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# Dynamics of galactic nuclei: mass segregation and collisions

**Marc Freitag[1], James E. Dale[2], Ross P. Church[2,3] and Melvyn B. Davies[2]**

[1]Institute of Astronomy, Madingley road, Cambridge, CB3 0HA, UK
email: freitag@ast.cam.ac.uk

[2]Lund Observatory, Box 43, SE 22100, Lund, Sweden

[3]Centre for Stellar and Planetary Astrophysics, Monash University, Vic. 3800, Australia

**Abstract.** Massive black holes (MBHs) with a mass below $\sim 10^7\,\mathrm{M}_\odot$ are likely to reside at the centre of dense stellar nuclei shaped by 2-body relaxation, close interactions with the MBH and direct collisions. In this contribution, we stress the role of mass segregation of stellar-mass black holes into the innermost tenths of a parsec and point to the importance of hydrodynamical collisions between stars. At the Galactic centre, collisions must affect giant stars and some of the S-stars.

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## 1. Introduction

It is now firmly established that Sgr A*, the weak radio source at the centre of the Milky Way, is a massive black hole (MBH) with a mass of $M_\bullet \simeq 4\times10^6\,\mathrm{M}_\odot$. The cluster of stars around it can be observed at resolutions as high as $\sim 0.002\,\mathrm{pc}$ in the near infrared, allowing us to witness the unique stellar dynamical processes at play in a galactic nucleus (e.g., Eisenhauer *et al.* 2005; Schödel *et al.* 2007, and Schödel, these proceedings).

A simple model for the stellar density within a few parsecs of Sgr A*, compatible with the observed stellar kinematics is given by

$$\rho(R) \simeq \frac{3-\gamma}{4\pi}\frac{M_\bullet}{R_{\mathrm{infl}}^3}\left(\frac{R}{R_{\mathrm{infl}}}\right)^{-\gamma} \simeq 5\times10^6\,\mathrm{M}_\odot\mathrm{pc}^{-3}\left(\frac{R}{0.1\,\mathrm{pc}}\right)^{-1.5}, \tag{1.1}$$

where $R_{\mathrm{infl}} \simeq 2\,\mathrm{pc}$ is the influence radius and $\gamma \simeq 1.5$. Well inside $R_{\mathrm{infl}}$, the (1–D) velocity dispersion follows a Keplerian profile,

$$\sigma(R) \simeq \sqrt{\frac{1}{1+\gamma}\frac{GM_\bullet}{R}} \simeq 260\,\mathrm{km\,s}^{-1}\left(\frac{R}{0.1\,\mathrm{pc}}\right)^{-0.5}. \tag{1.2}$$

Stars exchange energy and angular momentum through 2-body relaxation, i.e. a multitude of 2-body scatterings, over a timescale (Spitzer 1987),

$$t_{\mathrm{rlx}}(R) = \frac{0.339}{\ln(M_\bullet/\langle m\rangle)}\frac{\sigma^3(R)}{G^2\langle m\rangle\rho(R)} \simeq 4\times10^9\,\mathrm{yr}, \tag{1.3}$$

where we have a constant average mass $\langle m\rangle = 1\,\mathrm{M}_\odot$. We note that for $\gamma = 1.5$, the relaxation time is approximately constant well within the sphere of influence.

Assuming that the Sgr A* cluster is typical and that one can scale to other galactic nuclei using the $M-\sigma$ relation in the form $\sigma = \sigma_{\mathrm{MW}}(M_\bullet/4\times10^6\,\mathrm{M}_\odot)^{1/\beta}$ with $\beta \approx 4-5$ (Ferrarese & Merritt 2000; Tremaine *et al.* 2002), one can estimate the relaxation time inside the sphere of influence in a galactic nucleus hosting an MBH of mass $M_\bullet$ to be

$t_{\rm rlx} \approx 4 \times 10^9\,{\rm yr}\,(M_\bullet/4 \times 10^6\,{\rm M}_\odot)^{(2-3/\beta)}$. This rough relation suggests that MBHs less massive than about $10^7\,{\rm M}_\odot$ typically inhabit nuclei where relaxation plays an important role. These are the MBHs which can produce gravitational waves detectable by LISA (e.g., Hogan 2007) and probably dominate the rate of accretion flares due to tidal disruption of stars (Wang & Merritt 2004).

We now consider the timescale for direct collisions between stars. We assume two populations of stars, with stellar masses $m_1$ and $m_2$, stellar radii $r_1$ and $r_2$, and Maxwellian velocity distributions of (1–D) dispersions $\sigma_1$ and $\sigma_2$. The average time for a star of type 1 to collide with a star of type 2 is

$$t_{\rm coll} = \left[\sqrt{8\pi} n_2 \sigma_{\rm rel} (r_1 + r_2)^2 \left(1 + \frac{G(m_1+m_2)}{\sigma_{\rm rel}^2 (r_1+r_2)}\right)\right]^{-1}, \qquad (1.4)$$

with $\sigma_{\rm rel}^2 = \sigma_1^2 + \sigma_2^2$ (Binney & Tremaine 1987). At very small distances from the MBH, using equations 1.1 and 1.2 and setting $m_2 = \langle m \rangle = {\rm M}_\odot$ and $r_2 = {\rm R}_\odot$, the collision time for a star of radius $r_1 \equiv r_*$ is $t_{\rm coll}(R) \approx 10\,{\rm Gyr}\,[(r_* + {\rm R}_\odot)/2\,{\rm R}_\odot]^{-2}\,(R/0.02\,{\rm pc})^2$. This suggests that a few thousand main-sequence (MS) stars should have suffered from at least one collision in the Galactic centre.

## 2. Mass segregation in galactic nuclei

The main effect of 2-body relaxation in a galactic nucleus is to produce mass segregation (Freitag, Amaro-Seoane, & Kalogera 2006; Hopman & Alexander 2006). Stellar-mass black holes (SBHs) are $10-20$ times more massive than the average star. In our stellar-dynamical models of the Galactic nucleus, 2000 to 3000 of them accumulate in the innermost 0.1 pc over a timescale of $3-5$ Gyr. Without mass segregation, only 200 to 300 SBHs would be expected there. The population within 1 pc tallies $\sim 20\,000$. They are swallowed by the MBH at a rate of about one per Myr. SBHs dominate the mass density within $\sim 0.1$ pc of the MBH. There they form a cusp compatible with the profile predicted by Bahcall & Wolf (1976), $\rho(R) \propto R^{-\gamma}$ with $\gamma = 1.75$, while all lighter objects (including the neutron stars) form shallower cusps with $\gamma \simeq 1.3-1.5$.

Possible observational consequences of a population of of SBHs in the Galactic centre are mentioned by Freitag *et al.* (2006). They include their appearance as X-ray sources, accreting from a companion star or from interstellar gas (Muno *et al.* 2005; Deegan & Nayakshin 2007) and minute deflections of the trajectories of the S-stars (Weinberg, Milosavljević, & Ghez 2005). SBHs can spiral into MBHs by emission of gravitational waves. If it is not perturbed into a direct plunge or a wider non-inspiralling orbit before it reaches a period of about $10^4$ s an SBH can become a continuous source for LISA, detectable at several Gpc (see review by Amaro-Seoane *et al.* 2007). The segregation of SBHs is key to obtain inspiral rates of observational interest ($\gtrsim 10^{-8}\,{\rm yr}^{-1}$ per galaxy). It is also possible that LISA will detect a few bursts of gravitational radiation emitted by SBHs at the pericentre of very eccentric but long-period orbits around the Galactic MBH (Hopman, Freitag, & Larson 2007).

## 3. Collisions at the Galactic centre

Collisions are unlikely to play an important role in the global dynamics of the Sgr A* cluster or to provide the Galactic MBH with significant amounts of gas in comparison with tidal disruptions or stellar winds (Freitag *et al.* 2006). However collisions certainly occur in the Galactic centre, with potentially important observational consequences. This

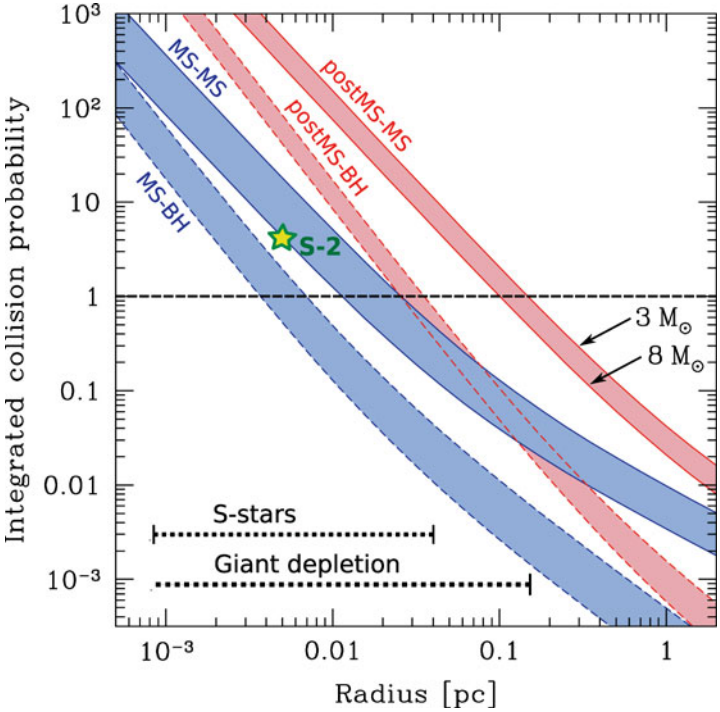

**Figure 1.** Collision probabilities at the Galactic centre. We plot the probability for a star of 3 or $8\,\mathrm{M}_\odot$ to collide with a MS star or a stellar-mass BH, integrated over the MS or post-MS phase of its evolution, $P_{\mathrm{coll}} = \int t_{\mathrm{coll}}^{-1} dt$ (Dale *et al.*, in preparation). When $P_{\mathrm{coll}}$ is larger than one, it can be interpreted as the expected number of collisions during this phase, neglecting perturbations of the stellar evolution caused by previous collisions. Stellar evolution models are used to determine $r_*(t)$. We assume the field MS stars are $0.5\,\mathrm{M}_\odot$ objects and follow a density profile $n(R) = n_0(R/0.1\,\mathrm{pc})^{-\gamma}$ with $n_0 \simeq 10^7\,\mathrm{pc}^{-3}$ and $\gamma = 1.4$. The BHs have a mass of $10\,\mathrm{M}_\odot$, $n_0 \simeq 5 \times 10^5\,\mathrm{pc}^{-3}$ and $\gamma = 1.8$. These profiles are inspired by detailed stellar dynamical models (Freitag *et al.* 2006). We indicate the range of radii where depletion of bright giants is observed, where the S-stars are, and an estimate of the value of $P_{\mathrm{coll}}$ for S-2.

point is conveyed by Fig. 1 in which we plot an estimate of the collision probability over the MS and post-MS lifetime of massive stars. As possible impactors, we consider MS stars and (mass-segregated) SBHs. One notices that, during their MS phase, many S-stars must experience one or several collisions with MS stars or SBHs.

To complement the work of Freitag & Benz (2005) on MS–MS collisions, we are performing a large series of simulations of high-velocity encounters between stars and SBHs, using the "Smoothed Particle Hydrodynamics" (SPH) method. A snapshot from one of our runs is shown in Fig. 2. First results suggest that SBHs can be damaging even without a direct hit, by raising large tides in a MS star and causing it to swell. Puffed-up stars would be much larger and more fragile targets until they contract back to a normal size.

Furthermore, a star is much more likely to be struck once it has become a giant. Nearly all stars within 0.1 pc of the Galactic centre must collide during their post-MS life. The population of bright giants is observed to be significantly depleted within $\sim 0.15$ pc of the Galactic centre (Genzel *et al.* 1996). We are investigating whether collisions can be responsible, either by stripping the giants' envelopes (Bailey & Davies 1999) or by reducing the mass of MS stars, thus preventing them from becoming giants.

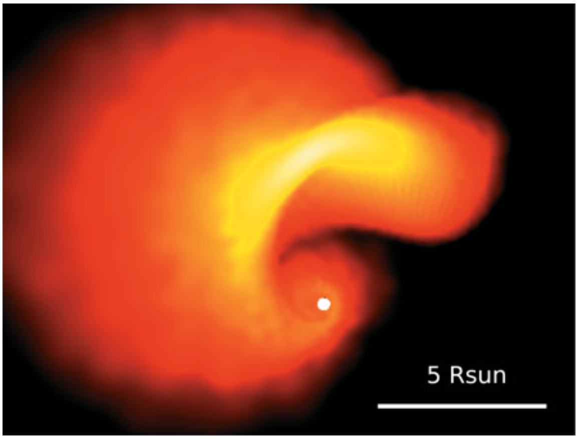

**Figure 2.** Snapshot of a SPH simulation of a collision between a $1\,\mathrm{M}_\odot$ MS star and a $10\,\mathrm{M}_\odot$ black hole (white dot). The relative velocity (at large separation) is $873\,\mathrm{km\,s}^{-1}$ and the pericentre distance assuming point-mass Keplerian trajectories is $0.5\,\mathrm{R}_\odot$ (Dale *et al.*, in preparation).

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## References

Amaro-Seoane, P., Gair, J. R., Freitag, M., Miller, M. C., Mandel, I., Cutler, C. J., & Babak, S., 2007, *Classical and Quantum Gravity* 24, 113

Bahcall, J. N. & Wolf, R. A., 1976, *ApJ* 209, 214

Bailey, V. C. & Davies, M. B., 1999, *MNRAS* 308, 257

Binney, J. & Tremaine, S., 1987, *Galactic Dynamics*. Princeton University Press

Deegan, P. & Nayakshin, S., 2007, *MNRAS* 377, 897

Eisenhauer, F., Genzel, R., Alexander, T., Abuter, R., Paumard, T., Ott, T., Gilbert, A., Gillessen, S., Horrobin, M., Trippe, S., Bonnet, H., Dumas, C., Hubin, N., Kaufer, A., Kissler-Patig, M., Monnet, G., Ströbele, S., Szeifert, T., Eckart, A., Schödel, R., & Zucker, S., 2005, *ApJ* 628, 246

Ferrarese, L. & Merritt, D., 2000, *ApJ* (Letters) 539, L9

Freitag, M., Amaro-Seoane, P., & Kalogera, V., 2006, *ApJ* 649, 91

Freitag, M. & Benz, W., 2005, *MNRAS* 358, 1133

Genzel, R., Thatte, N., Krabbe, A., Kroker, H., & Tacconi-Garman, L. E., 1996, *ApJ* 472, 153

Hogan, C. J., 2007, *The New Science of Gravitational Waves*. Preprint, astro-ph/0709.0608

Hopman, C. & Alexander, T., 2006, *ApJ* (Letters) 645, L133

Hopman, C., Freitag, M., & Larson, S. L., 2007, *MNRAS* 378, 129

Muno, M. P., Pfahl, E., Baganoff, F. K., Brandt, W. N., Ghez, A., Lu, J., & Morris, M. R., 2005, *ApJ* (Letters) 622, L113

Schödel, R., Eckart, A., Alexander, T., Merritt, D., Genzel, R., Sternberg, A., Meyer, L., Kul, F., Moultaka, J., Ott, T., & Straubmeier, C., 2007, *A&A* 469, 125

Spitzer, L., 1987, *Dynamical evolution of globular clusters*. Princeton University Press

Tremaine, S., Gebhardt, K., Bender, R., Bower, G., Dressler, A., Faber, S. M., Filippenko, A. V., Green, R., Grillmair, C., Ho, L. C., Kormendy, J., Lauer, T. R., Magorrian, J., Pinkney, J., & Richstone, D., 2002, *ApJ* 574, 740

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

Weinberg, N. N., Milosavljević, M., & Ghez, A. M., 2005, *ApJ* 622, 878