Captures of stars by a massive black hole: Investigations in numerical stellar dynamics.

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Abstract.
Among the astrophysical systems targeted by LISA, stars on relativistic orbits around massive black holes (MBHs) are particularly promising sources. Unfortunately, the prediction for the number and characteristics of such sources suffers from many uncertainties. Stellar dynamical Monte Carlo simulations of the evolution of galactic nucleus models allow more realistic estimates of these quantities. The computations presented here strongly suggest that the closest such extreme mass-ratio binary to be detected by LISA could be a low-mass MS star (MSS) orbiting the MBH at the center of our Milky Way. Only compact stars contribute to the expected detections from other galaxies because MSSs are disrupted by tidal forces too early.

INTRODUCTION
An object of stellar mass orbiting a MBH with a mass below $10^7 M_\odot$ would become an ideal source of gravitational waves (GW) for LISA in the last few years before plunge through the horizon, if compact enough to withstand the tidal forces. Such systems will be detectable to distances as large as a few hundreds Mpc. From the gravitational signal emitted by the stars as they spiral in, precise information about the mass and spin of MBHs can be obtained [1].

While considerable progress has been achieved in computing the orbit of a small body around and its GW signal [2, 3], our understanding of the other aspects of the problem are still far from satisfactory. At one end, astronomers will have to detect and measure the parameters of such sources by using signal–processing algorithms still to be devised. On the other end of the process, Nature has to create sources by sending stars onto relativistic orbits, through processes and with rates still debated [4]. The usual conservative approach –also applied here– is to assume that galactic nuclei are spherical and to rely on 2-body relaxation to bring stars onto “capture orbits”, for which, by definition, GW emission is the main agent of evolution.

SIMULATIONS
To simulate the relaxational stellar dynamics of spherical galactic nuclei, we rely on our Monte Carlo (MC) code which, besides captures, includes all the important physics: cluster self-gravity, 2-body relaxation, stellar collisions, tidal disruptions and stellar evolution [5, 6]. The specific advantage of the MC approach is that it treats the various
aspects of the stellar dynamics (collisions, mass-segregation. . . ) in a self-consistent way. Furthermore, the simulations do not only provide us with capture rates but with the distribution of stellar and orbital parameters of captured objects. Among the downsides are the important statistical noise due to the rarity of capture events and the need to use a number of particles much lower than the number of stars. Also, as the simulation proceeds, the structure of the cluster evolves, making it difficult to get “instantaneous” rates corresponding to a well defined nucleus model.

We concentrate here on a model set to represent the nucleus of the Milky Way [7], with a central BH of mass \(2.6 \times 10^6\ M_\odot\) and a total mass in stars of \(8.67 \times 10^7\ M_\odot\). A stellar population with a standard initial mass function and an age of 10 Gyrs is assumed. There is no initial mass segregation. Various simulations were carried out with \(2-6 \times 10^6\) particles. We refer to [8] for more details about these simulations.

In the MC runs, we detect captures by comparing the time scale for inspiral through GW emission, \(T_{GW}\) [9] to the time required by relaxation to induce a significant change of pericenter distance, \(T_{\text{mod}}\). If \(T_{GW} < T_{\text{mod}}\), the star is considered captured because, in most such cases, relaxation will not be able to move it to a safer orbit (for ideas to implement a more accurate criterion, see [10]).

We bracket the effects of tidal interactions between the MBH and MSSs by adopting either an optimistic or a pessimistic prescription (from the point of view of the severity of the decrease in the number of detectable Sgr A* GW sources). The (over-)optimistic scenario is to neglect all tidal interactions until the star enters the Roche zone, of radius \(R_R = R_*(2M_{\text{BH}}/M_*)^{1/3}\), at which point it is completely disrupted in one pericenter passage. In the (over-)pessimistic approach, one considers the cumulative energy transferred to the star by tides, \(E_{\text{tid}}\), assuming a parabolic orbit, an \(n = 1.5\) polytropic structure [11], complete conversion into heat and no radiation of this energy. The star is considered lost (as a source) when \(E_{\text{tid}}\) reached 20% of its self-binding energy.

RESULTS

The MC simulations yield capture rates for a MW-like galaxy of order \(2 \times 10^{-6}\) to \(10^{-5}\) yr\(^{-1}\) for MSSs, \(4 \times 10^{-7}\) to \(10^{-6}\) yr\(^{-1}\) for white dwarfs (WDs) and around \(5 \times 10^{-8}\) yr\(^{-1}\) for neutron stars\(^1\) (NSs) and stellar black holes (SBHs), with large statistical uncertainties for these rare species.

To investigate the detectability of a given capture event, we compute the GW-driven orbital evolution [3] and GW emission [12] and, for a choice of the distance to the source, \(D\), compare the GW amplitude with LISA sensitivity [13, 14]. Figures 1 and 2 illustrate this for a MSS and a SBH event, respectively. Applying such computations to all capture events during some time interval, one determines the expected number of captured stars around Sgr A* (\(D = 8\) kpc) that are emitting above any given LISA signal-to-noise ratio (\(S/N\)). The most striking results concern MS stars. The predicted number of sources with \(S/N \geq 10\) is of order 3-5 if one uses the optimistic treatment of tidal interactions,

\(^1\) Natal kicks were not included, so the NS rate is likely overestimated.
FIGURE 1. Capture of a low-mass MSS. The top panel shows the evolution of the orbital frequency (solid line, left ordinate axis) and eccentricity (dashes, right axis), as a function of the time left to reach the last stable orbit. We indicate the eccentricity, $e_0$, and pericenter distance, $R_0$ (in units of the Schwarzschild radius, $R_S = 2.5 \times 10^{-7}$ pc), when capture was detected during the MC simulation. On the lower panel, we plot the LISA signal-to-noise ratio for the 20 first harmonics, of frequencies $n \cdot f_{\text{orb}}$, of the quadrupolar component of gravitational radiation. The curves are labelled with their $n$ values. The mission was assumed to last only one year. The left ordinate axis corresponds to the Galactic center, the right axis to a galaxy at a distance of 100 Mpc. On the dotted segments, the pericentre distance is inside the Roche zone, so the MSS is certainly destroyed. On the dashed segments, the star may have already suffered from strong tidal damage, according to our pessimistic assumption (see text). Even considering only the solid segments, which are robust with respect to the effects of tides, one sees that this source would have a LISA S/N $\geq 10$ during of order 1–2 million years, if situated at the MW center. Note that only considering the 20 first harmonics leads to a slight underestimate of the time spent at S/N $\geq 1$. On the other hand, MS sources in distant galaxies clearly never reach detectable amplitudes.

and still of order $0.5 - 2$ with the pessimistic approach. Only MSSs with masses lower than $0.1 M_\odot$ are resilient enough to tidal forces to contribute. Their GW signal is too weak to be detected from extra-galactic nuclei. The probability for a Sgr A* WD source with S/N $\geq 10$ is $0.1 - 0.5$ and around 0.01 for NSs and SBHs.

ACKNOWLEDGMENTS

The routines to compute the orbital evolution around a MBH were kindly provided by Kostas Glampedakis. This work was initiated at Caltech, with a fellowship from the Swiss National Science Foundation and complementary support from NASA under grant
FIGURE 2. Similar to Figure 1 but for a SBH. If situated at the Galactic center (Sgr A*), the captured object would emit with $S/N \geq 10$ for a few $10^5$ yrs (up to $10^6$ yrs if higher harmonics are considered). Given a capture rate lower than $10^{-7}$ yr$^{-1}$, this is not long enough to ensure a good detection probability. On the other hand, due to the relatively high mass of a SBH, such an event can be seen to distances as large as a few hundreds of Mpc and will probably dominate extra-galactic detection rates.

NAG5-10707. The work of the author at the Astronomisches Rechen-Institut is funded in the framework of project SFB-439/A5 of the German Science Foundation (DFG). Financial support from NASA to attend this conference is acknowledged.

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