Stellar Processes near Sgr A

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1. Introduction

The relative proximity of the Galactic massive black hole (MBH) offers a unique opportunity to study from up close the various modes in which stars in the high density cusp around the MBH interact with it and with each other. Extensive, well documented observational efforts are directed at using stellar dynamics to determine the primary parameters of the central dark object, its mass, size, location, motion and nature (see e.g. [16, 22] for recent reports). In this brief overview I will focus on other aspects of stellar processes near SgrA*: (1) The extreme conditions in the inner Galactic center (GC): high density, strong tidal fields and high velocities, and their implications for the stars there, specifically star-star interactions and mass segregation. (2) The prospects of probing post-Newtonian (PN) physics by high precision orbital solutions and by gravitational lensing effects. (3) The different modes of strong interactions of stars with the MBH and their observable consequences, and the important role of accelerated relaxation mechanisms. A comprehensive treatment of these topics can be found in [3].

2. Stellar dynamics in a high density cusp

The existence of a high density stellar cusp around the Galactic MBH was long predicted theoretically for a wide range of formation scenarios (e.g. [11, 52]), but was only recently established empirically with high confidence ([47] and Schödel et al, this volume). The density in the inner $\sim 0.01$ pc rises to $\sim 10^8 M_\odot pc^{-3}$, or $\times 10^9$ higher than in the Solar neighborhood. In such a high density environment, where the typical velocities are $\sim 1000$ km s$^{-1}$, collisions are frequent (mean time between collisions shorter than the main sequence (MS) lifetime of a Sun-like star) and energetic (relative velocities above the typical escape velocity from the surface of a MS star). These conditions are quite different from those in a high density core of a globular cluster, where collisions are slow.

2.1. Star-star collisions

High velocity collisions between giants and dwarfs can lead to the disruption of the giant envelope if the collision is close enough to head-on. This leaves a low-luminosity hot core that is invisible in the infrared (IR), where the stars in GC are observed. There are indeed indications of a gradual disappearance of luminous giants toward the center, in the inner $1.5''$. This trend is well modeled by the collisional destruction of giant envelopes [1, 3] (Fig. 1).

In an environment dense enough for effective collisional destruction, near misses, where the stars interact tidally but are not destroyed, are frequent. In such hyperbolic collisions, energy and angular momentum are transferred from the orbit to the stars, but because the orbit is highly unbound, the stars do not form a binary but continue on their separate way. The tidal energy...
Figure 1. Stellar L-band luminosity as function of projected distance from SgrA*. Filled circles are spectrally identified late-type stars, open circles are spectrally unidentified stars (S. Trippe & T. Ott, priv. comm.). The contours represent results from detailed modeling of collisional destruction in a steep density cusp [1]: from top to bottom, contours correspond to less than 0.5, 1, and 1.5 brighter stars per 0.25′′. The model is statistically consistent with the data.

Figure 2. The mean accumulated stochastic spin-up over 10 Gyr of 1\,M⊙ stars in the GC, due to close tidal star-star encounters, as function of the distance from the MBH [7].

is dissipated relatively quickly, but the excess angular momentum is not so easily discarded. Stochastic tidal spin-up by multiple near-collisions can lead to a high mean stellar spin for long-lived stars if magnetic breaking is inefficient [7]. The mean spin remains high (0.1–0.3 of the centrifugal break-up rotation) over a large volume, \( r \lesssim 0.3 \, \text{pc} \), because the decrease in the number of collisions farther away from the MBH is compensated by the higher tidal efficiency in slower collisions (Fig. 2). High spin changes the evolution and appearance of stars [32]. The MBH potential thus indirectly affects the internal properties of stars around it in a substantial fraction of its dynamical radius of influence.

2.2. Extreme mass segregation

The deep potential of the Galactic MBH leads to the accumulation of a very large number of massive objects around it over the lifetime of the Galaxy. Mass segregation particularly affects stellar black holes (SBHs), which are both much more massive than the mean star and essentially eternal [37, 36]. Such a dense cluster of SBHs may contain up to \( \sim 0.01 \) of all Galactic SBHs in a mere \( 10^{-10} \) of the Galactic volume. It is a curious twist of scientific progress that at present more is known about the mass function of MBHs than of SBHs. For that reason, and because SBHs may be implicated in a variety of interesting phenomena (gravitational wave (GW) emission, X-ray binaries, collisions with stars and the formation of “exotic objects”, accelerated relaxation) that it is of great interest to detect their presence and study their properties. This has turned out to be a very challenging task. There are broadly three detection strategies:

**Direct detection** Dynamical detection of the diffuse dark mass around the MBH by deviations of stellar orbits from Keplerian motion requires very high precision observations. At present only upper limits are available on the enclosed mass [46, 38], and these are still more than
an order of magnitude higher than the drain limit \cite{6} (the maximal number of SBHs that can be packed around a MBH before they start rapidly scattering each other into the MBH). The X-ray emission from accretion of the ISM by isolated SBHs is too weak for detection \cite{42}. The spatial distribution of X-ray binaries suggests a central concentration consistent with mass segregation, but this is still of low statistical significance \cite{40}. SBHs will modify the gravitational lensing properties of the MBH \cite{13}, however the lensing event probability is very small \cite{7}. SBHs may form exotic stellar objects by collisions and mergers \cite{50}, but the overall appearance of such objects is predicted to be quite similar to normal giants (e.g. \cite{12}).

**Environmental effects** A high central concentration of massive objects will increase the number and efficiency of destructive stellar collisions and decrease the relaxation time. However, a collisionally depleted region is expected in any case in the innermost parts of the high density cusp, while the determination of the relaxation time is highly uncertain.

**Light test particles** Mass segregation implies the central depletion of light objects. Several candidate light test particles were considered. Near the MBH, where SBHs ($\sim 10 \, M_\odot$) dominate the mass density, neutron stars ($\sim 1.5 \, M_\odot$) are light objects. Radio pulsars, if observed, could trace mass segregation \cite{14, 43}. However, electron scattering by the Galactic ISM severely hinders their detection. The distribution of white dwarf cataclysmic variables appears to be centrally depleted \cite{39}, but this occurs on the $\sim 1$ pc scale, where mass segregation is unlikely to be significant. A promising class of light test particle, as discussed further below, are the horizontal branch “red clump” (RC) giants.

RC giants have light ($0.5$–$2 \, M_\odot$) and long-lived ($t > 10^9$ yr) progenitors, and are easily observable with an IR magnitude of $K \sim 15.5$ (Fig. 3). There are indications that the RC giants are suppressed in the center compared to other stars (\cite{21} and Schön Individuals et al, this volume). If mass segregation is the underlying cause, then it must differentiate much more sharply between high and low mass stars than is predicted by the Bahcall-Wolf solution ($r^{-7/4}$ for the massive objects, $r^{-3/2}$ for the light ones) \cite{11} (Fig. 4; M. Levi, MSc thesis). There are indeed indications that in a population typical of the GC, which has a much wider range of masses than the globular cluster population considered by Bahcall & Wolf and where the SBHs are a small fraction of the population by number, the slope of the SBHs is as steep or even steeper than $r^{-2}$ \cite{28}.

### 3. Post-Newtonian physics

General Relativity (GR) is the least tested of the theories of the four fundamental forces of nature. It is therefore of interest to test it near the Galactic MBH. GR predicts that physics depends only on the relativistic parameter $\Upsilon \equiv r_g/r$ ($r_g \equiv GM/c^2$) and not on the mass, composition or compactness ($C \equiv r_g/R$) of the massive object. Alternative theories of gravity could behave differently. Figures (5, 6) show that stellar orbits near SgrA$^*$ can potentially probe a region in $(M, \Upsilon, C)$ space that has never been probed before, and in terms of $M$, a region that is inaccessible to compact pulsar binaries, albeit at a lower accuracy than pulsar-based tests of GR \cite{30}.

#### 3.1. Post-Newtonian effects in the Doppler shift measurements

Recent developments in integral field IR spectroscopy (e.g. \cite{16}) now allow measurement of the stellar Doppler shift, $z$, with high accuracies of $\Delta z \sim 10^{-4}$. Some of the stars orbiting the MBH attain velocities at periapsis of $v_p \sim \text{few} \times 0.01$. It is therefore possible to detect with high confidence $\beta^2$ PN effects (the transverse Doppler shift and gravitational redshift, with $z_{\text{PN}} \sim \beta^2 > \Delta z$) in astrometric and spectroscopic orbital data monitored with existing instruments over a decade \cite{54} (Figs. 7, 6). Neglecting these PN effects when modelling the orbits would bias the measured MBH mass and distance at a level of a few percent. This could interfere with the
Figure 3. The K-band luminosity function (KLF), mean mass and fraction of old stars in the population according to a continuous star formation population synthesis model for the GC [10]. The RC giants are prominent around $K \sim 15.5$ mag.

Figure 4. Comparison between the observed KLF inside $1.5''$ and $9''$ [21] and a strong mass-segregation model (M. Levi, MSc thesis 2006). Note the absence of the RC feature in the smaller field. The expected K magnitude of the RC feature is marked by a cross.

Figure 5. Post-Newtonian exploration space ($\Upsilon, C$). GC orbital tests (upper right) are compared to pulsar tests exiting instruments and with SKA (kindly modified from [30] by M. Kramer).

Figure 6. Post-Newtonian exploration space ($M, \Upsilon$). GC orbital tests (upper right) are compared to pulsar tests with existing instruments and with SKA (kindly modified from [30] by M. Kramer).
3.2. Gravitational lensing

Another class of PN phenomena that could be detected in principle in the GC is gravitational lensing (GL) by the MBH. GL effects could be observed as a change in the stellar surface density around the MBH [51], as variable macrolensed (resolved multiple images) far-background stars [2], as microlensed (unresolved multiple images) near-background stars [10], or as microlensing by a composite MBH–SBH lens [4, 13]. However, the prospects of GL by the MBH are not encouraging. Estimates of the optical depth of the far background sources, while highly uncertain, indicate that there may not be enough such sources. The near background sources, while numerous, are not enough to exhibit detectable surface density variations, and their GL cross-sections are too small to be likely sources of microlensing.

4. Strong interactions with the MBH

Some of the most spectacular stellar processes possible in the GC involve strong, close interactions between a star and the MBH. The term “strong” in this context is defined as any interaction that cannot be described by Newtonian gravity operating on point masses. This could be because the stars’ internal degrees of freedom can no longer be ignored, or because dissipative interactions have to be included, or because GR effects must be taken into account.

4.1. Modes of interaction

It is instructive to classify strong stellar interactions with the MBH by analogy to atomic processes (Fig. 9). In spite of the fundamental differences between a macroscopic classical system and a microscopic quantum one, this analogy suggests a classification scheme for the various modes of strong star–MBH interactions, which not only provides the ”bookkeeping” needed to keep track of all the permutations, but also provides some analytical tools for calculating cross-sections, rates and branching ratios (e.g. [6]). There are three possible end results when an object (star, binary) is deflected into a nearly radial orbit that approaches the MBH: (1) it can be destroyed immediately (“infall”), (2) it can be destroyed after many orbital periods, if some form of orbital dissipation gradually shrinks the orbit (“inspiral”) [8, 9, 26], and (3)
it can be re-scattered after one or more cycles to a wide orbit that is safe from the MBH (“scattering”) [5]. Infall processes (e.g. tidal disruption) have been studied extensively by many authors [24, 18, 29, 15, 49], and estimates of the infall event rate, $\Gamma_{\text{infall}}$ can be obtained. Inspiral (e.g. by GW emission from compact remnants orbiting the MBH, or by tidal heating) has by comparison a much smaller rate, $\Gamma_{\text{inspiral}} \sim 0.01\Gamma_{\text{infall}}$, since the inspiraling star must avoid re-scattering, and therefore must start its journey much closer to the MBH where the orbital period is short. Scattering (e.g. tidal scattering) has a rate that is is almost equal to the infall rate, $\Gamma_{\text{scatter}} \sim \Gamma_{\text{infall}}$, because stars are easily deflected from a nearly radial orbit. In addition, interactions with binaries involve 3-body exchange scenarios, when an incoming single star interacts with a MBH-star “binary” [6], or when an incoming binary is tidally disrupted by the field of the MBH ([23, 41] and Perets et al, this volume). Such exchange interactions involve the capture of one star and the energetic ejection of the other.

4.2. Loss-cone theory
The rate of the various close interaction processes is determined by the efficiency at which objects are scattered to orbits that take them near the MBH. Phase space diffusion in angular momentum $J$ to low-$J$ orbits (“loss-cone” orbits) is much faster than diffusion in energy to tightly bound orbits. The refilling of the loss-cone proceeds in two regimes (Fig. 10). Close to the MBH, where the loss-cone is geometrically large and the orbital times are short, the change in $J$ per orbit is small relative to the size of the loss-cone $J_c$, and once a star is inside the loss-cone it is promptly destroyed so the loss-cone is empty. The loss-cone refilling process can therefore be viewed as diffusion across the loss-cone boundary, and it proceeds at a rate $d\Gamma/d \log r \sim N_e(<r)/\log(J_c(r)/J_c)\tau_r(r)$, where $J_c$ is the maximal (circular) angular momentum and $\tau_r$ is the relaxation time. Far from the MBH, where the loss-cone is geometrically small and
Figure 10. Schematic depiction of loss-cone refilling by 2-body scattering. Stars on orbits that intersect a small volume around the MBH (loss-cone orbits, $J < J_{\text{lc}}$) are destroyed. Tight orbits near the MBH have a large loss-cone and short orbital periods, so that the perturbation by scatterers lead to gradual diffusion into the loss-cone and the loss-cone is always empty. In contrast, wide orbits away from the MBH have a small loss-cone and long orbital periods, so that stars scatter across the loss-cone, which is always full.

4.3. Efficient loss-cone refilling

Two-body relaxation is a slow process, and it constitutes the bottleneck for the rates of close interactions with the MBH. Because of the interest in such processes, and their implications for a variety of open issues such as the feeding mechanisms of MBHs and their relation to the $M/\sigma$ relation [17, 20], or the stalling problem of MBH binaries (e.g. [35]), there have been various attempts to identify more efficient loss-cone refilling mechanisms. These broadly fall into three categories.

Non-spherical potentials The phase space structure of orbits in non-spherical potentials can repopulate the loss-cone even without relaxation. Triaxial potentials lead to chaotic orbits that go through the entire available phase space. Chaotic orbits dramatically enhance the close-interaction rates [34]. However, there are doubts whether triaxiality can be maintained very close to the MBH (e.g. [25]). Axisymmetric potentials lead to centrophilic orbits that preferentially populate the loss cone and can lead to a moderate increase in the tidal disruption rate [33].

Resonant relaxation Approximate symmetries in the potential (in particular the almost point mass potential very near the MBH) significantly slow down the evolution of the scatterers and introduce coherent torques on the scattered stars, which lead to $J$ changes that grow rapidly as $\Delta J \propto t$ rather than in the slow random walk fashion $\Delta J \propto \sqrt{t}$ of normal relaxation [44, 45]. Resonant relaxation may have implications for the observed dynamical structures in the GC [27, 31], as well as for the rates of GW emission events from compact remnants inspiraling into MBHs (see Hopman & Alexander, this volume).

Massive perturbers Galaxies contain sub-structures well above the stellar mass scale, such as giant molecular clouds, stellar clusters, and perhaps also intermediate mass BHs. Massive perturbers (MPs) can significantly shorten the relaxation time [53]. The observed MPs in

the orbital times are long, the change in $J$ per orbit is larger than $J_{\text{lc}}$ and the loss-cone is always full, and the rate is $d\Gamma/d\log r \sim \{M_*/[M_* + M_* N_*(< r)]\} [J_{\text{lc}}/J_{\text{c}}(r)]^2 N_*(< r)/P(r)$, where $P$ is the orbital time [41]. The maximal local contribution to the total rate is attained when the loss-cone is filled. However, the scale that contributes most for the total loss-cone refilling rate depends on the run of $N_*$, $J_{\text{c}}$, $t_*$, $P$ with $r$ and the size of $J_{\text{lc}}$. For 2-body stellar relaxation, which is the minimal assured relaxation process in any stellar system, and for the process of tidal disruption of single stars by the MBH, most of the contribution comes from roughly the radius of dynamical influence of the MBH, $r_h \sim 2–4$ pc. For the Galactic MBH, the tidal disruption rate is $10^{-5}–10^{-4}$ yr$^{-1}$ [9]. In contrast, inspiral processes such as GW by compact remnants involve only objects much closer to the MBH, inside few $\times 0.01$ pc [26] and therefore much lower rates, $10^{-9}–10^{-7}$ yr$^{-1}$ per galaxy [26, 28], depending on the degree of mass segregation.
the GC are indeed numerous enough to play a major role in accelerating loss-cone refilling, in particular for 3-body exchange processes, whose large loss-cone cannot be refilled by regular stellar 2-body relaxation. Relaxation by MPs may thereby explain the presence of the mysterious S-stars very near the MBH and the origin of the observed hyper-velocity stars (see Perets, Hopman & Alexander, this volume). MPs may also play an important role in accelerating the coalescence of merging MBH binaries [41].

5. Conclusion
The many different ways in which stars interact with a MBH and react to its presence reveal a wide and rich range of physical processes in the realms of stellar dynamics, General Relativity and gravitational wave physics, stellar structure, stellar evolution and the physics of compact remnants. The proximity of the Galactic MBH offers us the opportunity to study these processes in greater detail than will ever be possible in other galaxies. These processes have local, testable implications for the GC, as well implications on cosmological scales and for fundamental physics.

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