RAGtime 27

Workshops in Opava, 10 –14 November 2025

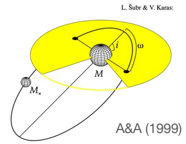
Stars and stellar systems near black holes

Vladimír Karas, Václav Pavlík & Petra Suková (Astronomical Institute, Prague)

Michal Zajaček (Masaryk University, Brno)

Abstract. The long-term evolution of the orbit of a satellite intermediate-mass black hole captured by a massive galactic nucleus has been examined. Repetitive transits across the accretion disk slab create a turbulent wake, where material is pushed out of the disk plane. In the embedded phase the orbit decays via continuous hydrodynamical interaction together with losses caused by the gravitational wave emission.

INTRODUCTION



We examine a model which contains:

- A massive galactic nucleus (a rotating black hole, $M \approx 10^8 M_\odot$)
- An accretion disc (an equatorial planar slab as the first approximation)
- Individual satellites (IMBH), or a cluster of satellites (the mass of each one $m \ll M$) within the innermost ≈1 pc around the nucleus.

We study individual transits and the long-term evolution of orbital parameters:

- local interaction between the satellite and the disk material
- gravity of the centre (Newtonian versus Kerr metric, dragging effects);
- gravity of the disc ($M_d \ll M$);
- effects of the radial density profile of the disc and mutual scattering of the satellites on their orbit (two-body relaxation).

THE ASTROPHYSICAL JOURNAL, 536:663–667, 2000 June 20

HYDRODYNAMIC DRAG ON A COMPACT STAR ORBITING A SUPERMASSIVE BLACK HOLE

RAMESH NARAYAN
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; rnarayan@cfa.harvard.edu
Received 1999 July 23; accepted 2000 February 1

ABSTRACT

The proposed Laser Interferometer Space Antenna is expected to detect gravitational waves from compact stars spiraling into supermassive black holes in distant galactic nuclei. Analysis of the inspiral events will require careful comparison of the observed signals with theoretical waveform templates. The comparison could be seriously compromised if nongravitational torques modify the orbit of the star. This paper estimates the torque exerted on an orbiting star as a result of hydrodynamic interactions with an accretion flow around the supermassive black hole. It is argued that the majority of inspiral events will take place in low-luminosity galactic nuclei in which the mass accretion rate is low and the accretion occurs via an advection-dominated flow. The hydrodynamic torque is negligibly small in such systems and will have no effect on gravitational wave experiments.

The timescale on which J changes as a result of gravitational wave emission is (e.g., Shapiro & Teukolsky 1983)

$$t_{gw} = \frac{J}{|dJ/dt|} = \frac{5}{32}\frac{c^5}{G^3}\frac{a^4}{M^2\mu} . \quad (11)$$

Let us express this in practical units. We write $a = 10 r_1 R_g$, and we define $P_2 = P/100$ s, where $P = \pi/\Omega$ is the period of the quadrupolar gravitational waves (this period is equal to one half the period of the orbit). Then

$$t_{gw} = 24 \frac{m_6^2 r_1^4}{m_1} \text{ yr} = 0.35 \frac{P_2^{8/3}}{m_1 m_6^{2/3}} \text{ yr} . \quad (12)$$

The time to merger is given by

$$t_m = \frac{t_{gw}}{8} = 3.0 \frac{m_6^2 r_1^4}{m_1} \text{ yr} = 0.044 \frac{P_2^{8/3}}{m_1 m_6^{2/3}} \text{ yr} . \quad (13)$$

Narayan, ApJ (2000)
Karas & Šubr, A&A (2001)
Chatterjee et al, J.Phys. (2022)

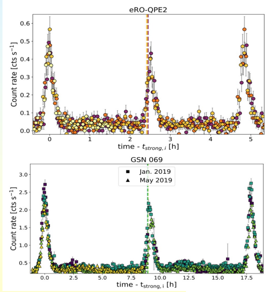
PHYSICAL REVIEW D **84,** 024032 (2011)

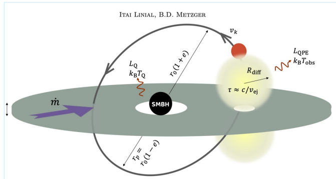
Observable signatures of extreme mass-ratio inspiral black hole binaries embedded in thin accretion disks

Bence Kocsis,[1] Nicolás Yunes,[2,1] and Abraham Loeb[1]
[1]*Harvard-Smithsonian Center for Astrophysics, Institute for Theory & Computation, 60 Garden Street, Cambridge, Massachusetts 02138, USA*
[2]*Department of Physics and MIT Kavli Institute, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA*
(Received 12 April 2011; published 19 July 2011; publisher error corrected 15 August 2012)

We examine the electromagnetic and gravitational wave (GW) signatures of stellar-mass compact objects (COs) spiraling into a supermassive black hole (extreme mass-ratio inspirals), embedded in a thin, radiation-pressure dominated, accretion disk. At large separations, the tidal effect of the secondary CO clears a gap. We derive the conditions necessary for gap opening in a radiation-pressure dominated disk and show that the gap refills during the late GW-driven phase of the inspiral, leading to a sudden electromagnetic brightening of the source. The accretion disk leaves an imprint on the GW through its angular momentum exchange with the binary, the mass increase of the binary members due to accretion, and its gravity. We compute the disk-modified GWs both in an analytical Newtonian approximation and in a numerical effective-one-body approach. We find that disk-induced migration provides the dominant perturbation to the inspiral, with weaker effects from the mass accretion onto the CO and hydrodynamic drag. Depending on whether a gap is present, the perturbation of the GW phase is between 10 and 1000 rad per year, detectable with the future Laser Interferometer Space Antenna at high significance. The perturbation is significant for disk models with an effective viscosity proportional to gas pressure but much less so if proportional to the total pressure. The Fourier transform of the disk-modified GW in the stationary phase approximation is sensitive to disk parameters with a frequency trend different from post-Newtonian vacuum corrections. Our results suggest that observations of extreme mass-ratio inspirals may place new sensitive constraints on the physics of accretion disks.

ASTROPHYSICAL MOTIVATIONS AND CONTEXT





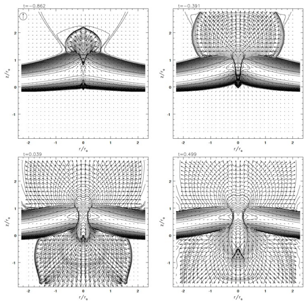
QPE: Quasi-periodic eruptions are recurring X-ray bursts originating in nuclei of low-mass galaxies.

Arcodia et al., A&A (2022)

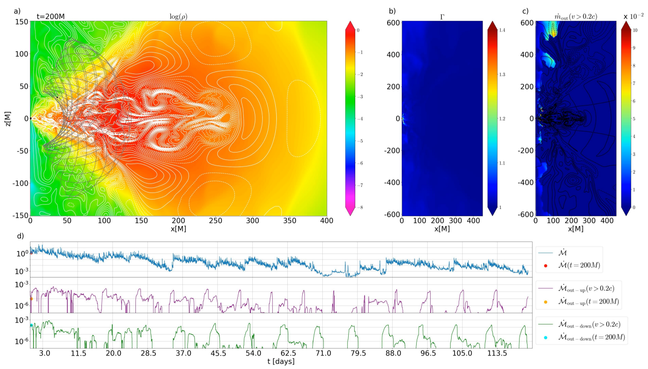
HYDRODYNAMICS OF SATELLITE-DISC COLLISIONS

Previously we assumed very simplified estimates for the drag acting on the satellite when it crosses the disc. Our assumptions enabled us to discuss processes like circularization of the orbit. We also showed how the orbit becomes inclined into the disc plane, quite independently of the details of satellite-disc collisions. Such knowledge is however necessary to study details of the temporal evolution.

Two-dimensional hydrodynamical simulations have been performed for the case of a black hole which crosses the disc perpendicularly [Ivanov et al]. It has been shown that such collision results in two-side outlows of gaseous material from the disc.



This figure captures four subsequent moments (time is indicated) of the collision. The black hole moves from top to bottom. Contours of equal density ρ are shown with a constant step in log ρ. The arrows represent fluid velocity. Formation of shocks and two oppositely directed fountains is visible.



Suková et al., ApJ (2021)

Improved gravitational radiation time-scales: significance for LISA and LIGO-Virgo sources

Lorenz Zwick,[1,2★] Pedro R. Capelo,[1] Elisa Bortolas,[1] Lucio Maver[1] and Pau Amaro-Seoane[3,4,5,6]

$$t_P R Q_f = \underbrace{\frac{5c^5(1+q)^2}{256G^3M^3q}\frac{a_0^4}{f(e_0)}}_{\text{Peters' formula}} \underbrace{8^{1-\sqrt{1-e_0}} \exp\left(\frac{2.5r_S}{a_0(1-e_0)}\right)}_{\text{eccentricity and PN correction}} .$$

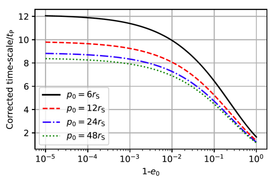
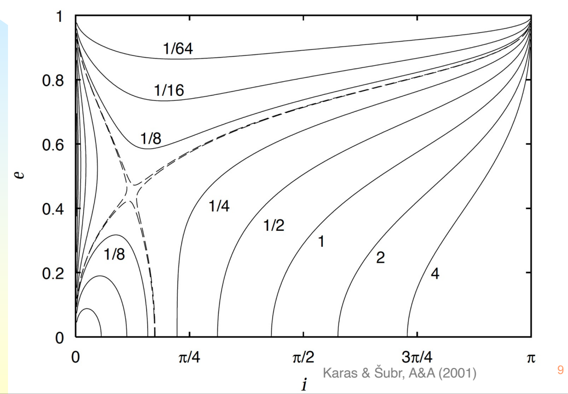


Figure 6. We show the combination of the correction factors R and Q_f as a function of initial eccentricity for different initial periapses. Even though the PN correction is only of fractional order by itself, it can compound with the eccentricity-correction factor for very eccentric orbits. GW sources such as EMRIs are expected to originate from precisely these regions of parameter space (high eccentricity and low periapsis). For such sources, using the corrected Peters' formula (equation 41) can resolve errors of up to one order of magnitude in the time-scale of GW-induced decay, without needing to resort to numerical integration.

qualitative result: *PN orbits decay more quickly than what Peters' formula predicts, when comparing binaries with identical initial energy and angular momentum.*

MNRAS **495,** 2321–2331 (2020)

RESULTS: ROLE OF HYDRO vs. GW EMISSION EFFECTS



Karas & Šubr, A&A (2001)