DYNAMICAL FRICTION ON GALACTIC CENTER STAR CLUSTERS WITH AN INTERMEDIATE-MASS BLACK HOLE

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ABSTRACT

Numerical simulations of the dynamical friction suffered by a Galactic center star cluster harboring an intermediate-mass black hole (IMBH) have been performed. Gerhard has suggested that dynamical friction, which causes a cluster to lose orbital energy and spiral in toward the Galactic center, may explain the presence of a cluster of very young stars in the central parsec, where star formation might be prohibitively difficult because of strong tidal forces. However, numerical simulations by Kim & Morris showed that this is possible only if the cluster initially has an extremely dense core. Hansen & Milosavljević recently suggested that the presence of an IMBH in the cluster core might stabilize the core against tidal disruption during the inspiral through dynamical friction and thus might easily deliver young stars down to the central parsec. We find that the presence of an IMBH does lower the minimum initial core density required to transport young stars down to the central parsec, but this is possible only when the mass of the IMBH is at least ~10% of the total cluster mass. This fraction is significantly higher than that estimated by Portegies Zwart & McMillan with numerical simulations of IMBH formation by successive merging of stars in the cluster core, so it does not appear that a realistic IMBH can help transport young stars into the central parsec.

Subject headings: galaxies: star clusters — Galaxy: center — Galaxy: kinematics and dynamics — methods: N-body simulations — stellar dynamics

1.INTRODUCTION

The central parsec of the Galaxy contains a cluster of very young stars, including ~16 very luminous He i emission-line stars (Krabbe et al. 1995; Paumard et al. 2001) as well as many O and B stars (Eckart et al. 1999). Krabbe et al. (1995) find that the properties of these stars can be accounted for by a burst of star formation between 3 and 7 Myr ago. The He i stars appear to have been massive (> 40 $M_\odot$) stars with stellar ages of ~5 Myr (Paumard et al. 2001). Krabbe et al. (1995) estimate that the number of OB stars with $L \geq 3 \times 10^3 L_\odot$ and Wolf-Rayet stars (WNL, WCL, and He i stars) in the central parsec is ~50. We define these objects as young massive stars (YMSs) and estimate their progenitor masses to be ~40 $M_\odot$. Despite their very young ages, in situ formation of these stars may be inhibited by the strong tidal forces in the central parsec. It is not clear that the maximum density of gas currently in the central parsec can be as high as the Roche density required for a cloud to remain bound, $\sim 4 \times 10^3$ H cm$^{-3}$ (1 pc/R) for Galactocentric radius $R$. Jackson et al. (1993) report a density of a few times $10^5$ cm$^{-3}$ at a distance of ~1 pc, while Christopher et al. (2004) argue that densities approaching the limiting Roche density can be found at a distance of ~2 pc (see the discussion in § 3).

One possibility is that the gravitational collapse leading to the formation of the present cluster of young stars in the central parsec was triggered by infall of a particularly dense gas cloud, which experienced compression by shocks including cloud-cloud collisions, self-intersecting gas streams, or violent explosions near or at the central black hole (Morris 1993; Sanders 1998; Morris et al. 1999). Alternatively, the star cluster could have formed outside the central parsec, where tidal forces are relatively weaker and star formation is consequently less problematic, and later migrated into the Galactic center (GC). Gerhard (2001) proposes that dynamical friction can bring a massive young star cluster, initially embedded in its parent molecular cloud, into the central parsec during the lifetime of its most massive stars, depending on the initial location and mass of the cluster. The drag force represented by dynamical friction, acting in the direction opposite to the cluster motion, is due to the induced “wake” of background stars. If the star cluster is massive enough, the resulting deceleration can in principle be large enough to cause the cluster to spiral into the GC.

Kim & Morris (2003, hereafter Paper I) performed numerical simulations of dynamical friction suffered by star clusters near the Galactic center and found that dynamical friction can indeed bring star clusters formed outside the central parsec into the central parsec. However, this is possible only if the cluster is either very massive ($\sim 10^6 M_\odot$) or is formed near the central parsec ($\leq 5$ pc). In both cases, the cluster should have an initially very dense core ($\sim 10^5 M_\odot$ pc$^{-3}$). These extreme requirements make the dynamical friction scenario rather implausible. Clusters with smaller masses, larger Galactocentric radii, and/or smaller core densities either (1) completely evaporate before reaching the central parsec owing to increasingly strong tidal forces that the cluster must endure during the inward migration or (2) do not reach the central parsec within the lifetime of YMSs.

McMillan & Portegies Zwart (2003) presented semianalytic calculations of the inspiral of star clusters near the GC to study the parameter space in which the cluster can reach the central parsec of the Galaxy within a few million years. While they performed simplified semianalytic calculations to explore a wide range of parameter space, Paper I implemented a numerical treatment that models both the cluster and the inner part of the Galaxy with a large number of particles to accurately model the final dissolution phase of the cluster. The amount of mass deposited in the central parsec can be estimated more accurately in this way, and this estimation was the main goal of Paper I.

Recently, Hansen & Milosavljević (2003) suggested that if a cluster formed outside the central parsec harbors an intermediate-mass black hole (IMBH) they would be able to deliver young stars down to the central parsec. However, numerical simulations by Kim & Morris showed that this is possible only if the cluster initially has an extremely dense core. Hansen & Milosavljević recently suggested that the presence of an IMBH in the cluster core might stabilize the core against tidal disruption during the inspiral through dynamical friction and thus might easily deliver young stars down to the central parsec. We find that the presence of an IMBH does lower the minimum initial core density required to transport young stars down to the central parsec, but this is possible only when the mass of the IMBH is at least ~10% of the total cluster mass. This fraction is significantly higher than that estimated by Portegies Zwart & McMillan with numerical simulations of IMBH formation by successive merging of stars in the cluster core, so it does not appear that a realistic IMBH can help transport young stars into the central parsec.

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number of particles for the cluster is $10^5$, making the mass of each cluster particle $\sim 10 M_\odot$ (this number is not exactly $10 M_\odot$ because $M_\odot$ includes the mass of the IMBH, which is represented by a single particle).

The Plummer density profile we adopted above is only for the stellar component, and we place an IMBH at the center of this profile. However, an equilibrium configuration may not always be achievable when an IMBH is added to this profile [a part of the distribution function $f(E)$ may become negative if the IMBH mass added is too large; see Binney & Tremaine 1987, p. 237, for details]. It turns out that for the mass range of the IMBHs we consider in the present study, equilibrium is not available without modifying the adopted stellar density profiles. We find that equilibrium is achievable when stars inside a certain small radius from the cluster center, $r_{\text{in}}$, are removed (once the simulation begins, the initial void of stars near the IMBH will be quickly filled by stars that are deflected into the void by two-body interactions, and the cluster will approach the new equilibrium). The values of $r_{\text{in}}$ that we choose are the minimum radii that allow equilibrium for the system and are shown in Table 1. Each simulation has a different initial central density ($\rho_0$) because of different $r_{\text{in}}$ values.

The initial orbital eccentricity is expressed in terms of the initial orbital velocity, $v_{\text{cent}}$, relative to the circular velocity at a given $R$, $v_{\text{circ}}$, and our clusters initially have a tangential velocity only. Our simulations have $v_{\text{cent}}/v_{\text{circ}}$ of either 0.5 or 0.2. Such significantly noncircular initial orbits might result from cloud-cloud collisions, which is one of the possible mechanisms for forming a relatively massive cluster near the central parsec. Such highly eccentric initial orbits will make the dynamical friction more effective, as the cluster will experience its largest tidal forces near its periapse position. Since this assumption favors the process we are investigating, it strengthens our conclusion in what follows that the process is unlikely to be operating in the GC.

As discussed in Paper I, clusters with $\gtrsim 10^6 M_\odot$ would initially contain more than a thousand YMSs, which is more than an order of magnitude larger than currently observed in the central parsec (there are very few YMSs outside this region except for two very young star clusters at least 30 pc from the GC with a mass of order of $10^4 M_\odot$, the Arches cluster and the Quintuplet cluster). On the other hand, if $M_\odot$ is less than $10^4 M_\odot$, the number of YMSs in the cluster would be only a fraction of what is currently observed in the central parsec, and one would need successive inspirals of several clusters to explain the observed number of YMSs. Thus, we choose $M_\odot = 10^5 M_\odot$ for our clusters.

### 3. RESULTS

Figure 1 compares the evolution of the radial distribution of cluster particles of simulation 1 (simulation 8 of Paper I) and simulation 2, which have the same initial conditions except that the former does not have an IMBH. The orbital evolution shows a periodic oscillation simply because the clusters initially have elliptical orbits. This plot dramatically shows the role of the IMBH in making the cluster core more stable against tidal disruption and prolonging its inward migration to a smaller Galactocentric radius. While the whole cluster of simulation 1 completely disrupts when reaching $R = 1$ pc and is spread over the region between 0.8 and 3.5 pc, in the case of simulation

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**TABLE 1**

| Simulation | $v_{\text{cent}}$ ($v_{\text{in}}$) | $M_{\text{initial}}$ ($M_\odot$) | $\rho_0$ ($M_\odot$ pc$^{-3}$) | $r_{\text{in}}$ (pc) |
|------------|-----------------|-----------------|-----------------|----------------|
| 1          | 0.5             | 11.4 $\times$ 10$^7$ | 0.00            | 0.00          |
| 2          | 0.5 $\times$ 10$^4$ | 5.5 $\times$ 10$^7$ | 0.06            | 0.05          |
| 3          | 0.5 $\times$ 10$^5$ | 7.2 $\times$ 10$^7$ | 0.05            | 0.05          |
| 4          | 0.5 $\times$ 10$^6$ | 8.7 $\times$ 10$^7$ | 0.04            | 0.05          |
| 5          | 0.5 $\times$ 10$^7$ | 7.2 $\times$ 10$^7$ | 0.05            | 0.05          |

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4 We do not address in the present study how such an IMBH would be formed.

5 The value of $M_{\text{initial}}$, for models 2 and 3 in Table 1 of Paper I are erroneous and should read $4.3 \times 10^7$ and $6.0 \times 10^7 M_\odot$, respectively.

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See Paper I for references to work on these clusters.
2, where the cluster harbors an IMBH at its center, only the halo of the cluster disrupts outside the central parsec and the core continues to spiral in to the central parsec. Although the location of the IMBH is not plotted in this figure, we find that the IMBH and the core are tightly bound to each other until the core is dissolved inside the central parsec at \( \sim 3.5 \) Myr.

Paper I showed that without the IMBH, a 10\(^5\) \( M_\odot \) cluster must have \( \rho_c \) of at least \( \sim 10^5 \) \( M_\odot \) pc\(^{-3}\) to deliver its core to the central parsec within the lifetime of the YMSs, but simulation 2 lowers this requirement by almost 2 orders of magnitude. The initial \( \rho_c \) of simulation 2, \( 5.5 \times 10^6 \) \( M_\odot \) pc\(^{-3}\), can often be observed in the cores of dense globular clusters and is close to the density estimated for the early phase of the Arches cluster (Kim et al. 2000).

Figure 2b shows the location of the IMBH and the mass of the cluster stars (not including the IMBH) located inside the central parsec, \( M_{1pc} \), as a function of time for simulation 2; \( M_{1pc} \) increases as the IMBH enters the central parsec and reaches its asymptotic value when the cluster core is completely dissolved. The stellar mass deposited in the central parsec is \( \sim 8 \times 10^3 \) \( M_\odot \) for simulation 2, which is approximately 3 times larger than that of simulation 1 (Fig. 2a). Clusters formed near the GC are expected to undergo very rapid dynamical mass segregation during the first few \( 10^5 \) yr (Kim et al. 1999). Thus, by the time the core sinks to the central parsec and dissolves therein, the core will be largely dominated by the most massive stars. If we assume that the typical mass of a YMS is 50 \( M_\odot \) and the number of central parsec stars presumed to be YMSs is 50, then the total mass of YMSs in the central parsec is \( 2.5 \times 10^5 \) \( M_\odot \). This value is sufficiently less than \( M_{1pc} \) at the end of the simulation that, allowing for a reasonable initial mass function, we expect that almost all YMSs formed in the cluster of simulation 2 are transported into the central parsec.

The value of \( M_{1pc} \) at the end of simulation 1 is \( \sim 2.5 \times 10^5 \) \( M_\odot \), which equals the estimated mass of YMSs in the
central parsec. But only a few stars of simulation 1 are located inside $R = 0.8$ pc, while most of the observed YMSs are located inside $R = 0.8$ pc. The presence of the IMBH in simulation 2 not only increases $M_{1\,pc}$ but also transports the core stars deeper into the GC, as shown in Figure 1.

It may appear that simulation 2 is a good scenario to explain the presence of YMSs in the central parsec, but there is nonetheless a rather serious problem with it: the IMBH in simulation 2 is too massive compared to the total cluster mass (20% of the cluster mass). The typical core mass in a cluster is ~1% of the cluster mass, so even if all the stars in the cluster core turn into an IMBH, it is still far smaller than the IMBH of simulation 2. Furthermore, Portegies Zwart & McMillan (2002) estimate that an object resulting from the runaway growth of the cluster to the central parsec is $\sim 10^{-7} M_{\odot}$ (an inferred mass fraction required to explain the YMSs in the central parsec).

Clusters having IMBHs smaller than that of simulation 2 would be more realistic, but then the stabilization of the cluster core by the IMBH would be less effective. By comparing simulations 2, 3, and 4 (Figs. 2b, 2c, and 2d), which have the same initial conditions except for the IMBH mass, we find that the minimum IMBH mass fraction required to bring the core of the $10^7 M_{\odot}$ cluster to the central parsec is $\sim 10^{-7} M_{\odot}$; $M_{1\,pc}$ at the end of simulation 4 is almost the same as that of simulation 1, where there is no IMBH. It takes more than 6 Myr for the core of simulation 3 to migrate to the central parsec and dump the stars there, and this time is close to the upper limit of the estimated age of the YMSs in the central parsec.

A more eccentric initial cluster orbit could be more effective for the inward migration of the cluster core because the cluster would experience higher Galactic stellar densities at earlier times. However, simulation 5 (Fig. 2e), which has $v_{\text{in}}/v_{\text{circ}} = 5$, shows that $M_{1\,pc}$ is not sensitively dependent on the initial eccentricity of the cluster orbit.

We also performed a couple of simulations with an initial density profile from the King model (King 1966) with a concentration parameter $W_0 = 9$, which represents a highly concentrated profile for a cluster, but found that the results are nearly identical to the simulations with the Plummer initial profiles. This shows that our results are probably not sensitive to the choice of the initial density profile. Initial $R$-values other than 5 pc were not tried in the present study, but as found in Paper I, survival of the cluster depends on the initial $R$, but not sensitively on the initial $R$.

After trying and considering various different initial conditions for the cluster, we conclude that the presence of an IMBH that occupies less than ~10% of the total cluster does not greatly increase the amount of stars deposited in the central parsec.

The simulation method adopted in the present study properly describes dynamical friction but may not accurately follow internal dynamical evolution of star clusters owing to the use of a rather large softening parameter (see Paper I) as well as to the uniformity of the model stellar masses, which cannot therefore reproduce mass segregation in the cluster. The two-body relaxation times at the core of our clusters are of order $10^7$ yr, so some cluster cores may experience significant dynamical evolution during our simulation periods. In star clusters with a black hole of a considerable mass, the core density gradually decreases by the loss of stars to the black hole and the expansion of the core (Rauch 1999; Freitag & Benz 2002). This density decrease is probably underestimated in our simulations; thus, the actual initial core densities and black hole mass fraction required to explain the YMSs in the central parsec are probably even higher than implied by our results.

We note that from high spatial resolution millimeter line observations of the inner four parsecs of the GC, Christopher et al. (2004) found that some of the molecular clumps in the circumnuclear disk (1.2 $\geq R/1$ pc $\geq 2.5$) appear to be dense enough to surpass the Roche limit in the central parsec. The virial densities of their clumps range between $10^7$ and $10^8$ H cm$^{-3}$, and the virial masses range between $10^7$ and $10^8 M_{\odot}$. Simulations in Paper I suggest that a cluster formed from the heaviest clump in the Christopher et al. observations (an inferred $\sim 10^8 M_{\odot}$) may be able to spiral into the central parsec within the lifetime of the YMSs, even without an IMBH.

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