortunately, identifying a spiral arm structure in such sparse data is challenging. Nevertheless, the $m=1$ mode pattern gives rise to a global non-trivial structure that is reflected by over-densities and asymmetries expected to exist in the disk. Figures 1-2 show the resulting structure of a disk during and after 6 Myrs of evolution; for comparison we show similar data for the outcome of a disk evolved in isolation (Figure 1, left), showing a smoother, thinner disk with no evidence of asymmetries, nor warping nor clumping as seen in the NSC-embedded disk. Consequently, even if a bona-fide spiral structure could not be identified with current data, over-density clumps are expected to exist. These may explain the origin of the puzzling IRS13 clump without invoking the existence of a (non-detected) IMBH. Moreover, our models predict the existence of a clear asymmetry in the disk. Identifying the latter could be currently difficult to disentangle from potential differential extinction over different regions in the GC disk (Genzel et al. 2010), but could potentially be better resolved in the future.

5. SUMMARY

We explored the dynamics of the stellar disk orbiting the massive black hole in the Galactic center through N-body and hybrid self-consistent-field method simulations, accounting for the realistic effects of the stellar cluster in which the disk is embedded. Our results reveal a novel behavior of the nuclear stellar disk, producing spiral arms, warping, asymmetries and clumping in the disk. We find that the collective effects introduced by the nuclear stellar cluster play a key role in determining the evolution of the disk and its structure. Such behavior is robust, and can arise from a wide range of initial conditions. Our results potentially provide an explanation for the origin of the peculiar kinematic features in the observed GC disk (warping, clumping and asymmetry), and give rise to additional predictions such as the possible existence of a spiral arm structure which could be explored with observational data in the coming years. Moreover, such processes should similarly affect the evolution of other galactic nuclear disks, including stellar disks formed in disks of active galactic nuclei and may similarly affect the evolution of gaseous disks in galactic nuclei. Consequently, the same processes could be important for the evolution of nuclear maser disks and active galactic nuclei, and possibly even for their fueling at small, pc scales, in similar ways as spiral structures in a large-scale galactic disk play a role in the heating of the disk and fueling gas and stars into its inner regions.

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