Decadal Survey White Paper: Probing Stellar Dynamics in Galactic Nuclei

Contributors: Tal Alexander, Pau Amaro-Seoane, Aaron Barth, Curt Cutler, Jonathan Gair, Clovis Hopman, David Merritt, Cole Miller, Sterl Phinney, Doug Richstone

Lead Author:
M. Coleman Miller
University of Maryland, Department of Astronomy
College Park, MD 20742-2421
(301) 405-1037
miller@astro.umd.edu

1 Introduction

This whitepaper is directed to the Galaxies Across Cosmic Time panel of the Decadal Survey. We have also submitted it to the Galactic Neighborhood panel, because the science discussed here is relevant to our Galactic center as well as to the properties and evolution of galaxies and their central supermassive black holes since a redshift of $z \sim 1$.

In the last $\sim 10-15$ years it has become progressively more evident that, far from being passive receptacles of matter in galactic centers, supermassive black holes have a key role in driving the evolution of galaxies and galaxy clusters. It is therefore important to conduct a variety of observations and theoretical simulations of galactic nuclear dynamics to evaluate the interactions between black holes and their environments. Here we demonstrate that detections of low-frequency gravitational radiation from inspirals of stellar-mass objects into supermassive black holes will open a unique window into stellar dynamics in galactic nuclei. Analysis of these inspirals will allow us to measure black hole masses and spins with unprecedented precision, and provide clues to the properties and interactions of the otherwise invisible stellar remnants expected in galactic nuclei. It will also complement work on nuclear dynamics, hyper-velocity stars, and other electromagnetic observations.

2 Properties and evolution of supermassive black holes

Supermassive black holes (SMBHs) accreting gas in galactic nuclei were first proposed in the 1960s [39, 46] to explain the enormous luminosities of the newly-discovered quasars. Dynamical measurements in the last decade and a half have verified Lynden-Bell's (1969) suggestion that SMBHs are present even in many quiescent, giant galaxies, and indeed for black hole masses $M_{\rm BH} \gtrsim 10^7\ M_\odot$ (bulge luminosity $\gtrsim 10^{10} L_\odot$) the SMBH mass is correlated with the velocity dispersion σ of the bulge via the $M-\sigma$ relation: $M_{\rm BH} \propto \sigma^{4-5}$ (e.g., [10]). This suggests that, at least for large SMBHs, black hole growth and galaxy evolution are tightly coupled.

Black hole mass measurements are, however, challenging, especially for lower-mass SMBHs. The primary source of black hole masses nearby is direct observations and modeling of motions of stars and gas orbiting the centers of galaxies coupled with dynamical models. These measurements are always limited by the spatial resolution of the observations, by degeneracy between the orbital distribution functions and BH mass, and by degeneracy between the mass of stars in the galactic center and the BH mass. These limitations are not likely to be greatly reduced in the next decade. With a few exceptions, the better measurements remain uncertain by a factor of two, and some are only good to a factor of ten. Methods such as reverberation mapping or those based on correlations between emission line width and mass are calibrated by the direct dynamical measurements and are thus even more uncertain. Indeed, even the number density of the galaxies that would host black holes in the $\sim 10^{5-7}\ M_\odot$ range is uncertain by at least an order of magnitude, and depends on the estimator used (e.g., [2, 15]).

In a parallel fashion, we understand the growth of large SMBHs because comparisons of the current mass density of SMBHs in the universe (dominated by masses around $10^8\ M_\odot$) with the integrated light from quasars (also dominated by central engines with $M_{\rm BH} \sim 10^8\ M_\odot$) imply that most of their mass has been acquired via radiatively efficient gas accretion [43, 25]. In contrast, we know comparatively little about how SMBHs grow to $M_{\rm BH} \sim 10^{5-7}\ M_\odot$ (a range that obviously includes the SMBH at the center of our own Milky Way, at $\sim 4 \times 10^6 M_\odot$). This could occur via gas accretion, as for more massive black holes. It could also occur by accretion of multiple stars coming in from random directions [17]; by mergers with stellar-mass black holes, neutron stars, or intermediate-mass black holes (IMBHs)[1] formed in star clusters [36, 35] (accretion of compact objects would not generate significant luminosity, and would thus evade the Eddington limit and possibly allow rapid early growth); or even by exotic mechanisms such as the accretion of dark matter [34] or direct production from collapse of supermassive stars [42]. Thus the early growth of all SMBHs, and the history of current lower-mass SMBHs, is an open question that has bearing on early structure formation and galaxy evolution.

Precision measurements of the masses of low-mass SMBHs are required to untangle their evolutionary processes. During the past few years, 8m-class telescopes with adaptive optics have been employed for a small but growing number of dynamical detections of SMBHs in very massive, bulge-dominated galaxies [20, 33]. However, current observational capabilities are not well suited to detection of lower-mass black holes in the nuclei of disk-dominated or dwarf galaxies, due to the smaller gravitational radius of influence of low-mass black holes, and as indicated above it is likely that future mass uncertainties using these methods will still be at least a factor of two even with the next generation of large ($\sim 25-30$m) ground-based telescopes. As an alternate method, as we discuss below detection of low-frequency gravitational waves from extreme mass ratio inspiral events (EMRIs) will determine the mass of the primary BH to a relative precision of about 10^{-4}, better than the best current measurements. Although small in number, these measurements have great potential: even though it will probably be rare that an EMRI is observed from near an SMBH whose mass has been estimated by electromagnetic methods, in a statistical sense the mass distribution obtained using EMRIs could expose unrecognized errors or improve the confidence in the current estimates, and they might point the way toward improvements in the current suite of techniques.

Spin measurements are also important because they allow us to distinguish between prograde gas accretion (which is expected to spin the SMBHs up to values of $a/M = cJ/GM^2 \gtrsim 0.9$; [5]), mergers with comparable-mass black holes (which characteristically yield $a/M \sim 0.7$ in many cases; [3]), and accretion of many masses with uncorrelated direction (e.g., stars or compact objects), which is expected to produce $a/M \ll 1$ [45]. It is currently possible in some cases to measure spin using X-ray observations of Fe Kα profiles [38], but these are uncommon and the typical uncertainties are significant: often

---

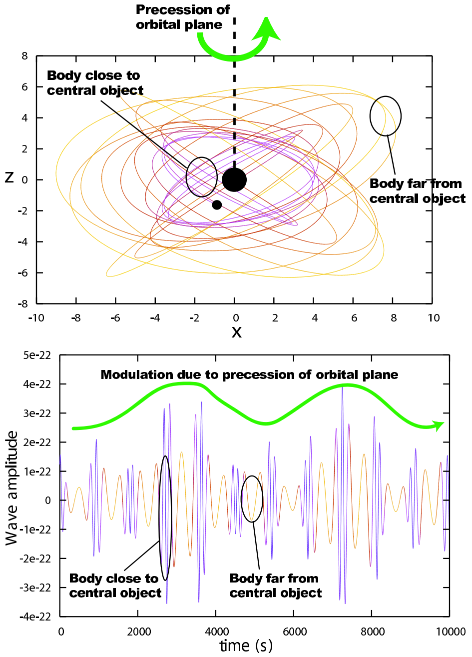
[1] Intermediate mass black holes are hypothetical black holes with masses in the range $10^2 M_\odot < M_\bullet < 10^4 M_\odot$. Currently the only evidence for their existence is indirect, in contrast to the direct dynamical evidence for stellar-mass and supermassive BHs.

$|\Delta(a/M)| \gtrsim 0.1$ unless the spins are near maximal [7]. There is also an active current discussion about the assumptions that underlie this method of spin determination (e.g., if emission can extend somewhat inside the innermost stable circular orbit, this would be interpreted as a spin greater than the actual one).

3 The Promise of Low-Frequency Gravitational Waves

In contrast to the electromagnetic methods described above, low-frequency space-based gravitational-wave detectors, which will focus on the band 10^{-4} Hz $< f < 10^{-1}$ Hz, are particularly sensitive to gravitational waves from SMBHs in the range $10^5 - 10^7 M_\odot$. Whereas main-sequence stars that are captured by such SMBHs are tidally disrupted before they pass through the SMBH's event horizon, stellar-mass compact objects (black holes, neutron stars, and white dwarfs) get swallowed whole. A reasonable fraction of such compact objects will slowly spiral into the SMBH (as opposed to be being swallowed directly, on the first "pass" by the SMBH). The slowly inspiraling compact objects will have gravitational wave frequencies of $f > 10^{-4}$ Hz years before they are ultimately swallowed, and will hence undergo $\sim 10^5$ orbits at these frequencies. These inspirals will be detectable to cosmological distances, with detection rates estimated at tens per year [12]. Of the three classes of compact object, BH inspirals are expected to dominate the detection rate, both because higher mass means greater GW amplitude (and hence a larger detection volume, out to $z \sim 1$) and because mass segregation concentrates the heaviest objects closest to the SMBH.

The highly relativistic orbits of EMRIs, lying within $\sim 5{-}10$ Schwarzschild radii of the SMBH, display extreme versions of both relativistic pericenter precession and Lense-Thirring precession of the orbital plane about the SMBH's spin axis (see Figure 1). The large number of cycles and complexity of the orbits encode wonderfully detailed information concerning the system's physical parameters. The mass of the compact object, the mass and spin of the SMBH, and the eccentricity of the orbit (at some fiducial instant–say 6 months before plunge), will typically all be determined to fractional accuracy $\sim 10^{-4}$. The orbit's inclination with respect to SMBH spin will be measured to $\Delta(\cos)\iota \sim 10^{-3} - 10^{-2}$ [4, 21]. Analysis of these orbits will also yield precise tests of the predictions of general relativity in strong gravity, in a way that is complementary to electromagnetic observations with proposed projects such as GRAVITY [9]. Any IMBHs captured by SMBHs would be observable out to very high redshift; e.g., $10^{2-3} M_\odot$ IMBHs spiraling into SMBHs with $M(1+z)$ in the range $3 \times 10^5 - 3 \times 10^6 M_\odot$ could be detected out to $z = 20$, with the IMBH mass typically determined to better than 1% (and significantly better than that for redshifts z less than a few). Such observations could produce the first definitive evidence of the existence of IMBHs. These precise measurements will be invaluable for studies of the many dynamical processes expected in galactic nuclei, which we now discuss.



Cartoon of an EMRI orbit, as viewed from the side (top panel) and emitted gravitational wave (bottom panel). The gravitational wave is characterized by higher amplitude and frequency radiation associated with extreme pericenter precession when the body is close to the central object, and lower amplitude and frequency radiation when the body is further away. There is an overall modulation due to precession of the orbital plane. The waveform is colored to illustrate this structure. (Taken from J Gair, Phil. Trans. Roy. Soc. A366, 4365 (2008)).

4 Galactic center dynamics and extreme mass ratio inspirals

4.1 Observations of the Galactic center

Extensive near-infrared and X-ray observations of the inner parsec of the Galactic center reveal a remarkably detailed and surprising picture. Components include a $4\times10^6 M_\odot$ black hole [14] embedded in an extended population of old, relaxed stars [40], an isotropic cluster of seemingly normal young hot stars within few $\times\, 0.01$ pc from the SMBH, very massive young stars orbiting coherently in a disk [23, 6] (possibly formed from a fragmenting accretion disk), and a few X-ray point sources [32].

The origin, evolution, and physical processes governing this system remain mysterious; e.g., the spin of the SMBH is completely unknown, and the population of dark compact objects around the SMBH is also unknown. Theory predicts that the central parsec harbors $O(10^4)$ stellar black holes (BHs) that sank there over the Galaxy's lifetime [30, 11, 19, 1], together with the stellar BHs that are believed to be produced locally by the unusual mode of massive star formation in a disk. This hypothesized cluster of black holes dominates the dynamics of the inner ~ 0.01 pc of the galaxy, and interacts with gas and stars there. For example, it likely drives rapid resonant relaxation [37]. The existence of such a cluster cannot yet be dynamically confirmed [31, 13]; in general, very little is known empirically about the birth and mass functions of stellar BHs. Given their important role for the dynamics of regions close to SMBHs, this represents a significant gap in our understanding of galactic nuclei. Conversely, the Galactic center, which harbors up to 10^{-3} of all Galactic stellar BHs in only $\sim 10^{-10}$ of the Galactic volume, provides a unique opportunity to study the properties of stellar BHs. In addition, the Galactic center may contain several intermediate-mass black holes [16, 35, 26].

4.2 How EMRI observations of other galaxies will probe galactic dynamics

The puzzles posed by the center of our Galaxy and others couple long-standing key questions in stellar dynamics, gas dynamics, star formation and stellar evolution. At the same time, these systems offer exciting prospects for significant progress because of the wealth of data available on complex structures strongly constrained by the extreme environment. In particular, the presence of so many stellar BHs in the vicinities of SMBHs in galactic centers makes it possible to uniquely combine the powers of high-precision electromagnetic observations with those of low-frequency gravitational radiation from EMRIs, which will place constraints on the stellar contents and dynamics.

Specific examples include:

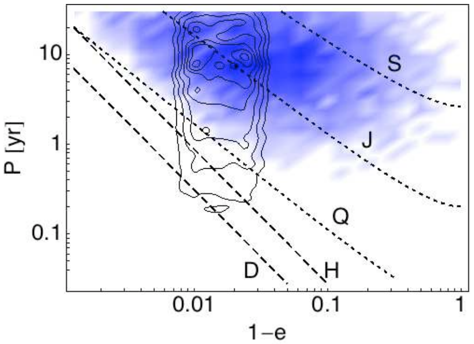
- Mass segregation will drive many stellar black holes towards the center. As a result, the rate at which EMRIs will be detected via gravitational waves is estimated to be roughly 10^{-7} per galaxy per year. For an instrument such as the Laser Interferometer Space Antenna (LISA), which will probe out to a redshift $z \sim 1$, the net detection rate is expected to be tens to hundreds per year [12]. The eccentricities and inclinations of EMRIs in the $f > 10^{-4}$ Hz gravitational wave band will be signatures of their origin through processes such as two-body scattering (for a recent review see [12]), tidal separation of binaries ([28]; see Figure 2), or settling of stellar-mass black holes via repeated interaction with an accretion disk [29, 22]. The effects of tidal separation may already have been seen, as this process is the leading candidate to explain the so-called hypervelocity stars observed escaping from our Galaxy (e.g., [8]). Combining gravitational wave and electromagnetic observations is key to understanding and interpreting stellar populations there.

- Discovery of EMRIs will provide unique information about the mass spectrum of stellar black holes in galactic nuclei, in particular their upper mass limit. This is key for understanding the formation of stellar BHs and their relation to their progenitors.

- Detection of EMRIs will also give the distribution of the SMBH spins for SMBHs of masses up to few$\times 10^6 M_\odot$ [4], and thus help to disentangle the formation history of SMBHs.

- The detection of the inspiral of an IMBH into a SMBH will give direct evidence for the existence of IMBHs [27], and identify a major dynamical component in galactic centers.

- EMRIs involving low-mass white dwarfs spiraling into SMBHs with $M \lesssim 10^5\ M_\odot$ may yield a strong and extended electromagnetic outburst due to the tidal destruction of the white dwarf and subsequent accretion of gas [41]. For more on this process, please read the white paper on tidal disruptions led by Suvi Gezari.



Simulations of binary disruption capture and subsequent orbital evolution of stars on highly relativistic orbits around the Galactic MBH (T. Alexander 2009, private communication).
The initial period and eccentricity (contour lines) evolve over 10 Myr due to relaxation, GW emission, tidal interactions and collisions with compact remnants. Of the 40% of stars that survive destruction (blue area) by tidal heating (H) or disruption (D) (dashed lines), many are found on tight eccentric orbits (below the plotted lines), where relativistic precession ($> 5\mu$as/yr) due to the Schwarzschild periapse shift (S), frame dragging (J), and the MBH quadrupole moment (Q) can be detected by high-precision IR interferometry and used to measure the MBH spin and test GR [44].

5 Summary

Observations of extreme mass ratio inspirals via low-frequency gravitational radiation will yield unprecedented precision in the measurements of the masses and spins of supermassive black holes, and of the masses of the stellar-mass objects that spiral into them. They may provide definitive evidence of the existence of intermediate-mass black holes, and the properties of EMRIs will allow us unique glimpses into stellar dynamics near SMBHs. As a result, especially when combined with future electromagnetic observations of galactic nuclei, low-frequency gravitational wave observations will play a key role in determining how black holes affect the evolution and environments of galaxies and the universe, and how galaxies and their evolution affect the population of black holes.

References

[1] Alexander, T., & Hopman, C. 2008, ArXiv e-prints (arXiv:0808.3150)
[2] Aller, M. C., & Richstone, D. 2002, ApJ, 124, 3035
[3] Baker, J., Campanelli, M., Lousto, C. O., & Takahashi, R. 2004, PRD, 69, 027505
[4] Barack, L., & Cutler, C. 2004, PRD, 69, 082005
[5] Bardeen, J. M. 1970, Nature, 226, 64
[6] Bartko, H., et al. 2008, ArXiv e-prints (arXiv:0811.3903)
[7] Brenneman, L. W. 2007, PhD thesis
[8] Brown, W. R. et al. 2009, ApJ, 690, 1639
[9] Eisenhauer, F. et al. 2008, 2008 SPIE proceedings, vol. 7013, p. 70132A
[10] Ferrarese, L., & Ford, H. 2005, Spa. Sci. Rev., 116, 523-624

[11] Freitag, M., Amaro-Seoane, P., & Kalogera, V. 2006, ApJ, 649, 91
[12] Gair, J. R. 2008, ArXiv e-prints (arXiv:0811.0188)
[13] Ghez, A. M., et al. 2008, in IAU Symposium, Vol. 248, 52–58
[14] Gillessen, S., et al. 2008, ArXiv e-prints (arXiv:0810.4674)
[15] Greene, J. E., & Ho, L. C. 2007, ApJ, 667, 131
[16] Hansen, B. M. S., & Milosavljević, M. 2003, ApJL, 593, L77
[17] Hills, J. G. 1975, Nature, 254, 295
[18] Hopman, C., & Alexander, T. 2005, ApJ, 629, 362
[19] —. 2006, ApJL, 645, L133
[20] Houghton, R. C. W., et al. 2006, MNRAS, 367, 2
[21] Huerta, E. A., & Gair, J. R. 2008, arXiv:0812.4208
[22] Levin, Y. 2007, MNRAS, 374, 515
[23] Levin, Y., & Beloborodov, A. M. 2003, ApJL, 590, L33
[24] Lynden-Bell, D. 1969, Nature, 223, 690
[25] Marconi, A., et al. 2004, MNRAS, 351, 169
[26] Merritt, D., Gualandris, A., & Mikkola, S. 2008, ArXiv e-prints (arXiv:0812.4517)
[27] Miller, M. C. 2005, ApJ, 618, 426
[28] Miller, M. C., Freitag, M., Hamilton, D. P., & Lauburg, V. M. 2005, ApJL, 631, L117
[29] Miralda-Escudé, J., & Kollmeier, J. A. 2005, ApJ, 619, 30
[30] Morris, M. 1993, ApJ, 408, 496
[31] Mouawad, N., et al. 2005, Astronomische Nachrichten, 326, 83
[32] Muno, M. P., et al. ApJL, 622, L113
[33] Nowak, N., et al. 2008, MNRAS, 391, 1629
[34] Ostriker, J. P. 2000, Physical Review Letters, 84, 5258
[35] Portegies Zwart, S. F., et al. 2006, ApJ, 641, 319
[36] Quinlan, G. D., & Shapiro, S. L. 1990, ApJ, 356, 483
[37] Rauch, K. P., & Ingalls, B. 1998, MNRAS, 299, 1231
[38] Reynolds, C. S., & Fabian, A. C. 2008, ApJ, 675, 1048
[39] Salpeter, E. E. 1964, ApJ, 140, 796
[40] Schödel, R., et al. 2007, A&A, 469, 125
[41] Sesana, A., et al. 2008, MNRAS, 391,718
[42] Shapiro, S. L., & Teukolsky, S. A. 1979, ApJL, 234, L177
[43] Sołtan, A. 1982, MNRAS, 200, 115
[44] Will, C. M. 2008, ApJ, 674, L25
[45] Young, P. J. 1977, ApJ, 212, 227
[46] Zeldovich, Ya., & Novikov, I. 1964, Dokl. Akad. Nauk. SSSR 158, 811