Dynamical Models of the Galactic Center

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Abstract. The distribution of late-type (old) stars in the inner parsec of the Milky Way is very different than expected for a relaxed population around a supermassive black hole. Instead of a density cusp, there is a \( \sim 0.5 \) pc core. This article discusses what sorts of dynamical models might explain this “conundrum of old age.” A straightforward interpretation is that the nucleus is unrelaxed, and that the distribution of the old giants reflects the distribution of fainter stars and stellar remnants generally in the core. On the other hand, a density cusp could be present in the unobserved populations, and the deficit of bright giants could be a result of interactions with these objects. At the present time, no model is clearly preferred.

The center of the Milky Way (MW) is special in terms of its location, only 8 kpc away. It is also home to perhaps the smallest supermassive black hole (SBH) with a well-determined mass. But in most respects, the center of our galaxy appears to be quite ordinary when compared with the centers of other galaxies of comparable luminosity. It contains a dense nuclear star cluster (NSC) that extends some ten parsecs from Sgr A* and that has a mass of \( \sim 10^7 M_{\odot} \) (Schödel et al. 2008). Population synthesis models suggest that star formation in the MW NSC has been continuous over the last 10 Gyr, and sites of recent star formation are apparent (Figer 2004a). These properties are typical of NSCs in other galaxies (Böker 2008).

Because of its proximity, the MW NSC can be resolved into individual stars. Number counts, together with reasonable guesses about the stellar mass function, imply a density at 1 pc from Sgr A* of \( \sim 10^5 M_{\odot} pc^{-3} \) (Genzel et al. 2003; Schödel et al. 2007), and this density is consistent with dynamical estimates based on stellar velocities (Oh et al. 2009). The implied, two-body relaxation time at 1 pc is roughly 10 Gyr, suggesting that there may have been enough time for the stars in the inner parsec to have attained a relaxed, quasi-steady-state distribution by now under the influence of random gravitational encounters. This assumption has been the basis for a great many theoretical studies of the MW nucleus over the last two decades (as summarized by T. Alexander in this volume). In a relaxed nucleus, the distribution of stars and stellar remnants is determined by just a handful of parameters: the total density outside the relaxed region; the slope of the initial mass function; the mass of the SBH.

On the other hand, continuous star formation implies that at least some stars in the MW NSC have been present for a time much less than the relaxation time. This is clearly the case for stars in the two, parsec-scale stellar disks, which formed roughly 6 Myr ago (Paumard et al. 2006; Bartko et al. 2009). Very recently, evidence has surfaced that even the old stars may not be relaxed. Number counts of the late-type stars reveal a core, a region of essentially constant
density near the SBH (Buchholz et al. 2009; Bartko et al. 2010). This is very different from the steep, power-law density cusp expected in a relaxed nucleus (Bahcall & Wolf 1976). While it is possible that the observations are conspiring to mislead us – there may still be a cusp in the fainter, unresolved stars, for instance – the new data compel us to re-examine the assumption of a relaxed steady state for the Galactic center. Among the issues at stake is whether the MW nucleus is well enough understood that it can serve as a template for other galaxies containing comparably-massive SBHs. These are the galaxies that would dominate the gravitational wave signal as observed with space-based telescopes like LISA (Hughes 2003).

1. Some new (and not so new) puzzles

Recent observations reveal the following facts concerning the inner parsec of the Milky Way.

- There is a core. Number counts of the late-type (old, cool) stars show a well-defined inner break with respect to the $\Sigma \sim R^{-0.8}$ dependence at $R \gtrsim 1$ pc (Buchholz et al. 2009; Bartko et al. 2010). Fitting of standard parametric models to the surface density gives a core radius (the radius at which the surface density falls to 1/2 of its central value) of $\sim 0.5$ pc (Fig. 1). The core size is independent of stellar luminosity down to the current completeness limit of $m_K \approx 15.5$ mag, corresponding to $1-3 M_\odot$ red giants (Dale et al. 2009). The deprojected (spatial) density profile $n(r)$ implies $\lesssim 2000$ stars within 1 pc of SgrA*, although the form of $n(r)$ at $r \ll r_c$ is poorly constrained (Do et al. 2009; Merritt 2009).

- The distributed mass inside 1 pc is $1.0 \pm 0.5 \times 10^6 M_\odot$. This value is derived from proper motion velocities of a sample of $\sim 6000$ stars in the projected inner parsec (Schoedel et al. 2009).

- Combined with the proper-motion mass estimate, measurement of the diffuse light in the inner parsec implies a K-band mass-to-light ratio for the unresolved stars of $\sim 1.4^{+1.4}_{-0.7} M_\odot/L_\odot K$ in this region (Schoedel et al. 2009). This $M/L$ is consistent with an evolved stellar population having a “standard” (Salpeter, Kroupa) IMF, in which a few percent of the mass is in the form of stellar-mass black holes (BHs) (Lockmann et al. 2009). However given the uncertainties, it is also consistent with a somewhat larger remnant fraction.

- Of the $\sim 200$ early-type (young, hot) stars in the projected central parsec, about half are Wolf Rayet and O stars occupying two stellar disks, which appear to have formed in a well-defined event 6 $\pm$ 1 Myr ago (Paumard et al. 2006; Lu et al. 2009; Bartko et al. 2009). The total mass associated with the disks is uncertain.

- The luminosity function (LF) of these young disk stars shows a deficit at K magnitudes fainter than $\sim 14$ mag, compared with the K-band LF expected for a young population with a standard IMF (Paumard et al. 2003).
The “missing” stars are mostly main-sequence B stars. One interpretation is that the disk stars formed with a “top-heavy” IMF, i.e. an IMF favoring massive stars. The young stars in the central parsec that do not lie in the disks (the S-stars, and the young field stars) appear to follow normal IMFs, with the expected predominance of main-sequence B-stars (Bartko et al. 2010).

Figure 1.  Left: Density of old stars at the Galactic center. Open circles are binned counts of late-type stars brighter than $m_K = 15$ mag (Buchholz et al. 2009). Filled circles show the density of all stars with $m_K \leq 15$ mag and $R \geq 20''$ (Schödel et al. 2007, after corrections for crowding and completeness). Dashed line is a broken-power-law model with $\Sigma \propto R^{-0.8}$ at large radii and inner slope of zero; the core radius, defined as the radius at which the surface density falls to 1/2 of its central value, is 0.49 pc. Arrows show the SBH influence radius and the expected outer radius of the Bahcall-Wolf cusp.

Right: Estimates of the relaxation time, assuming a single-mass population of Solar-mass stars. Dashed horizontal line indicates the mean age of stars that formed continuously over the last 10 Gyr. Other details are given in the text.

These observations are puzzling, and perhaps even inconsistent, for a number of reasons.

- There is no natural explanation for a parsec-scale core. For instance, the radius at which red giants would be expected to experience a collision with stellar-mass BHs, over their lifetimes, is roughly an order of magnitude smaller than $r_c$, even assuming that the BHs follow a steeply-rising, relaxed density profile near the SBH (Freitag et al. 2008). The assumption of a relaxed density profile in the BHs is problematic however, given that...

- There is no Bahcall-Wolf cusp in the stars. If the late-type stars have been present for a time longer than the two-body relaxation time $t_r$, their distribution should have relaxed by now to the quasi-steady-state form $n \sim r^{-7/4}$ inside $r_{cusp} \approx 0.2 r_{inf} \approx 0.5$ pc, where $r_{inf} \approx 2 - 3$ pc is the SBH influence radius (Bahcall & Wolf 1976). The result would be a
continuously-rising density of old stars, not the essentially flat core that is observed.

- The nuclear star cluster of the Milky Way, on scales \(1 \text{ pc} \lesssim r \lesssim 10 \text{ pc}\), appears to have undergone continuous star formation over the last 10 Gyr (Mezger et al. 1999; Philipp et al. 1999; Figer et al. 2004b). If the top-heavy IMF inferred for the stellar disks is typical of past star formation in the core, the mass-to-light ratio in the inner parsec should be much higher than observed by now, since a large fraction of stars would have evolved to BHs (Löckmann et al. 2009). Either star formation in the central parsec is just beginning, which would make the current epoch special, or the IMF associated with the event that formed the disks was atypical (or the inference of a top-heavy IMF is incorrect; e.g. Bastian et al. 2010).

2. Models

Dynamical models of the inner parsec can be divided into two broad classes.

1. *Unrelaxed (low-density) models.* These models postulate that the low density observed in the late-type giants is characteristic of the old populations generally in the core, including the fainter unresolved stars, and (possibly) the stellar remnants. In these models, the continued existence of a core is consistent with the long relaxation time implied by a low density (Fig. 1). Physical collisions between stars would be rare.

2. *Relaxed (high-density) models.* A relaxed, Bahcall-Wolf cusp is assumed to be present, but for some reason it is not seen in the distribution of the red giants. For instance, a high enough density of stellar BHs might destroy the giants, or push them out from the center.

Low-density models suffer from a certain lack of robustness, since it is easy to imagine mechanisms for refilling an empty core (star formation, enhanced relaxation, etc.) and not so easy to imagine ways of emptying it. High-density models, on the other hand, are in danger of violating the proper-motion constraint on the total mass in the core (by postulating too large a mass in BHs) or the constraint on the mass-to-light ratio (by postulating too large a fraction of BHs relative to stars).

A key parameter in any model is the relaxation time, which for a single stellar population is

\[
t_r = \frac{0.33\sigma^3}{G^2\rho \ln \Lambda} \approx 1.5 \times 10^{10} \text{ yr} \left( \frac{\sigma}{100 \text{ km s}^{-1}} \right)^3 \left( \frac{\rho}{10^5 \text{M}_\odot \text{pc}^{-3}} \right)^{-1} \left( \frac{m}{\text{M}_\odot} \right)^{-1} \left( \frac{\ln \Lambda}{15} \right)^{-1};
\]

where \(\sigma\) is the rms velocity in any direction, \(m\) is the mass of one star, \(\rho\) is the mass density, and \(\ln \Lambda\) is the Coulomb logarithm. If there is a range of mass groups, the concept of relaxation time becomes vague, but a natural generalization is to replace \(m\) in equation (1) by \(\bar{m}\), where

\[
\bar{m} \equiv \frac{\int N(m)m^2 dm}{\int N(m)mdm}.
\]
and \( N(m)dm \) is the number of stars with masses in the range \( m \) to \( m + dm \). With this replacement, \( t_r \) can be interpreted as the time for a test star’s velocity to be randomized by encounters with more massive objects (e.g. [Merritt] 2004). Standard IMFs predict \( \dot{m} \lesssim 1M_\odot \); if the density is dominated locally by stellar BHs, \( \dot{m} \lesssim 10M_\odot \); if there is even a small population of “massive perturbers” with \( m \gg 10M_\odot \), larger values of \( \dot{m} \) are possible ([Perets et al.] 2007).

Ignoring for the moment the possibility of massive perturbers, the relaxation time outside the core is quite well determined. Fits to the stellar kinematics at \( r \gtrsim 1 \) pc, together with the Jeans equation, give a mass density

\[
\rho(r) \approx \rho_0 \left( \frac{r}{1 \text{pc}} \right)^{-1.8}, \quad 1 \text{pc} \lesssim r \lesssim 10 \text{pc}
\]

([Genzel et al.] 2003; [Schödel et al.] 2007; [Oh et al.] 2009), with \( \rho_0 \approx 1.5 \times 10^5 M_\odot \text{pc}^{-3} \); the uncertainty in \( \rho_0 \) is probably less than 50%. Figure 1 shows the implied \( t_r \), assuming \( m = 1M_\odot \), for \( \rho_0 = (0.75, 1.5, 3) \times 10^5 M_\odot \text{pc}^{-3} \). At the SBH influence radius, \( r_{\text{infl}} \approx 2.5 \) pc, the relaxation time is \( \sim 2.5 \times 10^{10} \) yr, with a weak dependence on \( \rho_0 \). Thus assuming Solar-mass stars, the two-body relaxation time at the influence radius of the Milky Way SBH is substantially longer than the age of the Galaxy, and perhaps five times longer than the mean age of the stars. This is neither a new, nor a controversial, result. But it is worth emphasizing, since the time to establish a steady-state Bahcall-Wolf cusp is approximately \( t_r(r_{\text{infl}}) \) ([Preto et al.] 2004; [Merritt & Szell] 2006).

The mass implied by equation (2) inside 1 pc is \( \sim 1.6 \times 10^6 M_\odot \) for \( \rho_0 = 1.5 \times 10^5 M_\odot \). This is somewhat larger than the \( \sim 1 \times 10^6 M_\odot \) inferred from the proper motions, but not so much larger that one can rule out the hypothesis that the mass density continues to obey \( \rho \sim r^{-1.8} \) inside the observed core, as it would if a Bahcall-Wolf cusp were present.

Inside 1 pc, the relaxation time depends critically on the assumed mass density and its variation with radius. The latter is poorly constrained by the proper motion data ([Schödel et al.] 2009). Figure 1 shows \( t_r \), assuming that the mass is distributed as \( \rho \sim r^{-0.5} \), the steepest dependence consistent with the number counts of the late-type stars. If instead \( \rho(r) \sim r^{-7/4} \), \( t_r \) continues to drop toward Sgr A*, as \( t_r \sim r^{1/4} \). Given the uncertainties, it is not clear that the relaxation time at the Galactic center is anywhere shorter than 10 Gyr.

### 2.1. Unrelaxed models

Figure 2 shows the evolution of a single population of stars around the MW SBH, starting from a power-law density profile (eq. 2), with an initial core of radius 1 pc. The core “fills in” via gravitational encounters, on the expected time scale of \( t_r(r_{\text{infl}}) \approx 20 \) Gyr. By 5 Gyr, the core has shrunk to a size of \( \sim 0.5 \) pc, roughly the size of the core observed in the late-type stars (Fig. 1). Not until \( \sim 20 \) Gyr is a Bahcall-Wolf cusp fully established.

Because the density of the NSC beyond \( r_{\text{infl}} \) falls off as \( \rho \sim r^{-1.8} \) – roughly the same, \( r^{-7/4} \) dependence as in a Bahcall-Wolf cusp – the density in Figure 2 evolves in an approximately “self-similar” way: the core shrinks while the form of \( \rho(r) \) outside the core always obeys \( \rho \sim r^{-1.8} \). Initial cores in the range 1 – 1.5 pc produce final cores, after 5 – 10 Gyr, that are consistent in size with the
Figure 2. Evolution of the surface density $\Sigma(R)$, configuration-space density $\rho(r)$, and phase-space density $f(E)$ for a population of Solar-mass stars around the MW SBH, assuming an initial core size of 1 pc. Increasing line thickness denotes increasing time, $t = (0, 0.2, 0.5, 1, 2) \times 10^{10}$ yr. Dashed lines are the asymptotic forms corresponding to a Bahcall-Wolf cusp, i.e. $f \sim |E|^{1/4}$, $\rho \sim r^{-7/4}$.

observed core. The larger the initial core; the shorter the evolution time; or the longer the relaxation time $t_r$, the larger the final core.

Why should there be a core in the first place? Cores are ubiquitous features of luminous early-type galaxies; core radii are one to a few times $r_{\text{infl}}$, consistent with formation via three-body ejection of stars by the binary SBH that preceded the current, single SBH [Faber et al. 1997; Milosavljević & Merritt 2001]. This model of core formation does not seem totally excluded for the Milky Way, which might have experienced a major merger around the time of formation of the thick disk, $10^{-12}$ Gyr ago [Wyse 2001]. Furthermore the initial core size inferred above, $1 - 1.5$ pc, is comparable to $r_{\text{infl}}$. But the core in the Milky Way is probably a different sort of creature than the cores observed in luminous E-galaxies, since it sits at the center of a nuclear star cluster. Interestingly, the only other galaxy with a NSC that is near enough for a parsec-scale core to be resolved – the Local Group dwarf galaxy NGC 205 – also contains a core, of radius $\sim 0.4$ pc [Valluri et al. 2005].

Other ways of making a parsec-scale core include:

- **Inspiral of intermediate-mass black holes (IBHs).** A single IBH of mass $\sim 10^4 M_\odot$, spiralling in against a pre-existing stellar density cusp, creates a core of radius $\sim 0.05 - 0.1$ pc [Baumgardt et al. 2006]. Repeated inspiral events would create a larger core, although the displaced mass increases at a less than linear rate with the number of inspirals. Nevertheless, some models postulate one such event every $\sim 10^7$ yr [Portegies Zwart et al. 2006].

An inspiralling IBH was first proposed as a solution to the other grand problem of the Galactic center, the origin of the young stars (Hansen & Milosavljevic 2003). Subsequently, a very specific model was proposed for the formation and runaway growth of an IBH in a dense, inspiralling star cluster [Gürkan & Rasio 2005]. When the predictions of this particular
model – e.g., an extended tidal tail of young stars – were not verified, the idea fell out of favor (Paumard 2009). But invoking an IBH still has much to recommend it. For instance, an IBH is extremely efficient at randomizing the orbits of the S-stars, and the transition radius between the S-stars and the clockwise disk is roughly the expected stalling radius for an IBH (Merritt et al. 2009).

• An enlarged loss cone. Gravitational encounters drive a mass flux of \( \sim M_{\text{SBH}}/t_r(r_{\text{infl}}) \) into Sgr A*. The core that results from this diffusive loss process is very small: its size is comparable to the radius of the capture sphere – either the tidal disruption radius, \( r_t \approx 10^{-5} \) pc, or the Schwarzschild radius, \( r_{\text{Sch}} \approx 10^{-6} \) pc. The reason the core is so small is that the depleted orbits are continuously resupplied by diffusion from orbits of larger angular momentum and energy. If there were some way to transfer a mass in stars of \( \sim M_{\text{SBH}} \) into the SBH on a time scale \( \ll t_r \) – say, a crossing time – the resulting core would be much larger. This could happen if the NSC were appreciably triaxial, even if only transiently, since many orbits near a SBH in a triaxial cluster are “centrophilic,” passing arbitrarily close to the SBH after a finite time (Merritt & Poon 2004).

• Localized star formation. The phase-space density \( f(E) \) of an isotropic nucleus containing a core is roughly a delta-function in energy, \( f \sim \delta(E - E_0) \), with \( E_0 \) the gravitational potential at the core radius. (This can be seen in the initial conditions plotted in Fig. 2, right panel). Roughly the same initial conditions are implied by formation of stars in a narrow ring at a radius \( r_0 \), where \( \Phi(r_0) = E_0 \), if it is assumed that the stellar orbital eccentricities and orientations are randomized soon after the stars form. The two, young stellar disks have mean radii of \( \sim 0.25 \text{ pc} \) and the clockwise disk extends inward as far as \( \sim 0.05 \text{ pc} \) (Bartko et al. 2010), but it is not out of the question that the bulk of star formation took place in disks with radii \( \sim 0.5 \text{ pc} \) or greater.

Even if the distribution of late-type giants is unrelaxed, it is not necessarily the case that the stellar BHs also have a low central density, since they would have spiralled in relative to the stars (Morris 1993). However the inspiral time is a strong function of the stellar density, since the latter determines the dynamical friction force. Figure 3 shows inspiral times for 10\( M_\odot \) BHs in models of the NSC with stellar density \( \rho \sim r^{-\gamma} \) inside the core; thus \( \gamma \approx 1.8 \) corresponds to an unbroken power-law. For \( \gamma \ll 1 \), inspiral slows dramatically at a radius of \( \sim r_c/2 \); indeed, Chandrasekhar’s formula implies that the frictional force vanishes completely, at \( r \lesssim r_c/2 \), when \( \gamma = 0.5 \), although this prediction needs to be checked via careful \( N \)-body simulations.

“Massive perturbers” – giant molecular clouds, star clusters, etc. – are present in the NSC at \( r \gg r_c \), and could scatter stars into the central parsec, at a potentially much higher rate than two-body relaxation between Solar-mass stars (Perets et al. 2007). Almost all of the scattered stars would be on orbits that are unbound to the SBH; the density profile of these stars would be \( n \sim r^{-1/2} \) and their density near the SBH would be low. However, field binary stars that are deflected by massive perturbers onto eccentric orbits can undergo a three-body
exchange interaction with the SBH, resulting in capture of one of the stars onto a tight orbit around the SBH. The resultant radial distribution of the bound stars will reflect the uncertain semi-major axis distribution of the parent binary population. The rate of captures depends also on the binary fraction and on the distribution of perturber masses, both of which are poorly known. But estimates of the capture rate are as high as $\sim 10^{-4}\text{yr}^{-1}$ (Perets et al. 2007). The low observed density of late-type stars in the inner parsec places a limit on the effectiveness of this mechanism unless most of the captured stars are too faint to be observed.

### 2.2. Relaxed models

Most dynamical models of the Galactic center published in the last two decades fall into this category. The relevance of such models to the Milky Way is called into question by the apparent absence of a Bahcall-Wolf cusp in the old stars. The existence of a density cusp could be reconciled with the observed core if there is a change in the luminosity function at roughly the core radius, such that the fraction of bright giants is much smaller inside the core than outside. For instance, the $1-3M_\odot$ stars that are believed to dominate the number counts at magnitudes $m_K \approx 15$ might never have formed. This hypothesis is consistent with the apparently top-heavy mass function inferred for the stars in the two young stellar disks (Bartko et al. 2010), with the low integrated X-ray flux from the Galactic center (Nayakshin & Sunyaev 2005), and with some theoretical expectations about the mode of star formation near a SBH (Nayakshin et al. 2007). However, as noted above, such an IMF, if active over the entire lifetime of the NSC, would result in a much higher mass-to-light ratio than observed in the central parsec (Löckmann et al. 2009).
Another possibility is that the giant stars have been selectively destroyed by collisions with other members of the Galactic center population (Genzel et al. 1996; Alexander 1999; Bailey & Davies 1999). In a relaxed, multi-mass cusp, the densities of the light and heavy components (e.g. main sequence stars, stellar BHs) follow \( n \sim r^{-3/2} \) and \( n \sim r^{-2} \) respectively; the BHs are predicted to dominate the mass density inside a radius \( \sim 0.01 \) – 0.1 pc from Sgr A* (Hopman & Alexander 2006; Freitag et al. 2006). In such a dense cusp, the probability that a given star will suffer a physical collision with another star, or stellar remnant, over its lifetime is very high inside \( \sim 0.1 \) pc (Freitag et al. 2008).

The observational consequences of such a collision are less clear. Simulations suggest that in order to avoid evolving onto the red-giant branch, a \( 1 - 3M_\odot \) star must lose more than 90% of its mass (Dale et al. 2009). Even assuming a “super-relaxed” density cusp, in which the density of stellar BHs was arbitrarily increased to four times its value in the relaxed models, Dale et al. (2009) found the rate of such collisions to be far too small to explain the observed giant depletion.

![Figure 4](image.png)

Figure 4. Joint evolution of the density of stellar BHs (left) and low-mass stars (right) around a SBH, under the assumption that the BHs dominate the total density from the start. Curves show densities at times \((0.0, 0.25, 0.5, 1, 2)\) in units of the initial relaxation time at the influence radius. The stars are scattered by the BHs into a \( \rho \sim r^{-3/2} \) cusp, which retains its form as the density normalization drops with time, due to a continuous transfer of heat from the BHs.

At this meeting, M. Davies presented even more extreme models, in which stars were assumed to form continuously from a flat IMF, resulting in a core dominated by BHs throughout the inner parsec. If the mass in BHs in the inner parsec is increased to several million Solar masses, the collision rate becomes high enough to reproduce the observed giant depletion. These models would appear to severely violate the proper-motion constraint on the total mass and the mass-to-light ratio in the core (Schödel et al. 2009).

The collisional destruction model is nevertheless appealing, and some way might still be found to make it work. For instance, Dale et al. (2009) only considered collisions involving giants approximately halfway up the giant branch;
for $2 - 3M_\odot$ stars, the red giant phase is so short that collisions are more likely to occur before the giant branch, in spite of the star’s much smaller size (J. Lombardi, private communication). Since the collisional probability is a strong function of main-sequence mass, precise spectral typing of the observed giants might provide circumstantial evidence for such a model (Do et al. 2009).

It is sometimes argued (e.g. Löckmann et al. 2009) that a high enough number of stellar BHs could create a core, by sinking to the center and displacing the less-massive stars. Massive objects that dominate the local density have two effects on the distribution of the less-massive objects (e.g. Merritt et al. 2007). There is a transfer of heat from the “heavies” (BHs) to the “lights” (stars), with a characteristic time given approximately by equation (1), if $\tilde{m}$ is replaced by $m_{BH}$. In addition, the stars are scattered by the BHs, and driven, on roughly the same time scale, to an approximately uniform population of phase space. A constant $f$ in the $1/r$ potential of a SMBH implies a configuration-space density $n \sim r^{-3/2}$; thus the stars would exhibit a $r^{-3/2}$ cusp at $r \lesssim r_{\text{infl}}$: the amplitude of which would gradually decay as the BHs continue to heat the stars (Fig. 4). In order to make a bona-fide core, the heavies must expel the lights in a time $\ll t_r$; this happens, for instance, when a second SBH spirals in.

3. Conclusions

To the long-standing “paradox of youth” at the Galactic center, we can now add a “conundrum of old age” arising from the puzzling distribution of the late-type stars. While the most recent data do not compel an interpretation of the Galactic center as an unrelaxed system, they are broadly consistent with such a model. Even if the distribution of old stars is unrelaxed, there might still be a “dark cusp” of stellar remnants near Sgr A*. A key theoretical question is the efficiency of physical collisions at keeping $1 - 3M_\odot$ stars from reaching the red giant branch.

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References

Alexander, T. 1999, ApJ, 527, 835
Bahcall, J. N., & Wolf, R. A. 1976, ApJ, 209, 214
Bailey, V. C., & Davies, M. B. 1999, MNRAS, 308, 257
Bartko, H., et al. 2009, ApJ, 697, 1741
Bartko, H., et al. 2010, ApJ, 708, 834
Bastian, N., Covey, K. R., & Meyer, M. R. 2010, arXiv:1001.2965
Baumgardt, H., Guamanidis, A., & Portegies Zwart, S. 2006, MNRAS, 372, 174
Böker, T. 2008, Journal of Physics Conference Series, 131, 012043
Buchholz, R. M., Schödel, R., & Eckart, A. 2009, A&A, 499, 483
Dale, J. E., Davies, M. B., Church, R. P., & Freitag, M. 2009, MNRAS, 393, 1016
Do, T., Ghez, A. M., Morris, M. R., Lu, J. R., Matthews, K., Yelda, S., & Larkin, J.
2009, ApJ, 703, 1323
Faber, S. M., et al. 1997, AJ, 114, 1771
Figer, D. F. 2004a, The Formation and Evolution of Massive Young Star Clusters, 322, 49
Figer, D. F., Rich, R. M., Kim, S. S., Morris, M., & Serabyn, E. 2004b, ApJ, 601, 319
Freitag, M., Amaro-Seoane, P., & Kalogera, V. 2006, ApJ, 649, 91
Freitag, M., Dale, J. E., Church, R. P., & Davies, M. B. 2008, IAU Symposium, 245, 211
Genzel, R., Thatte, N., Krabbe, A., Kroker, H., & Tacconi-Garman, L. E. 1996, ApJ, 472, 153
Genzel, R., et al. 2003, ApJ, 594, 812
Ghez, A. M., Klein, B. L., Morris, M., & Becklin, E. E. 1998, ApJ, 509, 678
Ghez, A. M., et al. 2008, ApJ, 689, 1044
Gillessen, S., Eisenhauer, F., Trippe, S., Alexander, T., Genzel, R., Martins, F., & Ott, T. 2009, ApJ, 692, 1075
Gürkan, M. A., & Rasio, F. A. 2005, ApJ, 628, 236
Hansen, B. M. S., & Milosavljević, M. 2003, ApJ, 593, L77
Hopman, C., & Alexander, T. 2006, ApJ, 645, L133
Hughes, S. A. 2003, Annals of Physics, 303, 142
Levin, Y., Wu, A., & Thommes, E. 2005, ApJ, 635, 341
Löckmann, U., Baumgardt, H., & Kroupa, P. 2009, MNRAS, in press
Lu, J. R., Ghez, A. M., Hornstein, S. D., Morris, M. R., Becklin, E. E., & Matthews, K. 2009, ApJ, 690, 1
Merritt, D. 2004, Physical Review Letters, 92, 201304
Merritt, D. 2009, [arXiv:0909.1318]
Merritt, D., Gualandris, A., & Mikkola, S. 2009, ApJ, 693, L35
Merritt, D., Harfst, S., & Bertone, G. 2007, Phys.Rev.D, 75, 043517
Merritt, D., & Poon, M. Y. 2004, ApJ, 606, 788
Merritt, D., & Szell, A. 2006, ApJ, 648, 890
Mezger, P. G., Zylka, R., Philipp, S., & Launhardt, R. 1999, A&A, 348, 457
Milosavljević, M., & Merritt, D. 2001, ApJ, 563, 34
Morris, M. 1993, ApJ, 408, 496
Nayakshin, S., Cuadra, J., & Springel, V. 2007, MNRAS, 379, 21
Nayakshin, S., & Sunyaev, R. 2005, MNRAS, 364, L23
Oh, S., Kim, S. S., & Figer, D. F. 2009, Journal of Korean Astronomical Society, 42, 17
Paumard, T., et al. 2006, ApJ, 643, 1011
Paumard, T. 2009, Journal of Physics Conference Series, 131, 012009
Perets, H. B., Hopman, C., & Alexander, T. 2007, ApJ, 656, 709
Philipp, S., Zylka, R., Mezger, P. G., Duschl, W. J., Herbst, T., & Tuffs, R. J. 1999, A&A, 348, 768
Portegies Zwart, S. F., Baumgardt, H., McMillan, S. L. W., Makino, J., Hut, P., & Ebisuzaki, T. 2006, ApJ, 641, 319
Pretot, M., Merritt, D., & Spurzem, R. 2004, ApJ, 613, L109
Schödel, R., et al. 2007, A&A, 469, 125
Schödel, R., Merritt, D., & Eckart, A. 2008, Journal of Physics Conference Series, 131, 012044
Schödel, R., Merritt, D., & Eckart, A. 2009, A&A, 502, 91
Valluri, M., Ferrarese, L., Merritt, D., & Joseph, C. L. 2005, ApJ, 628, 137
Wyse, R. F. G. 2001, in Galaxy Disks and Disk Galaxies, Astronomical Society of the Pacific Conference Series, vol. 230, ed. J. G. Funes & E. M. Corsini, 71-80.