DYNAMICAL EVOLUTION OF THE YOUNG STARS IN THE GALACTIC CENTER: N-BODY SIMULATIONS OF THE S-STARS

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ABSTRACT

We use Newtonian N-body simulations to study the evolution of the orbital eccentricities of stars deposited near (≤ 0.05 pc) the Milky Way massive black hole (MBH), starting from initial conditions motivated by two competing models for their origin: formation in a disk followed by inward migration and exchange interactions involving a binary star. The first model predicts modest eccentricities, lower than those observed in the S-star cluster, while the second model predicts higher eccentricities than observed. The Newtonian N-body simulations include a dense cluster of 10 M☉ stellar-mass black holes (SBHs), expected to accumulate near the MBH by mass segregation. Perturbations from the SBHs tend to randomize the stellar orbits, partially erasing the dynamical signatures of their origin. The eccentricities of the initially highly eccentric stars evolve, in 20 Myr (the S-star lifespan), to a distribution that is consistent with the observed eccentricity distribution. In contrast, the eccentricities of the initially more circular orbits fail to evolve to the observed values in 20 Myr, arguing against the disk migration scenario. We find that 20%–30% of the S-stars are tidally disrupted by the MBH over their lifetimes, and that the S-stars are not likely to be ejected as hypervelocity stars outside the central 0.05 pc by close encounters with SBHs.

Key words: black hole physics – galaxies: nuclei – stars: kinematics

Online-only material: color figures

1. INTRODUCTION

In recent years, high-resolution observations have revealed the existence of many young OB stars in the Galactic center (GC). Accurate measurement of the orbital parameters of these stars gives strong evidence for the existence of a massive black hole (MBH) which dominates the dynamics in the GC (Ghez et al. 1998; Eisenhauer et al. 2005; Gillessen et al. 2008). Most of the young stars are observed in the central 0.5 pc around the MBH. The young star population in the inner 0.05 pc (the “S-stars”) consists exclusively of B-stars, in an apparently isotropic distribution around the MBH, with relatively high eccentricities (0.3 ≤ e ≤ 0.95; Gillessen et al. 2008). The young stars outside this region comprise O-stars in one or two disks, and present markedly different orbital properties (Levin & Beloborodov 2003; Bartko et al. 2009; Lu et al. 2009).

Since regular star formation in the region near the MBH is inhibited by tidal forces, many suggestions have been made regarding the origin of the S-stars. Many of these are probably ruled out by observations and/or by theoretical arguments (see Alexander (2005) and Paumard et al. (2006) for a review). The various scenarios for the origin of the S-stars predict very different distributions for their orbits, which in principle could be constrained by observations. However, it is not clear to what extent relaxation processes can produce changes in the distribution of orbital parameters after the stars have been deposited near their current locations. Here, we try to resolve this question. We use Newtonian N-body simulations to follow the evolution of stellar orbits around the GC MBH for 20 Myr, starting from various initial conditions that were motivated by different models for the origin of the S-stars. General relativistic (GR) orbital effects are beyond the scope of this study. In particular, we do not take into account relativistic Schwarzschild precession, whose direction is opposite to that which is due to the enclosed stellar mass, which could either enhance or suppress RR, depending on its magnitude relative to mass precession. In addition, we do not discuss here the possibility that an intermediate mass black hole was involved in the production and/or evolution of the S-stars, which is discussed in details elsewhere (see Merritt et al. 2009, and references therein). We find our Newtonian N-body results to be consistent with our analytical predictions, and compare them with current observations. We then discuss the implications for the validity of the models for the production of the S-stars. In addition, we study the possible ejection of the S-stars outside the inner 0.05 pc and the contribution of such ejected stars to the population of hypervelocity stars (as suggested by O’Leary & Loeb (2008)) and to the isotropic population of B-stars observed at distances of up to 0.5 pc from the MBH (i.e., at distances similar to those of the young O/WR stellar disks, but outside of these disks at high inclinations).

In Section 2, we summarize the different models for the origin of the S-stars and the predictions that they make for the stellar orbits at the time when the stars are first deposited near the MBH. Section 3 describes the Newtonian N-body simulations we carried out to follow the S-star orbital evolution starting from these initial conditions. Sections 4 and 5 present the results of these simulations and discuss the implications for the origin of the stellar populations of B-stars in the GC and for the population of hypervelocity stars observed in the Galactic halo (Brown 2008). Section 6 sums up.

2. MODELS FOR THE S-STARS ORIGIN

Many solutions have been suggested for the origin of the S-stars, but many of these have been effectively excluded (see Alexander 2005 and Paumard et al. 2006 for a review). Here, we focus on two basic models which differ substantially in their predictions for the initial orbital distribution of the S-stars and/or the time passed since their arrival/formation at their current
location. These are (1) formation of the S-stars in a stellar disk close to the MBH, followed by transport through a planetary-migration-like scenario to their current positions (Levin 2007) and (2) formation of the S-stars in binaries far from the MBH, followed by scattering onto the MBH by massive perturbers (e.g., giant molecular clouds) and tidal disruption of the binaries (Perets et al. 2007; Perets & Alexander 2008), leaving a captured star in a tight orbit around the MBH. Binary disruption scenarios similar to (2) have been proposed, in which the S-stars formed in a stellar disk (either the currently observed 6 Myr old disk, or an older, currently not observed disk) and later changed their orbits due to coherent torques through an instability of eccentric disks (Madigan et al. 2009); or through the Kozai mechanism resulting from the presence of two disks (Löckmann et al. 2008). The latter alternative is unlikely since the Kozai mechanism is quenched in the presence of a massive enough cusp of stars such as exists in the GC (Chang 2009; Madigan et al. 2009). In any case, all the binary-disruption scenarios imply very similar initial distributions for the captured S-stars, and may differ only in their relevant timescales.

In the following, we briefly discuss the initial distribution of the eccentricities and inclinations of the S-stars expected from the different scenarios for their production. The models are summarized in Table 1.

### 2.1. Binary Disruption by a Massive Black Hole

A close pass of a binary star near a MBH results in an exchange interaction, in which one star is ejected at high velocity, while its companion is captured by the MBH and left on a bound orbit. Such interaction occurs because of the tidal forces exerted by the MBH on the binary components. Typically, a binary (with mass $M_{\text{bin}}$, and semimajor axis, $a_{\text{bin}}$) is disrupted when it crosses the tidal radius of the MBH (of mass $M_*$), given by $r_t = a_{\text{bin}}(M_* / M_{\text{bin}})^{1/3}$. One of the binary components is captured by the MBH (Gould & Quillen 2003) on a wide and eccentric orbit while the companion is ejected with high velocity (Hills 1988).

The capture probability and the semimajor axis distribution of the captured stars were estimated by means of numerical simulations, showing that most binaries approaching the MBH within the tidal radius $r_t(a_{\text{bin}})$ are disrupted (Hills 1991, 1992; Gualandris et al. 2005; Bromley et al. 2006). The harmonic mean semimajor axis for three-bodies exchanges with equal mass binaries was found to be (Hills 1991)

$$\langle a_{\text{cap}} \rangle \simeq 0.56 \left( \frac{M_*}{M_{\text{bin}}} \right)^{2/3} a_{\text{bin}} \simeq 0.56 \left( \frac{M_*}{M_{\text{bin}}} \right)^{1/3} r_t,$$

where $a_{\text{bin}}$ is the semimajor axis of the infalling binary and $a_{\text{cap}}$ that of the captured star (the MBH-star “binary”). Most values of $a_{\text{cap}}$ fall within a factor 2 of the mean. This relation maps the semimajor axis distribution of the infalling binaries to that of the captured stars: the harder the binaries, the more tightly bound the captured stars. The periapse of the captured star is at $r_t$, and therefore its eccentricity is very high (Hills 1991; Miller et al. 2005),

$$e = 1 - r_t/a_{\text{cap}} \simeq 1 - 1.8(M_{\text{bin}}/M_*)^{1/3} \simeq 0.94 - 0.99,$$

for values typical of B-type main-sequence binaries and the MBH in the GC ($M_{\text{bin}} = 6-30 M_0$; $M_* = 3.6 \times 10^8 M_0$; $a_{\text{cap}} = (0.5-2) \times \langle a_{\text{cap}} \rangle$). Therefore, in order to study the evolution of S-stars from the binary disruption scenarios we assume that the initial eccentricities of S-stars are in the range $0.94-0.99$ (where most are close to the mean value of 0.98).

In principle, the binary disruption scenario has specific predictions for the semimajor axis distribution of the captured stars, which could also be used for constraining the model. However, such distribution is highly sensitive to differences in the (unknown) binary distribution in the GC region. The prediction of high eccentricities for the captured S-stars, instead, is robust and has only a weak dependence on the mass of the binary.

The inclinations of the captured S-stars in the massive perturbers scenario (Perets et al. 2007) are likely to be distributed isotropically since the stars originate in an isotropic cusp. Although in the disk instability scenario (Madigan et al. 2009) the progenitors of the captured stars form in the stellar disk, their original inclinations could be excited to higher inclinations than the typical inclinations observed in the stellar disk (Y. Levin 2009, private communication), and may resemble a more isotropic distribution.

### 2.2. Planetary Like Migration from the Young Stellar Disk(s)

Levin (2007) suggested that the S-stars could have formed in the currently observed stellar disk in the GC (Bartko et al. 2009; Lu et al. 2009), and then migrated inward in a way similar to planetary migration. The migration timescale expected from such a scenario could be as short as $10^5$ yr (for type I migration),

| No. | Origin | Initial Eccentricity | Time (Myr) | Model Probability$^a$ | Survival Fraction$^b$ | Refs. |
|-----|--------|----------------------|------------|-----------------------|-----------------------|-------|
| 1   | Capture following binary disruption due to disk instability in the currently observed disk | High | 6 | 0.3 (0.26) | 0.8 | 1 |
| 2   | Capture following binary disruption due to massive perturbers or to disk instability in an old non-observed disk | High | 20 | 0.69 (0.93) | 0.7 | 2 |
| 3   | Disk formation + planetary like migration (currently observed disk) | Low | 6 | $3.7 \times 10^{-3} (8 \times 10^{-3})$ | 0.9 | 3 |
| 4   | Disk formation + planetary like migration (possible old disk) | Low | 20 | 0.028 (0.06) | 0.8 | 3 |

Notes.

$^a$ Probability for the samples of the observed and simulated S-stars to be randomly chosen from the same distribution (see the text).

$^b$ Fraction of S-stars not disrupted by the MBH during the simulation (see the text).

References. (1) Madigan et al. 2009; (2) Perets et al. 2007; (3) Levin 2007.
which could be comparable to (although possibly larger than; Nayakshin et al. 2007) the lifetime of the gaseous disk. Recent analytic work (Ogilvie & Lubow 2003; Goldreich & Sari 2003; and references therein) has shown that eccentricity is likely to be damped during migration, unless eccentricity excitation occurs, which requires the opening of a clean gap in the disk. In the latter case, the migration timescale might be larger (Levin 2007), possibly inconsistent with the lifetime of the gaseous disk (Nayakshin et al. 2007). It is therefore more likely that the eccentricities of the stars are damped during the migration. Even eccentricity excitation, if such took place, is unlikely to excite very high eccentricities. The mean eccentricity of the observed stars in the stellar disk is 0.34 ± 0.06. Therefore, in order to study the evolution of the S-stars following their formation in a stellar disk, we assume them to have low eccentricities, or, being conservative, moderately high eccentricities (e_{max} = 0.5; where we use a thermal distribution of eccentricities, cutoff at e_{max}). These simulations include the less likely (Levin 2007) possibility that the stellar disk extended inward to the current region of the S-stars, in which case the S-stars were formed in situ and did not migrate.

3. THE N-BODY SIMULATIONS

To test these competing models, we carried out Newtonian N-body simulations of the inner Milky Way bulge using models containing a realistic number of stars. All integrations were carried out on the 32-node GRAPE cluster gravitySimulator at the Rochester Institute of Technology which adopts a parallel setup of GRAPE accelerator boards to efficiently compute gravitational forces. The direct summation code φGRAPE was used (Harfst et al. 2007). These simulations do not take into account GR effects. The simulations used a softening radius of \sim 4 R_\odot comparable to the radius of the S-stars r_s, so as to be able to follow even the closest encounters between stars.

Our initial conditions were based on a collisionally evolved model of a cusp of stars and stellar remnants around the GC MBH (Hopman & Alexander 2006b, hereafter HA06; see also Freitag et al. 2006). HA06 evolved the multi-mass isotropic Fokker–Planck equation representing the stellar distribution in the region extending to \sim 1 pc from the MBH; in their models the contribution to the gravitational potential from the distributed mass is ignored. HA06 fixed the relative numbers of objects in each of four mass bins by assuming a mass function consistent with continuous star formation. The 10 M_\odot stellar-mass black holes (SBHs) were found to follow a steep, n(r) \sim r^{-2} density profile near the MBH while the lower-mass populations (main-sequence stars, white dwarfs, neutron stars) had n \sim r^{-\alpha}, \ 1.4 \lesssim \alpha \lesssim 1.5. The SBHs were found to dominate the mass density inside \sim 0.01 pc.

Based on this model, we constructed an N-body realization containing a total of 1200 objects within 0.3 pc of the MBH: 200 “stars,” with masses of 3 M_\odot, and 1000 “black holes” with masses 10 M_\odot, around a MBH of 3 \times 10^6 M_\odot. We set \alpha = 2 for the SBHs and \alpha = 1.5 for the lower-mass stars, and each density component was tapered smoothly to zero beyond 0.1 pc when computing the corresponding f(E). Since the S stars may have masses as high as \sim 10 M_\odot, the higher mass stars in our simulations could also be treated as S-stars. We did not see any major differences in the evolution of the more massive and the less massive stars, and we discuss the evolution of both together.

The number of SBHs contained within a radius r in our N-body models was

\[ N(< r) \approx 600 \left( \frac{r}{0.1 \text{ pc}} \right) \]

implying a distributed mass within 0.1 pc of \sim 10^4 M_\odot. This is somewhat (\sim 2–3 x) lower than the mass in SBHs in the HA06 or similar (Morris 1993; Miralda-Escudé & Gould 2000; Freitag et al. 2006) models at the same radius, and a factor \sim 5 lower than the total mass (mostly in main-sequence stars) in the Fokker–Planck models. In this sense, the rates of evolution that we infer below can be considered to be conservative.

On the other hand, we note that the late-type (old) stars that dominate the number counts in this region have a much flatter density profile than predicted by the HA06 models, possibly even exhibiting a central “hole” (Figer et al. 2003; Zhu et al. 2008). Only the B-type stars in the nuclear star cluster show a steeply rising number density, \alpha = 1.1 ± 0.3 (Schödel et al. 2007; Gillessen et al. 2008), but they presumably constitute a negligible fraction of the total mass in this region, and in any case are far too young to have reached a collisional steady state around the MBH. While the origin of this discrepancy between models and observations is currently unresolved, it may imply that the other contributors to the distributed mass around the MBH, including the SBHs, also have a lower density than in the Fokker–Planck models. For instance, relaxation times at the GC may be too long for collisionally relaxed steady states to have been established in the last 10 Gyr (Merritt & Szell 2006).

Modeling of the stellar proper motion data (Trippe et al. 2008; Schoedel et al. 2009) implies a distributed mass within 1 pc of (0.5–1.5) \times 10^6 M_\odot, but these data are consistent with both rising and falling mass densities within this region and the distributed mass in the inner 0.1 pc is essentially unconstrained (Schoedel et al. 2009).

Because of these uncertainties, we discuss below how our results would vary if different numbers of SBHs were assumed. As discussed in the previous section, we studied two basic sets of initial conditions for the S-stars. In the first model, we assumed that the S-stars were captured by the MBH as in the binary disruption scenario (Gould & Quillen 2003), which leaves the captured stars in highly eccentric orbits (>0.94–0.99; cf. Section 2.1). Under these assumptions, the stars evolved for 6 Myr (if formed in the stellar disk) or longer (if the S-stars formed outside the central pc, i.e., not in the young stellar disk). We evolved the models for up to 20 Myr, which is comparable to the lifetime of the observed S-stars (although some may have longer lifespans). In the second scenario, we assumed that the S-stars formed in a gaseous disk and then migrated inward (or formed in situ in a disk extending close to the MBH). For this case we assumed the S-stars to have low eccentricities (<0.5), as typical of disk formation models, and to evolve for 6 Myr (the lifetime of the observed stellar disk). In order to check both scenarios, we selected the stars with initially high-eccentricity orbits (0.94 \leq e \leq 0.99) and low-eccentricity orbits (e < 0.5) and followed their evolution for a time appropriate to their presumed origin.

In addition to these evolutionary scenarios, we also studied the possibility of ejection of S-stars as hypervelocity stars, following a close encounter with a SBH in the vicinity of the MBH, as suggested by O’Leary & Loeb (2008). Our high-resolution simulations can accurately follow close encounters between stars, and therefore track any resulting high-velocity ejections of stars. Motivated by recent observations of B-type
4. RESULTS

4.1. Simulations versus Theory: Resonant Relaxation

We applied the correlation curve method (Eilon et al. 2009) to our simulations to identify the relaxation process responsible for the dynamical evolution of the stars (Figure 1). The method is able to detect and measure relaxation in nearly Keplerian N-body systems. In the isotropic system considered here, the angular momentum of the stars, \( J \), evolves both due to the slow stochastic two-body relaxation (e.g., Binney & Tremaine 1987) and to the rapid resonant relaxation (RR; Rauch & Tremaine 1996; Rauch & Inglalls 1998; Hopman & Alexander 2006a; Gürkan & Hopman 2007; Eilon et al. 2009). Two-body relaxation changes \( J \) in a random walk fashion, \( \frac{\Delta J}{J} = \frac{\sqrt{\tau}}{\tau_{NR}} \) over the long two-body relaxation timescale \( \tau_{NR} \approx \frac{2}{(N \log Q)} \), where \( J_c \) is the maximal (circular orbit) angular momentum for a given energy, \( Q = M_s / M_\odot \), \( N \) is the number of enclosed stars on the distance scale of interest, and time \( \tau = t / P \) is measured in terms of the orbital period on that scale. RR occurs when the symmetries of the potential act to constrain the stellar orbits (e.g., closed ellipses in a Kepler potential, or planar rosettes in a spherical one). As long as the symmetry is approximately maintained on the coherence timescale \( \tau_s \), the stars experience coherent torques, and \( \frac{\Delta J}{J_c} \sim \left( \frac{\sqrt{\tau}}{\tau_{RR}} \right) \). In a nearly Keplerian potential, as is the case in the inner parsec of the GC, RR can change both the angular momentum of J (“scalar RR”) and its direction (“vector RR”). In the Newtonian context, the coherence of scalar RR is limited by the precession of the apoapsis due to the enclosed stellar mass, on a timescale \( \tau_{RR} \sim Q / \sqrt{N} \). Note that we do not take into account in our simulations GR precession, which has the opposite sign, and could therefore, depending on its magnitude relative to mass precession, either increase or decrease the coherence time (cf. Hopman & Alexander 2006a). These additional effects are beyond the scope of this paper and would be discussed elsewhere. On timescales \( \tau > \tau_{RR} \), the coherent change \( \Delta J / \Delta \tau \) becomes the mean free path in J-space for a rapid random walk, \( \frac{\Delta J}{J_c} = \frac{\sqrt{\tau}}{\tau_{RR}} \), where \( \tau_{RR} \approx Q / \sqrt{N} \). The coherence of vector RR is self-limited by the change in the orbital orientation due to RR, and is even faster, \( \frac{\Delta J}{J_c} = \frac{\sqrt{\tau}}{\tau_{RR}} \), where \( \tau_{RR} \approx Q / \sqrt{N} \).

Figure 1 shows the rms change in the scalar and vector angular momentum of the stars in the simulation, as a function of the time lag \( \tau \) (correlation curves), up to the maximal time lag for which the simulation can still be analyzed with high statistical confidence, \( \tau_{max} \sim 10^4 \). In our simulation, the scalar

\[ e^\pm(\tau) = \left[ 1 - \left( \sqrt{1 - e_i^2} \pm \frac{\tau}{\tau_{RR}} \right)^2 \right]^{1/2}. \]

The magnitude of the predicted change in eccentricity agrees well with that observed in the simulations. For example, an S-star initially captured by a tidal event on a \( P = 500 \) yr (\( a \sim 0.04 \) pc), \( e_i = 0.97 \) orbit can evolve by RR to an \( e_f = 0.80 \) orbit in 20 Myr. The short vector RR timescale \( \tau_{RR} \sim 10^3 \) (\( \tau_{RR} \sim 5 \times 10^6 \) yr at 0.04 pc) implies full randomization of the orbital planes after 6 Myr, throughout the S-cluster volume, as is observed in the simulation. We therefore conclude that RR is the dominant mechanism responsible for the dynamical evolution of the S-stars and other stars close to the MBH in the GC.

4.2. S-star Eccentricities and Inclinations

In Figure 2, we show the final cumulative eccentricity distribution of the S-stars for the different origin models (Table 1). These are compared to the orbits of the observed S-stars (taken from Gillessen et al. 2008). The probabilities for the samples of

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3 For a spectrum of masses, \( \tau_M \sim Q / N (M_s) \) and \( \tau_{RR} \sim M_s / M_{eff} \), where \( M_s = 8.8 M_\odot \) and \( M_{eff} = (M_c^2) / (M_s) \). \( M_{eff} \approx 9.7 M_\odot \) for our simulation.
the observed and simulated S-stars to be randomly chosen from the same distribution (calculated using two-sample Anderson–Darling test; Scholz & Stephens 1987; similar results shown in the same distribution (calculated using two-sample Anderson–Darling test; Scholz & Stephens 1987; similar results shown in the same distribution) are given in Table 1. We find that the binary disruption model taking place at least 20 Myr ago is much favored over all other models tested here. We find 69% (93%) chance for the observed S-stars and the simulated stars in such model to originate from the same distribution (with the shorter timescale of 6 Myr consistent at the 30% (26%) level). In contrast, the disk migration scenarios seem to be excluded (for the given assumptions), since they have major difficulties in explaining the large fraction of eccentric orbits observed for the S-stars in the GC.

In principle, the timescales at which RR operates are shorter for stars with shorter periods, and therefore stars closer to the MBH should relax faster than those with larger separations. Such bias toward more relaxed eccentricity distribution cannot be observed with statistical significance with current statistics (both observational and simulations data are too small), and requires more data than currently available.

We find that the inclination distribution of the captured stars, initialized with the same inclination, is rapidly isotropized, to resemble a random distribution of inclinations (consistent with random at the ∼65% and ∼20% level, after evolution of 20 and 6 Myr, respectively). This is expected from the RR process, as discussed in the previous section (see also Figure 1). We conclude that the observed isotropic distribution of the S-stars angular momentum direction is consistent with all the S-stars production models studied here, and cannot be used to discriminate between them, although it constrains the lifetime of the S-stars system to be at least ∼4 Myr at the 95% level, assuming that all S-stars were initially put on the same plane.

4.3. Survival of the S-stars: Tidal Disruption, Ejection, and Hypervelocity Stars

As already discussed above, the S-stars can change their orbits due to their dynamical evolution. A star could therefore be scattered very close to the MBH and be disrupted by it, if its pericenter distance from the MBH becomes smaller than the tidal radius of the star $r_t = r_a (M_*/m_*)^{1/3}$. Many of the S-stars could therefore not survive for long close to the MBH.

We followed the orbits of stars in our simulations and calculated the fraction of stars that have been disrupted. For the tidal disruption calculations, all stars were assumed to have the typical main-sequence radius according to their mass. We consider a star as being disrupted if its pericenter became smaller than twice the tidal radius during the simulation (i.e., when it is strongly affected by the MBH tidal forces or even totally disrupted in one pericenter passage). We find that most of the S-stars survived to current times in all the models (see survival fractions in Table 1). The S-stars population in the GC therefore gives a good representation of all the S-stars formed/captured in this region. The production rate of the S-stars required to explain current observations is therefore only slightly higher (1.2–1.3 times higher) than that deduced from current number of S-stars observed.

In principle, the S-stars could be ejected by strong encounters to orbits with larger semimajor axes, putting them outside the 0.05 pc region near the MBH (Miralda-Escudé & Gould 2000), or even ejecting them as unbound hypervelocity stars (O’Leary & Loeb 2008). The softening radius used in our simulation was $r_{\text{soft}} = 4 R_\odot$, comparable to the radius of observed S-stars, allowing us to follow even very close encounters. Nevertheless, we find that only ∼10% of the stars were ejected outside of the central 0.05 pc, and even those had minimal semimajor axis in the end of the simulation not extending beyond 0.1 pc. We therefore conclude that such ejected S-stars cannot explain recent observations of many B-type stars outside the central 0.05 pc (H. Bartko 2008, private communication). Moreover, none of the 3 $M_\odot$ stars in our simulations have been ejected as a hypervelocity star, suggesting that ejection of hypervelocity stars through encounters with SBHs is not an efficient mechanism (see also Perets 2009a) for the related constraints on this mechanism.

We note that since our simulations can be rescaled, we can probe much higher stellar densities and smaller softening radius (see the next section). When such rescaling is used, in which all the 1200 stars are distributed between $3 \times 10^{-4}$ pc to 0.1 pc (rescaling the radii by half), we find five stars ejected beyond 0.1 pc (to have final semimajor axis of 0.1, 0.16, 0.16, 0.21, and 0.37 pc), but none ejected as hypervelocity stars or even as slow unbound stars. Our null results for hypervelocity stars ejection are consistent with the more conservative models used by O’Leary & Loeb (2008), where they refrain from extrapolating the stellar distribution to very small and radii from the MBH. In that regard, we note that the results of two-body interaction rates near the MBH are known to be sensitive to the assumption of an inner cutoff, and a too small cutoff (e.g., not taking into account depletion of star by collisions and tidal disruptions) could lead to unrealistically high rates (see, for example, the discussion by Hopman et al. 2007).

5. DEPENDENCE OF THE RESULTS ON THE ASSUMED DENSITY OF SBHs

As discussed above, the density of the SBHs that are responsible for the evolution in our $N$-body models is not well determined. Scaling the $N$-body results to different assumed values of $N$ is complicated by the fact that scalar RR has two regimes, coherent and random walk. In our models, the transition occurs at

$$t_M \simeq Q P/N \sim 3 \times 10^4 \left( \frac{N_{\text{SBH}}}{10^4} \right)^{-1} \left( \frac{P}{100 \text{ yr}} \right) \text{ yr} ,$$

where the $N_{\text{SBH}}^{-1}$ scaling is for scattering by SBHs of a given mass.
In the coherent regime, $\Delta t \lesssim t_M$, orbital angular momenta grow as

$$\frac{\Delta J}{J_c} \sim 10^{-4} \left( \frac{N_{SBH}}{10^3} \right)^{1/2} \frac{\Delta t}{P}. \quad (6)$$

In the diffusive regime, $\Delta t \gg t_M$,

$$\left| \frac{\Delta J}{J_c} \right| \sim \sqrt{\frac{\Delta t}{\tau_{RR}}} \approx 2 \times 10^{-3} \sqrt{\frac{\Delta t}{P}}, \quad (7)$$

independent of $N_{SBH}$.

We are interested in the orbital evolution of the S-stars over timescales of $\Delta t \sim O(10^7)$ yr. In our simulations and those with larger $N$, $\Delta t \gg t_M$. In this large-$N$ regime, changes in eccentricity are dominated by the diffusive relation and are therefore expected to be nearly independent of $N$ for timescales of interest, at least up to $N$-values of $\sim 10^3$ where the distributed mass begins to approach the mass of the MBH and RR is no longer effective. Only for $N_{SBH} \lesssim 10$ does $t_M$ approach $10^7$ yr and our results start depending significantly on $N_{SBH}$. However, such a small number of SBHs in the volume of interest is highly unlikely, and therefore our results are robust to the details of the SBH cusp model.

The Newtonian $N$-body simulations can also trivially be rescaled by

$$r \to Ar, \quad t \to A^{3/2}t \quad (8)$$

at fixed mass. This corresponds to placing the same number of SBHs into a smaller (larger) region and integrating for a shorter (longer) time. For instance, if we rescale our simulations to three times smaller distances (in which case the stars are distributed between $3 \times 10^{-4}$ and 0.05 pc), the integration time becomes $\sim 5$ Myr.

6. SUMMARY

The approximately thermal eccentricity distribution of the S-stars near the MBH in the GC, $N(< e) \propto e^2$, is not naturally predicted by either of the two leading models for their production: migration of stars formed in a gaseous disk; or capture of stars following binary disruption by the MBH. The former model predicts eccentricities that are too low, the latter too high. In this paper, we followed the dynamical evolution of orbits of various eccentricities near the GC MBH, including for the first time the cluster of SBHs that is expected to form around the MBH via mass segregation. We found that perturbations from the SBHs can reduce the eccentricities of initially highly eccentric orbits ($0.94 \lesssim e_{\text{final}} \lesssim 0.99$) into a distribution that is consistent with the observed one, in a time of approximately 20 Myr, comparable to S-star lifespans; some of the stars change their eccentricities by more than 0.5 to values as low as $e_{\text{final}} = 0.2$–0.4. We confirmed these $N$-body results via a theoretical analysis of the relaxation process, and used that analysis to argue that our results are not strongly dependent on the (unknown) normalization of the SBH density near the MBH. The same mechanism is unable to convert initially low-eccentricity orbits into very eccentric ones on the same timescale, arguing against the validity of the disk migration model for the origin of the S-stars. We also found that most S-stars are not disrupted by the MBH during their lifetime, and very few are ejected outside the central 0.05 pc near the MBH, and none having a semimajor axis beyond 0.1 pc. We did not find any hypervelocity star ejected in our simulation.

Evolution toward a thermal eccentricity distribution is a natural consequence of random gravitational encounters with a population of massive perturbers. In this paper, we considered the effect of a background of SBHs, which are expected on the basis of very general arguments to contribute a total mass of $\sim 10^3 M_\odot$ in the inner 0.1 pc around the MBH. We showed that they were effective at moderating the eccentricities of initially highly eccentric orbits. These results strengthen models in which the S-stars are formed from disrupted binaries, and disfavor models in which the S-stars are formed with low eccentricities. We do caution, however, that GR effects could affect these results, especially for the stars closest to the MBH. Further studies including GR effects are required in order to assess their importance.

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