THE NEED FOR A SECOND BLACK HOLE AT THE GALACTIC CENTER

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ABSTRACT

Deep infra-red observations and long-term monitoring programs have provided dynamical evidence for a supermassive black hole of mass $3 \times 10^6 M_\odot$ associated with the radio source Sagittarius A\* at the center of our Galaxy. The brightest stars orbiting within 0.1 parsecs of the black hole appear to be young, massive main sequence stars, in spite of an environment near the black hole that is hostile to star formation. We discuss mechanisms by which stars born outside the central parsec can sink towards the black hole and conclude that the drag coming from plausible stellar populations does not operate on the short timescales required by the stellar ages. We propose that these stars were dragged in by a second black hole of mass $\sim 10^{3-4} M_\odot$, which would be classified as an intermediate-mass black hole. We discuss the implications for the stellar populations and the kinematics in the Galactic center. Finally we note that continued astrometric monitoring of the central radio source offers the prospect for a direct detection of such objects.

Subject headings:

1. INTRODUCTION

Near-infrared imaging observations with speckle and adaptive optics techniques now allow the study of the central parsec of our Galaxy at an angular resolution of 0.05 arcseconds. Monitoring over the course of the last decade has provided the proper motions for many of the stars orbiting in the central parsec (Eckart & Genzel 1997, Ghez et al. 1998). Measurement of significant deviations from linear motion has yielded orbital solutions for several of the stars closest (< 0.016 pc) to the supermassive black hole (SBH) at the Galactic center (Eckart et al. 2002; Ghez et al. 2000, 2003a,b; Schödel et al. 2002). While the older, fainter stars exhibit an apparently isotropic distribution of stellar velocities, there exist separate populations of young stars, the motion of which appears to be dynamically unrelaxed. At distances $\sim$ 0.1 parsecs from the black hole lie a group of He emission-line stars (the IRS 16 cluster) belonging to a tangentially-anisotropic orbital family (Genzel et al. 2000). These stars, with K band magnitudes $\sim$9–14, are believed to be evolved, supergiant or Wolf-Rayet stars, with masses estimated at $30 - 100 M_\odot$ after correcting for the distance and the extinction towards the Galactic center (Ghez et al. 2003b). As such, these stars can only be $\sim 1 - 10$ Myr old. Closer to Sgr A* there is a coeval but apparently kinematically distinct population of stars (Genzel et al. 1997, 2003a,b; Gezari et al. 2002, Ghez et al. 2003a,b). This group is claimed to be radially anisotropic and of an earlier, O/B spectral type. It is the provenance of these two groups of stars and the origin of their peculiar kinematics that we wish to address.

2. PREVIOUS WORK

In situ formation of young massive stars is unlikely inside the central parsec as the tidal forces render it difficult for a sinking molecular cloud to survive long enough to form stars close to the SBH. Clouds that are sufficiently dense to resist tidal shear, $n \gtrsim 10^8$ cm$^{-3}$, are Jeans-unstable and fragment before they sink (Vollmer & Duschl 2001). An alternative suggestion (Levin & Beloborodov 2003) is that the stars formed in an extended, self-gravitating gaseous disk that had in the past existed close to the SBH. However there is no direct evidence to corroborate this hypothesis. To explain the non-coplanar orbits of the central cluster, Levin & Beloborodov 2003 propose that the orbits of the closest stars have been affected by Lens-Thirring precession due to an SBH spin that is not aligned with the disk axis.

If the young stars were not born in their current positions, they must have migrated inward from larger Galactocentric radii. Massive star clusters (Gerhard 2001, McMillan & Portegies Zwart 2003; Portegies Zwart, McMillan & Gerhard 2003) can sink via dynamical friction within Myrs but are tidally disrupted at a distance $> 1$ pc from the SBH where the specific gravitational binding energy is still $\sim 100$ times smaller than that of the most bound He-line star SO-2. Clusters impinging on the Galactic center on nearly-radial orbits are dispersed at their first passage near the SBH and result in a population of plunging, low-binding energy orbits unlike those of either the He line stars or of the central cluster.

Stars that form in the molecular clouds of the circum-nuclear disk (CND) at $\sim 1 - 2$ pc, as well as those that are deposited by the clusters disrupted at $\sim 1$ pc, diffuse toward orbits of larger binding energy on the local relaxation time scale:

$$T_{rel} \sim 3 \times 10^9 \text{yr} \left(\frac{\sigma}{100 \text{ km s}^{-1}}\right)^3 \left(\frac{M_*}{3M_\odot}\right)^{-1} \left(\frac{\rho}{2 \times 10^7 M_\odot \text{pc}^{-3}}\right)^{-1} \left(\frac{\ln \Lambda}{10}\right)^{-1},$$

where $\sigma$ is the local linear stellar velocity dispersion, $M_*$ is the average stellar mass, $\rho$ is the local stellar density, and $\ln(\Lambda)$ is the Coulomb logarithm. Not only does this

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exceed the age of the observed stars, but relaxation via star-star scattering would have also erased the observed kinematic peculiarities.

The fundamental reason for the long relaxation time is that the stellar velocity dispersion $\sigma \propto R^{-1/2}$ diverges as the Galactocentric radius $R$ decreases. Large velocities weaken the effect of gravitational focusing in stellar scattering and decrease the average amount of energy transferred in a single encounter. This limitation applies equally to all stellar mass objects. Only objects significantly more massive than a star can sink on the timescales required. Star clusters, however, are not dense enough to survive intact in the strong tidal fields (Portegies Zwart, McMillan & Gerhard 2003). Thus, the only astrophysical entity both massive and dense enough to satisfy the requirements is an intermediate-mass black hole (IBH). The orbital decay of an IBH is driven by dynamical friction on a shorter timescale $T_{df} \sim (M_*/M_{\text{IBH}})T_{\text{rel}} \sim 1 - 10$ Myr for an $10^{-3} - 4 M_\odot$ IBH. Furthermore, it has been argued that such black holes form generically in dense, young stellar clusters as a result of the segregation of massive stars to the cluster center (Spitzer 1969) followed by the runaway merging in stellar collisions (Portegies Zwart & McMillan 2002, Rasio, Freitag & Gurkan 2003).

3. STELLAR ORBITAL MIGRATION

A small fraction of the parent stellar cluster may remain bound to the IBH as it sinks in the Galactic potential, namely those stars originally located within the dynamical radius of influence of the IBH. Tidal stripping and ejection due to strong stellar encounters gradually remove stars from the cluster. In the absence of internal dynamical evolution, cluster stars orbiting at distance $r$ from the IBH will be lost when they slip over the cluster Roche limit $r = (M_{\text{IBH}}/M_{\text{SBH}})^{1/3} R$, where $R$ is the distance to the SBH.

However, stars are also ejected by scattering off other stars in the cluster. Using equation 37 of Lin & Tremaine (1980), the ejection timescale from a power-law cusp (Bahcall & Wolf 1970) dominated by the IBH is

$$T_{ej} \sim 1.4 \times 10^6$$ yr \(\times \left(\frac{\sigma_{cl}}{10 \text{ km s}^{-1}}\right)^3 \times \left(\frac{M_*}{10 M_\odot}\right)^{-1} \left(\frac{\rho_{cl}}{10^6 M_\odot \text{pc}^{-3}}\right)^{-1}, \quad (2)$$

where $\sigma_{cl}, \rho_{cl}$ are the velocity dispersion and stellar mass density of the parent cluster at the original dynamical radius of influence of the IBH.

The stars lost from the cluster are deposited over a range of radii. If stars are removed by tidal stripping alone, the profile of deposited stars reflects the original profile of the cluster, $\rho(R) \sim R^{-\gamma}$, where the Bahcall-Wolf value is $\gamma = 7/4$. The stars most tightly bound to the IBH will be lost at a distance from the SBH of

$$R \sim 0.2 \text{ pc} \left(\frac{M_{\text{IBH}}}{10^3 M_\odot}\right)^{-5/3} \left(\frac{M_*}{10 M_\odot}\right)^{-1} \left(\frac{\rho_{cl}}{10^6 M_\odot \text{pc}^{-3}}\right)^{-1} \left(\frac{\rho_{cl}}{10^6 M_\odot \text{pc}^{-3}}\right)^{-1} \left(\frac{\sigma_{cl}}{10 \text{ km s}^{-1}}\right)^4,$$  \quad (3)$$

Therefore to deposit the most bound star SO-2 at $R \sim 0.01$ pc, $M_{\text{IBH}} \sim 4 \times 10^3 M_\odot$ is required. If the IBH orbital decay is eccentric and self-similar (Valtonen & Harju 1989), the profile may not be smooth; the young stars will be deposited in batches at a discrete set of locations corresponding to successive pericenter passages of the IBH.

Even stars not directly bound to the IBH may be transported if their orbits come close that of the IBH. The dynamics of the interaction between stars and the SBH-IBH binary is very similar to the interaction of comets with the Sun-Jupiter binary. In the case of the Jupiter family comets, they are observed in the inner solar system after being scattered by Jupiter from orbits with much larger semi-major axes (Quinn, Tremaine & Duncan 1990). In a similar fashion, successive weak encounters with the IBH cause a random walk in the orbital parameters, and this can nudge the peribothra of some field stars inward. One difference is that the IBH is gradually moving inwards, in a fashion similar to planetary migration, for which planetesimal/comet scattering may also be a contributing factor (Murray et al. 1998) in some extrasolar systems. For this mechanism to be significant, the characteristic time $\mu^{-1/3}T_{\text{orb}}$ between close encounters with the IBH must be shorter than the time $\mu^{1/3}T_{df}$ in which the IBH migrates a distance equivalent to the radius of its own sphere of influence, where $T_{\text{orb}}$ is the stellar orbital period and $\mu = M_{\text{IBH}}/M_{\text{SBH}}$. This holds as long as

$$R < 1 \text{ pc} \left(\frac{M_{\text{IBH}}}{10^3 M_\odot}\right)^{-1/3} \left(\frac{\rho(1 \text{ pc})}{2 \times 10^3 M_\odot \text{pc}^{-3}}\right)^{-1}, \quad (4)$$

where we have assumed the stellar density $\rho \propto 1/R^2$ on these scales. Thus, the orbital decay of the IBH continues to push some stars inward even after the original cluster has been tidally disrupted. The efficiency of these processes, however, is low, because most scattered stars are ultimately ejected—producing the Oort cloud in the case of comets (Duncan, Quinn & Tremaine 1987, Fernandez & Ip 1983)—and a large population is needed at the outset. On the other hand, for an IBH born of a $10^3 M_\odot$ cluster, the efficiency of the process need only be $10^{-3}$ to explain the handful of IRS 16 stars.

Dynamical friction drags the IBH toward the SBH until it reaches a critical separation where the binding energy in stars with peribothra smaller than the SBH-IBH separation is the same as that of the IBH itself. Using the most recent determination of central stellar cusp mass by (Genzel et al. 2003), $M_{\text{cusp}} \sim 1.3 \times 10^4 M_\odot (R/1 \text{ pc})^{1.63}$, we infer this critical radius to be $R \sim 0.2 \text{ pc} \sim 0.008/M_{\text{IBH}}/10^3 M_\odot$. It could be smaller if there is a significant dark stellar population interior to this orbit. Subsequent orbital decay proceeds at a decreased rate contingent on how efficiently star-star scattering and other forms of orbital diffusion feed stars into the emptied region (usually called the “loss cone”), thereby providing new material for slingshot ejection by the binary (Begelman, Blandford & Rees 1980, Milosavljevic & Merritt 2002, Quinlan 1996). The binary shrinks by an octave for every $M_{\text{IBH}}$-worth of stars that are removed. Stars are usually ejected by the cumulative effect of several encounters, with their orbital parameters undergoing a random walk. If the separation decreases to 10 AU ($M_{\text{IBH}}/10^3 M_\odot$), the emission of gravitational radiation dominates and will expedite the
coalescence of the black holes within a million years.

4. The Distribution of Stars in the Inner Parsec

If the He-line stars are dynamically associated with the IBH, then their orbits must either be similar to the orbit the IBH had at some, perhaps earlier, stage of its infall, or must at least still cross the latter if they are in the process of being ejected by repeated scattering. To test this, we have examined the existing velocity data (Genzel et al. 2000; A. Ghez, private communication) for He-line stars with three measured velocity components. Combined with the projected position, we have information on 5 of the 6 phase space coordinates necessary to compute the orbits, as well as complete solutions for a few close to the SBH (Ghez et al. 2003a). To assess the importance of the unknown component (location along the line of sight, Z) we explored the range from \( Z = 0.5R_\perp \) to \( Z = 1.5R_\perp \), where \( R_\perp \) is the projected distance to Sgr A*.

Figure 1 shows the resulting orbits which are plotted in a specific energy-angular momentum diagram.

![Figure 1](image_url)

**Fig. 1.**—The filled circles show the He-line stars associated with the IRS 16 group. The error bars indicate the effect of varying the unknown \( z \) between \( z = 0.5R_\perp \) and \( z = 1.5R_\perp \). The open circles show the central cluster stars for which complete orbits can now be determined (Ghez et al. 2003b) (thus these error bars are real). Triangles indicate approximate values for central cluster stars for which complete orbits are not yet known. The solid line indicates the locus of orbits which cross an eccentric orbit with semi-major axis \( 1'' \) and eccentricity 0.82. An IBH on this orbit can interact with all the stars in the system as a whole, \( \Psi = 0 \) for a binary system (Backer & Sramek 1999; Reid et al. 1999). Assuming a circular orbit of the IBH, the amplitude of the gravitational slightshot of stars that diffuse into the gravitational potential of the IBH is dominated by physical collisions rather than two-body relaxation.

We find that the spectral differences between the central cluster stars and the IRS 16 stars lend support to this picture. Although both are young and massive, the former appear to be main sequence stars of roughly O or B type, while the latter are extended, evolved stars in the supergiant or the Wolf-Rayet stage. The more compact nature of the central cluster stars may indicate that the outer envelopes have been stripped in grazing collisions. Note that this is different from the alternative proposal (e.g., Genzel et al. 2003) in which the observed stars are assembled from lower mass objects in stellar mergers. The normal rotation rate of SO-2 (Ghez et al. 2003) and the potential radial anisotropy of the orbits are both consistent with a limited role of collisional interactions.

If an IBH is present at the Galactic center, there is also the possibility of directly observing high velocity stars that have been ejected from the region. This would especially be true if the SBH-IBH binary has hardened past the stalling radius and is continuing to evolve slowly via the gravitational slightshot of stars that diffuse into the loss cone. The velocities of the ejected stars will reflect the specific binding energy of the IBH at the time of ejection.

Direct constraint on the IBH hypothesis may be provided by the non-inertial motion of Sgr A*. The presence of an IBH at the Galactic center will be revealed in the apparent proper motion of the radio image of Sgr A* relative to the mean \( \sim 6 \) mas yr\(^{-1}\) solar drift (Backer & Sramek 1995; Reid et al. 1999). Assuming a circular orbit of the IBH, the amplitude of the gravitational reflex of SBH relative to the barycenter of the system as a whole, \( \Psi_{\text{ref}} \approx T_{\text{IBH}}/M_{\text{SBH}} \Psi \), where \( \Psi \) is the angular separation between the black holes, must be larger than the cumulative positional resolution \( \Delta \Psi \approx 1 \) mas of the radio telescope to achieve detection.

In turn, the total projected distance traversed by the SBH equals \( T_{\text{ref}} \) or \( T_{\text{IBH}} R_{\text{gc}}^2 (G/R_{\text{SBH}})^{1/2} \), for a monitoring program of duration \( T_m \) and distance to the Galactic center \( R_{\text{gc}} \approx 8 \) kpc, must also be larger than \( \Delta \Psi \). These constraints are summarized in Figure 2.
5. CONCLUSIONS

In this paper we have proposed a model that addresses the peculiar nature of the young stars in the Galactic center. Most importantly, the presence of an IBH can deliver the massive young stars to their observed location within the timescale required. In addition, our scenario provides a way to link the two disparate groups of stars (the IRS 16 group and the Sgr A* cluster) within a single evolutionary scenario.

The dashed lines indicate coalescence due to gravitational radiation (such as due to a grazing stellar collision). This may happen near the SBH if they receive a sufficiently large perturbation, during close encounters with the IBH. Most stars will end up with eccentric orbits before being scattered and trapped. However, this radial anisotropy is still uncertain because its determination is subject to severe selection effects.

Some questions remain open: Although the mass density of luminous stars can be measured, the true density profile of the central parsec is not well-known. Our adoption of the observed density profile is conservative as there are good reasons to believe that $10\, M_\odot$ black holes will have segregated within few relaxation times to dominate the density of the central cluster (Miralda-Escudé & Gould 2000; Morris 1993). If such a dark cusp exists, the central density could be as large as $10^3\, M_\odot\, pc^{-3}$ and thus the stalling radius of the IBH could be much smaller than estimated above. Alternatively, if the IBH infall is episodically recurring phenomenon, then the injection of a steady stream of IBH into the central parsec would help to maintain an evacuated region in the stellar distribution.

Finally, IBH are implicated in the formation of SBH in galaxies in a variety of ways (Rees 1984). Indeed, it has been suggested (Ebisuzaki et al. 2001) that SBH form from the collapse of a cluster of IBH. It is intriguing that to gradually accumulate the present SBH at the Galactic center by this process requires IBH captures at the rate

$$\Gamma \sim 3 \times 10^{-7}\, yr^{-1} \left( \frac{M_{\text{SBH}}}{3 \times 10^6 M_\odot} \right) \left( \frac{M_{\text{IBH}}}{10^4 M_\odot} \right)^{-1}. \quad (5)$$

With this rate one would expect the most recent entrant to be a few Myr old, which coincides with the time scale derived above from the stellar ages. Such a process could have a significant influence on the history of galactic nuclei (Hughes & Blandford 2003).

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