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Binary Disruption by Massive Black Holes: Hypervelocity Stars, S Stars, and Tidal Disruption Events

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ABSTRACT

We examine whether disrupted binary stars can fuel black hole growth. In this mechanism, tidal disruption produces a single hypervelocity star (HVS) ejected at high velocity and a former companion star bound to the black hole. After a cluster of bound stars forms, orbital diffusion allows the black hole to accrete stars by tidal disruption at a rate comparable to the capture rate. In the Milky Way, HVSs and the S star cluster imply similar rates of $10^{-5} - 10^{-3}$ yr^{-1} for binary disruption. These rates are consistent with estimates for the tidal disruption rate in nearby galaxies and imply significant black hole growth from disrupted binaries on 10 Gyr time scales.

Subject headings: Galaxy: kinematics and dynamics — Galaxy: halo — Galaxy: stellar content — stars: early-type

1. Introduction

Massive black holes with masses $M_\bullet \lesssim 10^9$ $M_\odot$ inhabit the centers of many galaxies. It is uncertain how these objects form and grow. Proposed ideas include the direct collapse of a primordial gaseous cloud (Eisenhauer et al. 2005; Begelman et al. 2006), accretion of gas from

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a surrounding disk (Debuhr et al. 2010), capture of stellar-mass objects from a nuclear cluster (Merritt & Poon 2004), and hierarchical merging of black holes (Volonteri et al. 2003). For all mechanisms, growing the most massive black holes is challenging. Gaseous accretion flows are limited by the need to shed angular momentum for gas to fall efficiently onto the black hole. Pairs of black holes tend to eject material from their vicinity, slowing orbit contraction and stalling the growth of either black hole (Miralda-Escudé & Gould 2000; Milosavljević & Merritt 2003).

Recent observations of candidate stellar tidal disruption events (TDEs; e.g., Gezari et al. 2009; van Velzen et al. 2011) have renewed interest in stellar capture hypotheses. When a single star wanders inside the black hole's tidal radius, the black hole shreds the star. Some material accretes onto the black hole and powers a flare (Rees 1988). Flare evolution depends on properties of the black hole and the shredded star (e.g., Loeb & Ulmer 1997; Strubbe & Quataert 2009; Lodato & Rossi 2011, and references therein). Observational and theoretical estimates suggest capture rates of $10^{-5} - 10^{-3}$ yr^{-1} per nearby galaxy (Wang & Merritt 2004; van Velzen et al. 2011), sufficient to grow a fairly massive black hole on cosmological time scales (e.g., Merritt & Poon 2004; Brockamp et al. 2011).

Here, we assess the contribution of binary stars to TDEs and the growth of black holes. Binary stars are a significant fraction of all stars (Abt 1983; Duquennoy & Mayor 1991). When a binary system wanders too close to a black hole, the three-body interaction ejects one binary partner at high speeds and leaves the other bound to the black hole (Hills 1988). In addition to predicting the ejected binary components as hypervelocity stars (HVSs), the Hills mechanism yields bound stars which serve as a mass reservoir for TDEs and black hole growth. Measurements of both the bound stars and the HVSs provide direct constraints on the capture frequency along with robust predictions for the frequency of TDEs and the rate of black hole growth in the Galactic Center.

We show that this binary model is consistent with observations of HVSs (Brown et al. 2005, 2012), and the S star cluster in the Galactic Center (Gould & Quillen 2003; O'Leary & Loeb 2008) (§2). We use a simple two-body relaxation model to show how captured stars can diffuse onto orbits that intersect the black hole, leading to a rate for TDEs similar to the observations (§3). Finally, we demonstrate the potential for the binary capture mechanism to grow supermassive black holes (§4).

2. Binary Disruption Rates from HVSs and S Stars

To motivate the binary star model, we consider the collision cross-section of the black hole, $\sigma_\bullet$. Black holes shred a single star with mass m and radius r at the tidal radius,

$$R_{\rm tidal} \approx \left(\frac{0.7\ {\rm M}_\bullet}{m}\right)^{1/3} r \approx 0.6 - 0.7 \left(\frac{{\rm M}_\bullet}{4\times10^6\ {\rm M}_\odot}\right)^{1/3} \left(\frac{r}{{\rm R}_\odot}\right)\ {\rm AU}\ . \qquad (1)$$

When ${\rm M}_\bullet \le 10^8\ {\rm M}_\odot$, this interaction occurs outside the Schwarzschild radius; the black hole accretes a fraction $f_{\rm acc} \approx 0.25$–0.50 of the stellar mass (Evans & Kochanek 1989; Ayal et al. 2000).

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More massive black holes have Schwarzschild radii exceeding $R_{\rm tidal}$; stars cross the horizon intact and $f_{\rm acc} \equiv 1$.

For encounters with a binary star having semimajor axis $a_{\rm bin}$ and component masses m_1 and m_2, the probability of a capture/ejection is $P_{cap} \approx 1 - D/175$ (Hills 1988), where $D \approx (R_{\rm close}/a_{\rm bin}) f(m, {\rm M}_\bullet)$, $R_{\rm close}$ is the distance of closest approach, and $f(m, {\rm M}_\bullet) \approx 1$–10 is a function of ${\rm M}_\bullet$ and $m_1 + m_2$. Conservatively setting $P_{cap} = 0.5$,

$$R_{\rm close} = 30 - 200 \left(\frac{a_{\rm bin}}{1~{\rm AU}}\right)~{\rm AU}~. \quad (2)$$

Adopting $\sigma_\bullet \approx \pi R_{\rm tidal}^2 \approx \pi R_{\rm close}^2$, interactions with binaries ($a_{\rm bin} \gtrsim 0.1$ AU) are $\gtrsim 100$ times more likely than interactions with single stars (Hopman 2009; Antonini et al. 2011).

The Hills (1988) proposal yields (i) ejected stars traveling out into the Galaxy and (ii) captured stars bound to the black hole. For ${\rm M}_\bullet \sim 4 \times 10^6~{\rm M}_\odot$ in Sgr A* (Eisenhauer et al. 2005; Ghez et al. 2008), expected ejection speeds are $\sim$ 1000–1500 km s^{-1}. Deceleration through the Galaxy reduces speeds to $\sim$ 500–1000 km s^{-1} at 40–100 kpc (Bromley et al. 2006; Kenyon et al. 2008). Predicted orbits for the resulting bound stars have semimajor axes $a \sim$ 1000–10000 AU and eccentricities $e \approx$ 0.95–1.0.

Observations reveal both HVSs and captured stars. Brown et al. (2005) discovered SDSS J090745.0+024507, a star with a spectral type (B9), age ($<$ 350 Myr), metallicity ([Fe/H]$\sim$ 0), radial velocity (850 km s^{-1}), and distance ($\sim$ 70 kpc) consistent with Hills' prediction (Brown et al. 2009). Surveys covering roughly 25% of the sky reveal $\sim$ 20 known HVSs with speeds sufficient to escape the Galaxy (Edelmann et al. 2005; Hirsch et al. 2005; Brown et al. 2009, 2012). Observed properties of these stars are consistent with a Galactic Center origin (Brown et al. 2012).

At the Galactic Center, the S star cluster is plausibly composed of the bound former partners of HVSs (Gould & Quillen 2003; Ginsburg & Loeb 2006; O'Leary & Loeb 2008). The $\sim$ 20 massive stars in this cluster have orbits with $a \lesssim$ 8000 AU and a broad range of e (Eckart & Genzel 1997; Ghez et al. 1998, 2008; Genzel et al. 2010). The semimajor axes are consistent with Hills' predictions. Although observed eccentricities are smaller than predicted, orbital diffusion after capture can reduce e substantially (Perets et al. 2009). The origin of these stars—or their binary progenitors—is uncertain. If they formed in young stellar disks in the Galactic Center (Löckmann et al. 2008; Madigan et al. 2009), their number count and orbital distribution may represent an atypical snapshot of the Galactic Center. A clear connection between the S stars and HVSs is key to testing the binary disruption scenario.

Measured production rates for HVSs and S stars suggest a similar formation mechanism (e.g., O'Leary & Loeb 2008). Known HVSs have masses of 2.5–3.0 ${\rm M}_\odot$ and travel times of 60–200 Myr (Brown et al. 2012). The production rate is roughly 1×10^{-6} yr^{-1}. Correcting this rate for unobserved, lower mass stars using a standard (differential) initial mass function (IMF) $\xi(m) \propto m^{-q-1}$ with q = 1.00–1.35, the production rate for HVSs of all masses is 2–8 $\times 10^{-5}$ yr^{-1}. S stars have masses exceeding 5 ${\rm M}_\odot$ and main sequence lifetimes $t_{ms} \lesssim$ 100 Myr (Ghez et al. 1998; Genzel et al.

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2010), yielding a production rate of 2×10^{-7} yr^{-1}. Accounting for lower mass stars implies a rate of 1–4 $\times 10^{-5}$ yr^{-1}. Within the errors, the rates implied by HVSs and S stars agree. The good agreement between the binary disruption rates derived from two populations with very different lifetimes suggests a common, steady production mechanism.

For a more realistic estimate of the binary disruption rate from HVSs and S stars, we assume continuous star formation (Figer et al. 2004), and steady, random scattering of binary stars toward the Galactic Center. Thus the pool of progenitors, accumulated over 10 Gyr, contains more older, lower mass stars than predicted by the IMF. To compensate for this population, we adopt $t_{ms} \lesssim 500$ Myr for HVSs and $t_{ms} \lesssim 100$ Myr for S stars. The inferred production rates increase by $\sim$ 10 Gyr/500 Myr = 20 for HVSs and $\sim$ 10 Gyr/100 Myr = 100 for S stars. Thus, the maximum rate for binary disruptions in the Galactic Center is roughly 1–2 $\times 10^{-3}$ yr^{-1}.

This range of rates agrees with predictions. In simple models, binaries interact with the central black hole at a rate of $n \langle v f_{\rm g} \sigma_\bullet \rangle$, where n is the number density of binaries, $v \sim 100$ km s^{-1} is a characteristic speed (Figer et al. 2003), and $f_{\rm g}\sigma_\bullet \sim 1 \times 10^8$ AU^2 is the cross-sectional area for $R_{\rm close} \sim 100$ AU (eq. [2]) and a gravitational focusing factor $f_{\rm g}$. For a central mass density ρ_0, $n \approx f_{\rm bin}\rho_0/m_{\rm avg}\,(1+f_{\rm bin})$, where $f_{\rm bin}$ is the fraction of stars in short period binaries and $m_{\rm avg} \approx$ 0.3 M$_\odot$ is the average mass of a star. In the solar neighborhood, the fraction of stars in binaries of all periods is $f_{\rm bin}$ = 0.5–0.7 (Abt 1983). For the short period binaries likely to produce HVSs ($P \lesssim 1$ yr), $f_{\rm bin} \approx 0.1$ (Yu & Tremaine 2003). The total disruption rate is then (see also Hills 1988; Yu & Tremaine 2003)

$$k_{\rm dis} \approx \frac{f_{\rm bin}}{1+f_{\rm bin}} \frac{\rho_0}{m_{\rm avg}} \langle v f_{\rm g} \sigma_\bullet \rangle \quad (3)$$

$$\approx 10^{-3}\ {\rm yr}^{-1} \quad (4)$$

for $\rho_0 = 1.4 \times 10^4$ M$_\odot$ pc^{-3} (e.g., Bromley et al. 2006) and $f_{\rm bin} = 0.1$. This rate agrees with the maximum rate of binary disruption implied by observations.

The maximum disruption rate assumes that scattering processes rapidly fill the "loss cone," the subset of Galactic Center orbits that pass close to the black hole. If scattering supplies binaries to the loss cone more slowly than disruption removes them, the disruption rate is comparable to the scattering rate. When two-body relaxation fills the loss cone, Yu & Tremaine (2003) derive $k_{\rm dis} \approx 10^{-5}$ yr^{-1} for $f_{\rm bin} = 0.1$. Because other processes can fill the loss cone, this estimate is probably a lower limit (Merritt & Poon 2004; Hopman & Alexander 2006; Perets et al. 2007). When the gravitational potential is nonaxisymmetric and orbits are chaotic, Merritt & Poon (2004) derive factor of ten larger scattering rates. The expected disruption rate is then $k_{\rm dis} \approx 10^{-4}$ yr^{-1}. Taken together, the broad range of theoretical estimates, $k_{\rm dis} \sim 10^{-5}$–10^{-3} yr^{-1}, is consistent with the binary disruption rates implied by observations.

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3. Long-term Orbital Evolution of the S Stars and Tidal Disruption Events

The inferred binary disruption rate agrees with estimates for TDEs from nearby galaxies. Observations of two candidate TDEs from long-term observations of galaxies in the Sloan Digital Sky Survey suggest one TDE per galaxy every $\sim 10^5$ yr (van Velzen et al. 2011). Candidates from GALEX data indicate a similar frequency (Gezari et al. 2009). The good agreement between the rates of binary disruption and stellar disruption plausibly suggests a common origin. To explore this connection, we consider the evolution of the orbits of bound stars.

Over 10 Gyr, binary disruption places $\sim 10^5$–10^7 bound stars in orbit around the central black hole. Just after capture, each star has a semimajor axis and eccentricity

$$a_{\rm bnd} \sim 1100 \left(\frac{a_{\rm bin}}{0.1~{\rm AU}}\right)\left(\frac{1~{\rm M}_\odot}{m_{\rm ej}}\right)\left(\frac{m_{\rm bin}}{2~{\rm M}_\odot}\right)^{1/3}~{\rm AU}, \tag{5}$$

$$e_{\rm bnd} = 1 - 0.005\left(\frac{R_{\rm close}}{10~{\rm AU}}\right)\left(\frac{1100~{\rm AU}}{a_{\rm bnd}}\right), \tag{6}$$

for $M_\bullet = 4\times10^6~{\rm M}_\odot$. These equations follow from conservation of energy and angular momentum, with coefficients from numerical simulations of binary disruptions (e.g., Hills 1988; Bromley et al. 2006).

Gravitational interactions among the bound stars produce changes in $a_{\rm bnd}$ and $e_{\rm bnd}$ on a relaxation time $\tau_{\rm rel}$. Stars with $t_{ms} \lesssim \tau_{\rm rel}$ explode as supernovae or evolve into red giants and white dwarfs (Frank & Rees 1976; Hils & Bender 1995; Hopman & Alexander 2006; Merritt 2010). Less massive stars may evolve onto orbits with periastron distances $a_{peri} \lesssim R_{\rm tidal}$. These stars produce TDEs and accrete onto the black hole (Rees 1988).

The rate of TDEs depends on $\tau_{\rm rel}$. If two-body scattering dominates, the relaxation time is

$$\tau_{\rm rel} \approx \frac{0.33M^2}{m_{\rm avg}^2 N\ln(0.4N)}\frac{P}{2\pi} \tag{7}$$

$$\approx 130\left(\frac{M_\bullet}{4\times10^6~{\rm M}_\odot}\right)^{5/6}\left[\frac{N\cdot\ln(0.4N)}{10^6\cdot12.9}\right]^{-1}~{\rm Myr} \tag{8}$$

when $\sim 10^6$ stars with an average mass of 0.3 ${\rm M}_\odot$ orbit at $\sim$ 5000 AU with orbital period P. Other processes, such as resonant relaxation, probably shorten the relaxation time (e.g., Hopman & Alexander 2006). Captured stars wander through $0 \le e \le 1$ on this time scale.

The relaxation time sets two properties for the bound population. Stars with $t_{ms} \lesssim \tau_{\rm rel}$ ($m \gtrsim$ 2–4${\rm M}_\odot$) evolve into supernovae or white dwarfs before they encounter the black hole. For a normal IMF, the fraction of stars that suffer this fate is a few per cent. The rest of the population establishes an approximate steady-state, where the black hole accretes a star for every captured star. For the current mass of Sgr A*, this process requires $\sim$ 0.1–1 Gyr. After this period, there is a tidal disruption event every 10^3–10^5 yr.

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Numerical simulations do not consider the long-term evolution of $\sim 10^5$–10^7 low mass stars bound to a central black hole. However, smaller simulations confirm the general features of this evolution (e.g., Perets et al. 2009). Gravitational interactions lead to global changes in a and e on the relaxation time $\tau_{\rm rel}$. At least 20% to 30% of bound stars suffer TDEs. Thus, Sgr A* should accrete a 0.1–0.5 $M_\odot$ star every 10^3–10^5 yr.

4. Growth of the Central Black Hole

The upper limit on the tidal disruption rate can add mass comparable to the total mass of Sgr A*. To explore how binary disruption impacts $M_\bullet$, we consider a model where the capture rate is the collision rate in equation (3). For a constant central density $\rho_0 = 10^4$ $M_\odot$ pc^{-3}, velocity v = 100 km s^{-1}, and binary fraction $f_{\rm bin} = 0.1$, our time-dependent calculations begin with an initial $M_\bullet = M_{\rm seed}$. Captured stars accumulate until time $t = \tau_{\rm rel}$ and then accrete with efficiency $f_{\rm acc}$ onto the black hole. The growth of $M_\bullet$ depends only on the initial mass and the accretion efficiency.

Figure 1 shows results for several seed masses and $f_{\rm acc} = 0.25$ and 1.00. In Figure 1, small seed masses and $f_{\rm acc} \le 1$ yield modest growth rates over 10 Gyr. Larger seed masses of a few $\times 10^5$ $M_\odot$ yield $M_\bullet \approx 4 \times 10^6$ $M_\odot$ within 10 Gyr.

To show how black hole growth depends on ρ_0 and $f_{\rm bin}$, we define a growth parameter

$$\eta = \left(\frac{f_{\rm acc}}{1}\right)\left(\frac{\rho_c}{\rho_0}\right)\left(\frac{f_{\rm bin}}{0.1}\right) \tag{9}$$

where ρ_c is the central mass density near the black hole. Thus, $\eta = 1$ corresponds to models with the Milky Way's central stellar mass density. Calculations with $\eta > 1$ ($\eta < 1$) yield larger (smaller) growth rates.

Figure 2 displays $M_\bullet$ at 10 Gyr as a function of η and the initial seed mass. In this model, massive black holes require large accretion efficiency, large central density, and a large fraction of short period binaries. Low values for η yield low $M_\bullet$. Figs. 1–2 imply that the current binary disruption rate implies a substantially lower mass for Sgr A* in the past.

To explore black hole growth in more detail, we add the evolution of $R_{\rm tidal}$ (eq. [1]) and $R_{\rm close}$ (eq. [2]) as the black hole grows in mass. Large gravitational focusing factors imply that the disruption rate is independent of v (eq. [3]). We also allow the central density to vary in time, adopting $\rho(t) \propto M_\bullet{}^{-\gamma}$ and γ = 1–2, as observed in elliptical galaxies (Faber et al. 1997). This density is bounded by a maximum initial density of $\rho_{\rm max} = 10^6$ $M_\odot$ pc^{-3}.

In this model, the mass accretion rate is

$$\frac{dM_\bullet}{dt} = \frac{2 f_{\rm acc} m_{\rm avg} \left(1 + e_{\rm tidal}\right)}{\tau_{\rm rel}}, \tag{10}$$

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which includes the rate of diffusion into orbits that exceed $e_{\rm tidal}$, the eccentricity corresponding to a perihelion distance of $R_{\rm tidal}$. The resulting growth of the black hole is not sensitive to the exact form of this equation. As in the simple model (Figs. 1–2), the rate invariably adjusts to achieve a steady state with a balance between capture of stars and the tidal shredding by the black hole.

Although there may be no direct causal connection between the black hole and the central density outside of its sphere of influence, our approach implies that the central density diminishes in time as $M_\bullet$ grows. Once the central density falls below $\rho_{\rm max}$, the numerical results suggest that the central density declines with time roughly as $\rho(t) \sim t^{-\beta}$, where $\beta \sim 1$.

Figure 3 summarizes our results. For an initial black hole seed mass of 10^5 $M_\odot$, the two curves show the central density as a function of black hole mass at t = 10 Gyr. For any $M_\bullet$ at 10 Gyr, models with $\gamma = 1$ require larger central stellar mass densities than models with $\gamma = 2$. Observations show considerable scatter about the general trend derived from local galaxies (Faber et al. 1997). Although we cannot discriminate among plausible sets of variables, the growth models yield a fair representation of the trend among galaxies with large central stellar mass densities. These models also appear to fare better than the power-law correlation $\rho \propto {M_\bullet}^{-1.3}$ from dynamical arguments (dashed line in the figure; Faber et al. 1997).

5. Summary

We develop a model for binary disruption in the Galactic Center. The model relates observations of HVSs in the halo and the S star cluster in the Galactic Center, TDEs in nearby galaxies, and the growth of central black holes. The black hole in the Galactic Center disrupts close binaries at distances $\lesssim R_{\rm close}$ (eq. [2]). One companion (the HVS) is ejected at high speeds; the other (S star) becomes bound to a black hole. Among the bound stars, dynamical interactions push some stars inside the tidal radius (eq. [1]). Shredding of stars inside $R_{\rm tidal}$ produces TDEs. After a relaxation time (eq. [7]), the rate of tidal disruptions roughly equals the capture rate. For large enough capture rates, binary disruptions add significant mass to the central black hole.

Current data suggest this picture is plausible. Observations of HVSs and S stars yield consistent production rates of 10^{-5}–10^{-3} yr^{-1}; these rates agree with theoretical estimates. For $\tau_{\rm rel} \approx 0.1$–1 Gyr, the expected rate for TDEs, 10^{-5}–10^{-3} yr^{-1}, is close to current estimates from small samples. More plentiful single stars may contribute to TDEs but the rate is at or below the level of the binary disruption channel (Brockamp et al. 2011). For rates associated with binary disruption, Sgr A* has grown by at least a factor of 2–4 in the past 5–10 Gyr. At higher rates, binary disruption can produce black holes with $M_\bullet \gtrsim 10^8$ $M_\odot$. This growth model yields clear relations between the final $M_\bullet$ and the central stellar mass density. These relations are reasonably consistent with existing data.

This model is attractive in connecting HVS and S stars in the Milky Way to TDEs in nearby galaxies. To test this connection, N-body simulations with larger numbers of stars bound to the

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black hole would improve estimates of the relaxation time and relations between the capture rate and the disruption rate. Theoretical investigations of TDEs involving the bound former partners of disrupted binaries might yield different light curves which could be tested by observations.

Several observations also provide essential tests.

- Extending HVS surveys to the southern sky with *SkyMapper* would improve estimates of the HVS production rate. In the future, *LSST* should detect candidates with lower mass and at larger distances in the halo. Spectroscopic confirmation with current 6–10-m telescopes and proposed 25–50-m telescopes would yield even better constraints on the HVS population.
- Discovery of lower mass stars among the bound star population yields another test of the binary disruption hypothesis. Deeper observations of the Galactic Center with existing large telescopes, the *James Webb Space Telescope*, and planned 25–50-m telescopes should reveal this population.
- Larger samples of candidate TDEs enable better comparisons of the binary disruption rate in the Milky Way with tidal disruption rates in external galaxies. Aside from existing surveys with the SDSS and *Pan-Starrs*, surveys with *SkyMapper* and *LSST* will yield strong constraints. In any picture, low mass stars should produce most TDEs. With constraints on the black hole mass, deriving a luminosity function for this process might place estimates on the mass function of disrupted stars. Rates as a function of central stellar mass density tests theories for the capture rate.

Calculations of black hole growth by tidal disruption predict a correlation between the stellar mass (velocity dispersion) and the final $M_\bullet$. Although our models cannot predict the observed $M_\bullet \propto \sigma^4$ relation, more sophisticated calculations could reveal $M_\bullet$-σ correlations which might be tested observationally.

REFERENCES

Abt, H. A. 1983, ARA&A, 21, 343

Aller, M. C., & Richstone, D. O. 2007, ApJ, 665, 120

Antonini, F., Lombardi, Jr., J. C., & Merritt, D. 2011, ApJ, 731, 128

Ayal, S., Livio, M., & Piran, T. 2000, ApJ, 545, 772

Begelman, M. C., Volonteri, M., & Rees, M. J. 2006, MNRAS, 370, 289

Brockamp, M., Baumgardt, H., & Kroupa, P. 2011, MNRAS, 418, 1308

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Bromley, B. C., Kenyon, S. J., Geller, M. J., Barcikowski, E., Brown, W. R., & Kurtz, M. J. 2006, ApJ, 653, 1194

Brown, W. R., Geller, M. J., & Kenyon, S. J. 2009, ApJ, 690, 1639

—. 2012, arXiv:1203.3543 (accepted in ApJ)

Brown, W. R., Geller, M. J., Kenyon, S. J., & Kurtz, M. J. 2005, ApJ, 622, L33

Debuhr, J., Quataert, E., Ma, C.-P., & Hopkins, P. 2010, MNRAS, 406, L55

Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485

Eckart, A., & Genzel, R. 1997, MNRAS, 284, 576

Edelmann, H., Napiwotzki, R., Heber, U., Christlieb, N., & Reimers, D. 2005, ApJ, 634, L181

Eisenhauer, F., et al. 2005, ApJ, 628, 246

Evans, C. R., & Kochanek, C. S. 1989, ApJ, 346, L13

Faber, S. M., et al. 1997, AJ, 114, 1771

Figer, D. F., et al. 2003, ApJ, 599, 1139

Figer, D. F., Rich, R. M., Kim, S. S., Morris, M., & Serabyn, E. 2004, ApJ, 601, 319

Frank, J., & Rees, M. J. 1976, MNRAS, 176, 633

Genzel, R., Eisenhauer, F., & Gillessen, S. 2010, Reviews of Modern Physics, 82, 3121

Gezari, S., et al. 2009, ApJ, 698, 1367

Ghez, A. M., Klein, B. L., Morris, M., & Becklin, E. E. 1998, ApJ, 509, 678

Ghez, A. M., Salim, S., Weinberg, N. N., et al. 2008, ApJ, 689, 1044

Ginsburg, I., & Loeb, A. 2006, MNRAS, 368, 221

Gould, A., & Quillen, A. C. 2003, ApJ, 592, 935

Hills, J. G. 1988, Nature, 331, 687

Hils, D., & Bender, P. L. 1995, ApJ, 445, L7

Hirsch, H. A., Heber, U., O'Toole, S. J., & Bresolin, F. 2005, A&A, 444, L61

Hopman, C. 2009, ApJ, 700, 1933

Hopman, C., & Alexander, T. 2006, ApJ, 645, 1152

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Kenyon, S. J., Bromley, B. C., Geller, M. J., & Brown, W. R. 2008, ApJ, 680, 312

Löckmann, U., Baumgardt, H., & Kroupa, P. 2008, ApJ, 683, L151

Lodato, G., & Rossi, E. M. 2011, MNRAS, 410, 359

Loeb, A., & Ulmer, A. 1997, ApJ, 489, 573

Madigan, A.-M., Levin, Y., & Hopman, C. 2009, ApJ, 697, L44

Merritt, D. 2010, ApJ, 718, 739

Merritt, D., & Poon, M. Y. 2004, ApJ, 606, 788

Milosavljević, M., & Merritt, D. 2003, in American Institute of Physics Conference Series, Vol. 686, The Astrophysics of Gravitational Wave Sources, ed. J. M. Centrella, 201–210

Miralda-Escudé, J., & Gould, A. 2000, ApJ, 545, 847

O'Leary, R. M., & Loeb, A. 2008, MNRAS, 383, 86

Perets, H. B., Gualandris, A., Merritt, D., & Alexander, T. 2009, ApJ, 702, 884

Perets, H. B., Hopman, C., & Alexander, T. 2007, ApJ, 656, 709

Rees, M. J. 1988, Nature, 333, 523

Strubbe, L. E., & Quataert, E. 2009, MNRAS, 400, 2070

Tremaine, S., et al. 2002, ApJ, 574, 740

van Velzen, S., et al. 2011, ApJ, 741, 73

Volonteri, M., Haardt, F., & Madau, P. 2003, ApJ, 582, 559

Wang, J., & Merritt, D. 2004, ApJ, 600, 149

Yu, Q., & Tremaine, S. 2003, ApJ, 599, 1129

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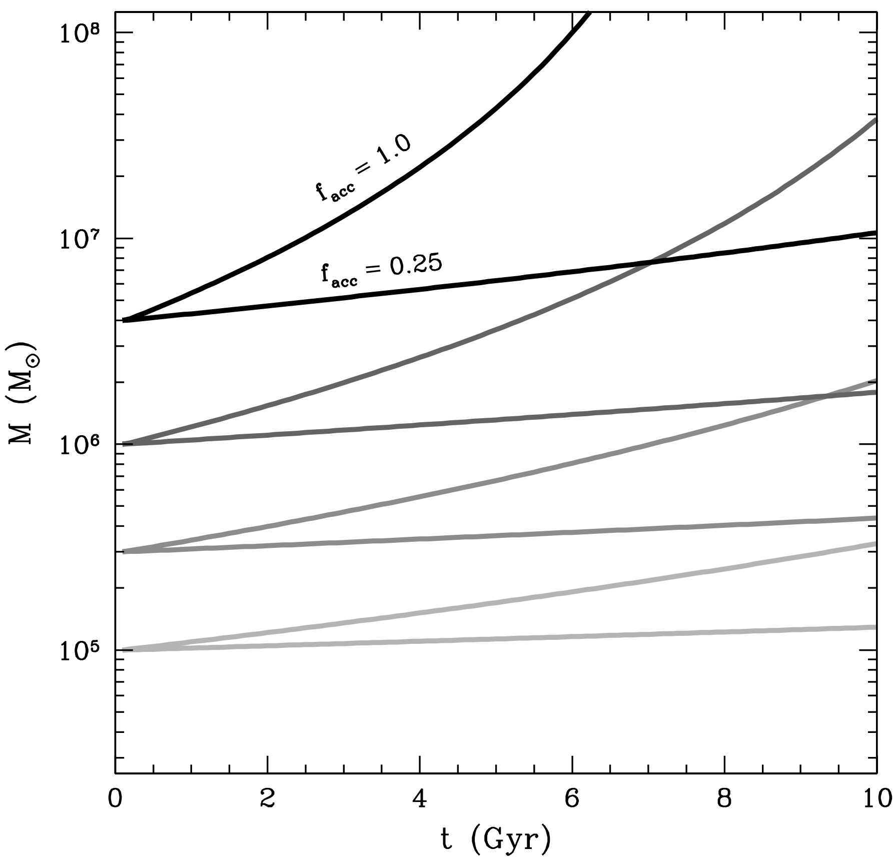

Fig. 1.— Growth of a black hole from a seed mass. Curves correspond to seed masses between 10^5 $M_\odot$ and 3.5×10^6 $M_\odot$. The lower (upper) curves have $f_{\rm acc} = 0.25$ ($f_{\rm acc} = 1$).

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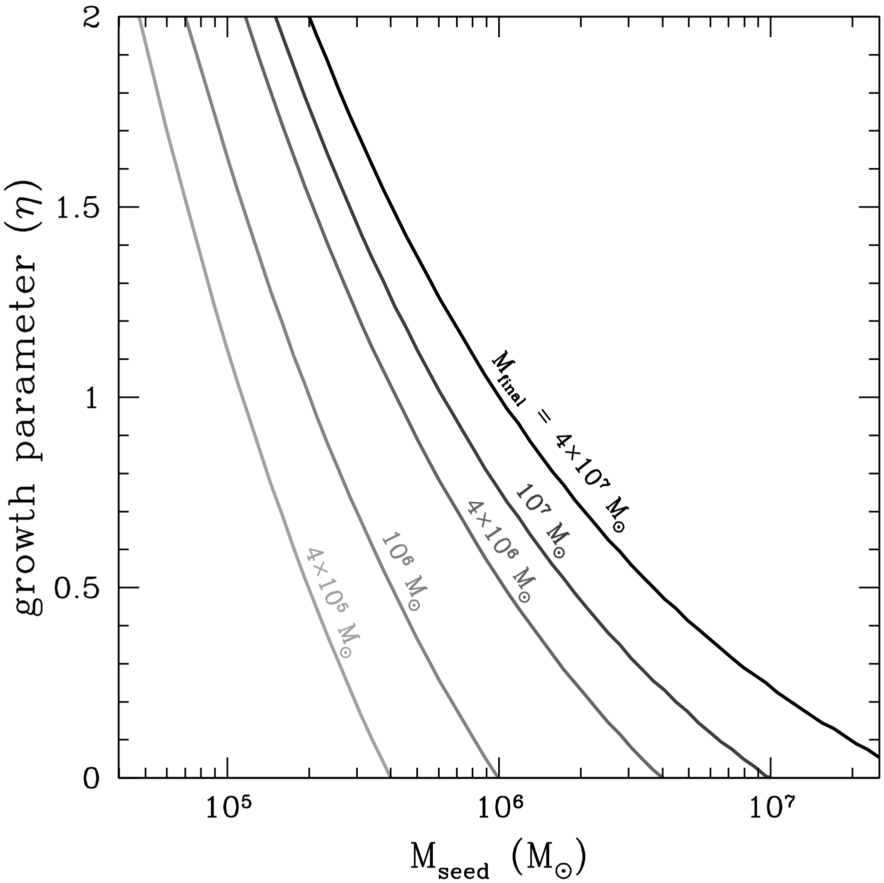

Fig. 2.— Tracks of constant final $M_\bullet$ as a function of the growth parameter η and the initial $M_\bullet$. For the accretion rates expected in the Galactic Center, initial masses of $\sim 10^6$ $M_\odot$ yield the mass of Sgr A* in 10 Gyr.

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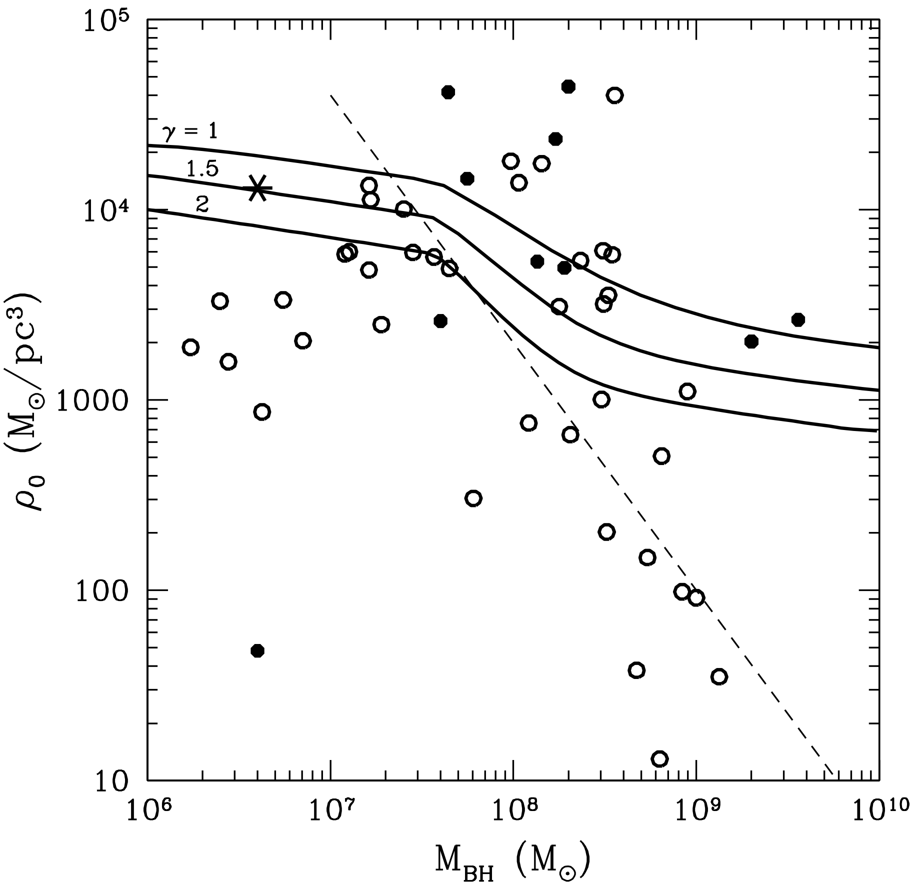

Fig. 3.— Central stellar mass density as a function of final black hole mass. For models with a seed mass of 10^5 $M_\odot$, $f_{acc} = 0.25$, and $\rho(t) \propto M_\bullet{}^{-\gamma}$, the upper ($\gamma = 1$), middle ($\gamma = 1.5$), and lower ($\gamma = 2$) solid lines show predicted relations between ρ_0 and $M_\bullet$ at 10 Gyr. We generate each curve by varying the *initial* density $\rho(t = 0)$, and letting $\rho(t)$ evolve as $M_\bullet$ grows. Thus, while a large initial density yields a large black hole mass, the present-day density ρ_0 is driven to a small value if $\gamma > 0$. Observations support this correlation. Filled circles show data from the Faber et al. (1997) sample with $M_\bullet$ from Aller & Richstone (2007). The open circles are from the same sample, but with the assumption that $M_\bullet \sim v^4$, where v is the measured velocity dispersion (Tremaine et al. 2002). The dashed line is a power-law relation with $\gamma = 1.3$, representative of galaxies in the local universe.

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