Accretion in strong gravity

689. WE-Heraeus-Seminar

4 – 8 February 2019
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Subject to alterations!

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 689. WE-Heraeus-Seminar:

The guiding theme of this seminar is the observation, the modelling and the theoretical description of accretion processes in systems where gravity is strong and nonlinear. Accreting matter are the objects which most closely approach compact objects like black holes or neutron stars and, therefore, are an ideal laboratory to explore the effects of strong gravity. Recently technological developments in observation techniques lead to a strongly improved accuracy in observing accretion discs and related phenomena. This trend will be continued in the next years, for instance with observations of ALMA and the James-Webb telescope, but also with survey telescopes like PanSTARRS or LSST. This development has to be paralleled by the theoretical description and modelling.

Basic open questions in accretion disc physics which will be discussed in this seminar include the description of viscosity and turbulence, in particular in the relativistic context, the effective equations of accretion, evolution of supermassive black holes, accretion discs in generalised theories of gravity, and GRMHD simulations. Summarized, the topics of this seminar are

- Observation of astrophysical accretion and related phenomena
- The basic equations of accretion and their structure
- Applications to accretion discs and the accretion process
- Numerical simulation of accretion in strong gravity

Scientific Organizers:

Dr. Eva Hackmann	Universität Bremen, ZARM, Bremen, Germany E-mail: eva.hackmann@zarm.uni-bremen.de
Prof. Dr. Wolfgang Duschl	Universität zu Kiel, Kiel, Germany E-mail: wjd@astrophysik.uni-kiel.de

Program

Program

Sunday, 3 February 2019

17:00 – 21:00	Registration	
from 18:30	*BUFFET SUPPER / Informal get together*	

Monday, 4 February 2019

07:30	*BREAKFAST*	
08:45 – 09:00	Eva Hackmann Wolfgang Duschl	**Opening and Welcome**
09:00 – 09:45	Marek Abramowicz	**Searching for Signals from Alien Civilizations**
09:45 – 10:30	Odele Straub	**Observational signatures of strong gravity in accretion discs**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Wolfgang Duschl	**Synthetic Surveys of Super-Massive Black Holes**
11:45 – 12:10	Debora Lančová	**Global GRRMHD simulation of thin accretion disk**
12:10	**Conference Photo** (in the foyer of the lecture hall)	
12:30	*LUNCH*	

Program

Monday, 4 February 2019

14:00 – 14:25	Roberto Oliveri	**Self-similar accretion in thin discs around near-extremal black holes**
14:25 – 14:50	Jiri Horak	**Accretion disks around relativistic radiating stars**
14:50 – 15:15	**Posterflash**	
15:15 – 15:30	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 18:00	**Postersession**	
18:30	*HERAEUS DINNER at the Physikzentrum (cold & warm buffet, free beverages)*	

Program

Tuesday, 5 February 2019

08:00	*BREAKFAST*	
09:00 – 09:45	Paul Romatschke	**Relativistic Hydrodynamics in Strong Gravity**
09:45 – 10:30	Domenico Giulini	**Generalised McVittie spacetime as a toy-model for the study of local mass/energy balances**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Volker Perlick	**Modelling jets with force-free electrodynamics**
11:45 – 12:10	Anabella Araudo	**Truncation of AGN jets by their interaction with stellar clusters**
12:10 – 12:35	Antonios Nathanail	**Plasmoid formation in relativistic jets (global GR-MHD simulations)**
12:35	*LUNCH*	
14:00 – 14:25	Baptiste Boutin-Basillais	**Non-relativistic m-body figures of equilibrium**
14:25 – 14:50	Banibrata Mukhopadhyay	**Power of magnetically arrested advective flows and dichotomy between blazar classes**
14:50 – 15:15	Cosimo Bambi	**Testing strong gravity using X-ray reflection spectroscopy**
15:15 – 15:45	*COFFEE BREAK*	
15:45 – 16:30	Vladimir Karas	**Regular and chaotic motion in strong gravity**
18:30	*DINNER*	

Program

Wednesday, 6 February 2019

08:00	*BREAKFAST*	
09:00 – 09:45	Johann Anton Zensus	**Imaging Event Horizon Scale Structure in Nearby Active Galactic Nuclei with mm-VLBI**
09:45 – 10:30	Andreas Eckart	**The central light-year of the Milky Way: How stars and gas live in a relativistic environment of a super-massive black hole**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Luciano Rezzolla	**On accretion flows on exotic compact objects**
12:00	*LUNCH*	
13:30	**Excursion**	
17:30 – 18:15	Axel Brandenburg	**Polarized gravitational waves from early universe hydromagnetic turbulence**
18:30 – 20:00	*DINNER*	

Program

Thursday, 7 February 2019

08:00	*BREAKFAST*	
09:00 – 09:45	Daniela Pugliese	**Accreting tori sequences: Ringed Accretion Disks**
09:45 – 10:30	Claus Lämmerzahl	**Accretion disks in axially symmetric space-times**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Oldrich Semerák	**Perturbation of a Schwarzschild black hole by a rotating thin disc**
11:45 – 12:30	Eva Hackmann	**Equilibrium configurations of charged fluids in strong gravity**
12:30	*LUNCH*	
14:00 – 14:25	Yosuke Mizuno	**Testing Theories of Gravity via Shadow Images of a Magnetized Accretion Flow onto a Black Hole**
14:25 – 14:50	Hector Raul Olivares Sanchez	**Telling black holes and boson stars apart using strong field images**
14:50 – 15:15	Matheus do Carmo Teodoro	**Simulations of accretion processes onto boson stars**
15:15 – 15:45	*COFFEE BREAK*	
15:45 – 16:30	Monika Moscibrodzka	**Towards Understanding Black Hole Accretion and Jet Launching**
16:30 – 16:55	Sergio Gimeno-Soler	**Magnetized accretion disks around Kerr black holes with scalar hair**
16:55 – 17:20	Alejandro Cruz-Osorio	**Non-linear evolution of magnetized-torus-BH: Comparison between magnetic field approaches**
18:30	*DINNER*	

Friday, 8 February 2019

08:00	*BREAKFAST*	
09:00 – 09:45	Jose Antonio Font	**Magnetised self-gravitating disks around black holes**
09:45 – 10:30	Tobias Illenseer	**Similarity solutions for self-gravitating accretion disks**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	John Hawley	**Tilted Disks Around Black Holes: Investigating the Alignment Mechanism**
11:45 – 12:30	Marcus Brüggen	**Signatures of accretion in the radio sky**
12:30 – 13:00	Eva Hackmann Wolfgang Duschl	**Poster awards and concluding remarks**
13:00	*LUNCH*	

End of the seminar and ***FAREWELL COFFEE*** / Departure

Please note that there will be no dinner at the Physikzentrum on Friday evening for participants leaving the next morning.

Posters

Posters

P01	Aroonkumar Beesham	**Accretion Discs in a BIon**
P02	Prasun Dhang	**A numerical study of MRI driven dynamo in radiatively inefficient accretion flows**
P03	Jannes Klee	**Numerical oversteepening in self-gravitating accretion disks**
P04	Sayantani Lahiri	**A toy model of viscous relativistic geometrically thick disk in Schwarzschild geometry**
P05	Tomas Ledvinka	**Properties of disk sources of the Kerr and Tomimatsu-Sato spacetimes**
P06	Sourabh Nampalliwar	**eXtreme gravity with X-rays: a study into the nature of compact objects using X-ray reflection spectroscopy**
P07	Ishika Palit	**Effects of adiabatic index on transonic solution of low angular momentum accretion flow**
P08	Bart Ripperda	**First-principle modelling of particle dynamics in black hole accretion disks**
P09	Kris Schroven	**The Role of Electric Charge in Relativistic Accretion**
P10	Audrey Trova	**Equilibrium of charged perfect fluid near black hole**
P11	Alexander Zakharov	**Constraints on parameters of alternative gravity theories with observations of the Galactic Center**
P12	Zahid Zakir	**Complete solution and visualization of the Oppenheimer-Snyder collapse**

Abstracts of Lectures

(in chronological order)

SEARCHING FOR SIGNALS FROM ALIEN CIVILIZATION

Marek Abramowicz

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If there exist advanced civilizations in the Milky Way, they must be aware of the unique position of the galactic centre: it hosts the massive black hole, closest to anyone in the Galaxy. We imagine that some may have placed material in an orbit around this black hole to study it, extract energy from it, or even for communication purposes. Its orbital motion will necessarily be a source of gravitational waves. We show that a Jupiter-mass on the innermost stable circular orbit can be sustained there for a few billion years by the energy output of a single star, and continuously emit gravitational waves that will be observable with LISA-type detectors anywhere in the Milky Way. Everyone who picks up this signal will unambiguously understand that the signal is of an artificial origin and that a very advanced technology is needed to keep it continuous.

Observational signatures of strong gravity in accretion discs

O. Straub[1]

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Conjured by the mathematics of general relativity black holes appear as singularities in the solutions of Einstein's field equation and depict regions of spacetime which are so compact that everything, even light gets trapped and can't escape. They are characterised by their event horizon, a unique boundary that causally separates the universe from the singularity in its interior and hinders their direct observation. Black holes are, however, far more than unobservable intellectual toys for theorists who like to use them to fathom the Universe. They exist in nature and, fortunately, they tend to attract, accelerate and accrete gas which in the process heats up and emits powerful radiation. Strong gravity of a black hole manifests itself in a range of peculiar radii, like the event horizon, the photon orbit, the ergosphere, and the innermost stable circular orbit. We can look for the unique signatures of these in the emitted light of accretion discs. Here, I discuss how observations reveal the presence of an innermost stable circular orbit and how we can use it to deduce the properties of a black hole.

Synthetic Surveys of Super-Massive Black Holes

W.J. Duschl[1,2], L. Bösch[1], and T. Breslein[1]

[1]Astrophysik Kiel im ITAP, Leibnizstr. 15, 24118 Kiel, Germany
[2]Steward Observatory, The University of Arizona, Tucson, AZ, USA

We present first results of simulations of a large number of (ultimately) super-massive black holes which are mainly growing due to accretion out of (originally) self-gravitating accretion disks which differ in their original parameters (mass, size, etc.) and the time at which the respective accretion process started. From the resulting luminosity-redshift distribution we ultimately want to solve the inverse problem and conclude on the parameter and age distributions of the disks.

Global GRRMHD simulation of thin accretion disk

D. Lančová[1]

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We simulated a geometrically thin and optically thick accretion disk which is stabilized by radial net flux of magnetic field, using global GRRMHD code Koral [1], [2]. The thin disk solution was published in [3] and we are extending the result presented there to reach even thinner stable disk with lower mass accretion rate, when the original disc is stable and relatively thin $\left({}^{h}/{}_{r} \sim 0.3\right)$ even for relatively high mass accretion rate $(\dot{M} \sim 0.8)$. The are studying basic properties of the accretion disk and comparing them to analytical solution and analyzing the stresses on the inner edge of the disc and the effective viscous parameter $\alpha_{eff}\,(r)$.

References

[1] A. Sądowski, Narayan, R., Tchekhovskoy, A., & Zhu, Y., Monthly Notices of the Royal Astronomical Society, **429**, 3533 (2013a)

[2] A. Sądowski, Narayan, R., McKinney, J. C., & Tchekhovskoy, A., Monthly Notices of the Royal Astronomical Society, **439**, 503, (2014b)

[3] A. Sądowski, Monthly Notices of the Royal Astronomical Society, **459**, 4367, (2016)

Self-similar accretion in thin discs around near-extremal black holes

G. Compère[1] **and R. Oliveri**[2]

[1]*Université Libre de Bruxelles, Belgium*
[2] *Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic*

Near-maximally spinning black holes display conformal symmetry in their near-horizon region, which is therefore the locus of critical phenomena. In this talk, we revisit the Novikov–Thorne accretion thin disc model and find a new self-similar radiation-dominated solution in the extremely high spin regime. Motivated by the self-consistency of the model, we require that matter flows at the sound speed at the innermost stable circular orbit (ISCO). We observe that, when the disc pressure is dominated by radiation at the ISCO, which occurs for the best-fitting Novikov–Thorne model of GRS 1915+105, the Shakura–Sunyaev viscosity parameter can be expressed in terms of the spin, mass accretion rate and radiative efficiency. We quantitatively describe how the exact thin disc solution approaches the self-similar solution in the vicinity of the ISCO and for increasing spins.

Talk mainly based on
Mon.Not.Roy.Astron.Soc. 468 (2017) no.4, 4351-4361

Accretion disks around relativistic radiating stars

J. Horak

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Thin accretion disks around radiating nonrotating relativistic stars are revisited. The attention is paid to both energetic and dynamical effects of the radiation on the disk structure. In addition to turbulent angular momentum transport, the radiation drag helps to remove the angular momentum from the matter and changes the structure of the disk.

Relativistic Hydrodynamics in Strong Gravity

Paul Romatschke

Department of Physics, University of Colorado, Boulder, Colorado 80309, USA

Hydrodynamics describes the slow dynamics of conserved quantities, such as energy density and momentum (such as encoded in the energy-momentum tensor). In the past decade or so, driven by experimental progress in high energy nuclear physics, a powerful first-principles derivation of hydrodynamics has emerged, which employs the framework of effective field theories instead of classical kinetic theory (see e.g. [1]). Similar to electromagnetism, where the dynamics of conserved charges goes hand-in-hand with the presence of electromagnetic fields, the dynamics of the energy-momentum tensor goes hand-in-hand with the presence of gravitational fields. Hence modern formulations of hydrodynamics are done in the presence of gravity, leading to "unconventional" curvature terms in the energy-momentum tensor that become important in the strong gravity regime. I will give a summary of these developments, recall what is known about these curvature terms, and point out potential observable consequences.

References

[1] P. Romatschke and U. Romatschke, *Relativistic Fluid Dynamics In and Out of Equilibrium – Ten Years of Progress in Theory and Numerical Simulations of Nuclear Collisions*, `arXiv:1712.05815`.

Generalised McVittie spacetime as a toy-model for the study of local mass/energy balances

D. Giulini

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and
Leibniz University of Hannover, Institute for Theoretical Physics, Riemann Center for Geometry and Physics, Appelstrasse 2, D-30167 Hannover, Germany

In this talk I will first present a generalisation of McVittie's solution based on Ref. [1] that describes a spherically symmetric black hole in a FLRW universe. The generalisation consists in allowing the cosmological dust-matter to radially fall into the hole. It turns our that the specific McVittie ansatz enforces the infall of matter to be accompanied by a radial outflow of heat of fixed relative magnitude. This motivates discussions of energy-balance and poses the question of how to separate the black-hole's energy from that of the ambient matter [2]. I show how this can be done in a rigorous geometric-analytic fashion in the spherically-symmetric case at hand.

References

[1] M. Carrera and D. Giulini, Phys. Rev. D. **81**, 043521 (2010)
[2] M. Carrera and D. Giulini, Rev. Mod. Phys. **82**, 169 (2010)

Modelling jets with force-free electrodynamics

V. Perlick

ZARM, University of Bremen, Germany

The powering of a jet and its interaction with an accretion disc in the vicinity of a black hole is a very complex phenomenon. It requires solving, on the background of a black-hole spacetime, the equations of Magnetohydrodynamics (MHD) which can usually be done only numerically. However, in cases where the matter of the jet and of the accretion disc can be modelled as a highly magnetised plasma, one may assume that the Lorentz force on the plasma matter vanishes. Under these idealised assumptions the dynamics of the matter decouples from the dynamics of the electromagnetic field and one is left with a comparatively simple system of equations for the electromagnetic field tensor alone. For these equations, which go under the name of "force-free electrodynamics", exact analytic solutions have been found on various black-hole spacetimes. In this talk I will give an overview on these solutions and I will discuss the question of whether or not they could give a valid -- albeit idealised -- model of jet powering.

Truncation of AGN jets by their interaction with stellar clusters

Anabella Araudo [1] **and Vladimir Karas** [1]

[1] *Astronomical Institute of the Czech Academy of Sciences, Prague, Czech Republic*

We study the effects of interaction of jets in Active Galactic Nuclei when they encounter stellar clusters surrounding the nucleus and passing across the inner jet. The interaction provides a scenario to address non–thermal processes and jet mass loading [1,2]. In jet–star interactions a double bow–shock structure is formed where particles get accelerated via diffusive mechanism [3,4]. Individual encounters have a limited effect [5,6], however, dense clusters of massive stars can truncate the jet as the cluster crosses the jet line near the jet launching region. Much of the jet kinetic energy density is transferred to the shock and it becomes available to accelerate particles. We conclude that the interaction of jets with clusters of massive stars is a promising way to explain detectable levels of gamma rays from Fanaroff–Riley class I of edge–brightened radio galaxies.

References

[1] S. Komissarov, MNRAS **269**, 394 (1994)
[2] A. Hubbard, E.G. Blackman, MNRAS **361**, 1717 (2006)
[3] A.T. Araudo, V. Bosch-Ramon, G.E. Romero, MNRAS **436**, 3626 (2013)
[4] S. Wykes, M. Hardcastle, A. Karakas, J. Vink, MNRAS **447**, 1001 (2015)
[5] W. Bednarek, P. Banasiński, ApJ **807**, 168 (2015)
[6] F.L. Vieyro, N. Torres-Alba, V. Bosch-Ramon, A&A **604**, 57 (2017)

Plasmoid formation in relativistic jets (in global GR-MHD simulations)

A. Nathanail

[1]*IInstitut für Theoretische Physik, Max-von-Laue-Strasse 1, 60438 Frankfurt, Germany*

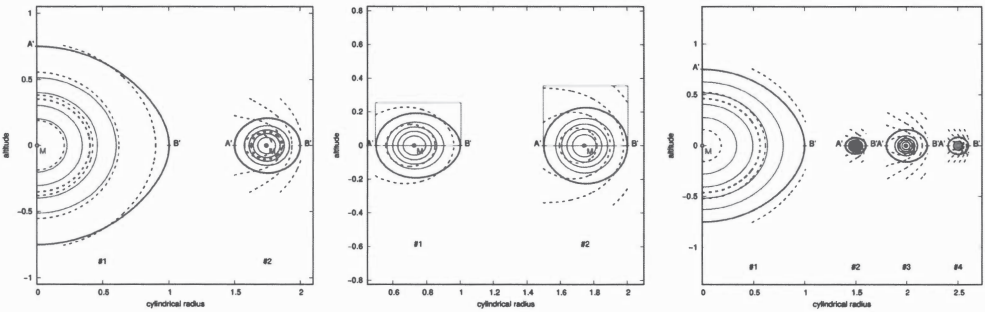
The Blobs, or quasi-spherical emission regions containing relativistic particles and magnetic fields, are often assumed in emission models of relativistic astrophysical jets. However their physical origin is still not yet well understood. We present the first global general-relativistic magnetohydrodynamic simulations that self-constistently follow reconnection layers during accretion onto a black hole. By initiating magnetic field configurations in the surrounding torus that we trigger magnetic reconnection in the vicinity if the black hole. During such events of reconnection quasi-spherical plasmoids filled with magnetic fields (and potentially with high-energy particles) are formed. Most of these magnetic plasmoids are unbobund upon their birth and propagate outwards. We follow their formation and their growth rate and we develop tools to track during their evolution. We point out that this is not a trivial thing to do and this developement is absolutely crucial to go to 3D simulations of such events where plasmoids are extremely difficult to track. We briefly discuss the implications of our results for the high-energy emission from relativistic jets.

Non-relativistic *m*-body figures of equilibrium

B. Boutin-Basillais[1] **and J.M. Huré**[1]

[1] *Laboratoire d'astrophysique de Bordeaux,Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, 33615 Pessac, France*

Multiple systems in mutual gravitational interaction are ubiquitous in the Universe. A particular motivation is to investigate the transitions from single-to-multiple bodies [1] which could apply in the environment of compact stars[2]. We present an efficient code that computes the non-relativistic equilibrium of self-gravitating *m*-fluids in differential rotation under axial symmetry. Each fluid (be an ellipsoid or a ring) is assumed to obey a polytropic equation-of-state. The equation set consists in the Poisson equation (solved with multigrid) coupled with Bernoulli-like equations linking the total gravitational potential, the centrifugal potential (to be prescribed) and the enthalpy field. For a set of polytropic indices and $2m - 1$ input geometrical parameters (axis ratios and relative orbital separations), the solution is captured with the Self-Consistent-Field method. The code has extensively been tested[3] for m=1 and we will present a survey of "ellipsoid+ring" configurations (ie m=2) in the incompressible hypothesis. We will show in particular how the solutions populate the ω^2-j^2-diagram[4] and their position relative to the Maclaurin and one-ring sequences. A few results obtained in the compressible case (see the figures) will be outlined.



▲ Examples of *m*-body configurations, with *m*=2 (*left and centre*) and *m*=4 (*right*).

References

[1] Ansorg, M. Kleinwächter, A. and Meinel, R., *MNRAS*, 2003, **339**, 515

[2] Pugliese, D. and Stuchlik, Z., *ApJS*, 2017, **229**, 20

[3] Huré, J.-M. and Hersant, F., *MNRAS*, 2017, **464**, 4761

[4] Hachisu, I., *ApJS*, 1986, **61**, 479

Power of magnetically arrested advective flows and dichotomy between blazar classes

Banibrata Mukhopadhyay

Department of Physics, Indian Institute of Science, Bangalore 560012

I will discuss how strong fields in an advective, possibly sub-Keplerian, accretion flow around a black hole could be. Such a flow further could power the system to explain luminosity. Our semi-analytical, 2.5-dimensional, two-temperature, disk-outflow coupled model is adequately able to explain a wide range of observed AGN classes. The proposed model further shows that classes of blazers can be explained with the variations of field strength and accretion rate. The talk is based on the work done by my group in last one decade or so, some of which are listed below.

References

[1] S. R. Rajesh, B. Mukhopadhyay, MNRAS **402**, 961 (2010)
[2] D. Bhattacharya, S. Ghosh, B. Mukhopadhyay, ApJ **713**, 105 (2010)
[3] B. Mukhopadhyay, D. Bhattacharya, P. Sreekumar, IJMPD **21**, 1250086 (2012)
[4] T. Mondal, B. Mukhopadhyay, MNRAS **476**, 2396 (2018)
[5] P. Dhang, P. Sharma, B. Mukhopadhyay, MNRAS **476**, 3310 (2018)
[6] T. Mondal, B. Mukhopadhyay, MNRAS **482**, L24 (2019)

Testing strong gravity using X-ray reflection spectroscopy

C. Bambi

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Einstein's theory of general relativity was proposed over 100 years ago and has successfully passed a large number of observational tests in the weak field regime. However, the strong field regime is largely unexplored, and there are many modified and alternative theories that have the same predictions as Einstein's gravity for weak fields and present deviations when gravity becomes strong. X-ray reflection spectroscopy is becoming a powerful tool for testing the strong gravity region around astrophysical black holes with electromagnetic radiation. In this talk, I will present some constraints from the analysis of X-ray data of the black holes in 1H0707-495 [1], Ark564 [2], and GS1354-645 [3].

References

[1] Z. Cao et al, PRL **120**, 051101 (2018)
[2] A. Tripathi et al, PRD **98**, 023018 (2018)
[3] Y. Xu et al, ApJ **865**, 134 (2018)

Regular and chaotic motion in strong gravity

Vladimír Karas

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We describe a mechanism for the acceleration of electrically charged matter from the black hole equatorial accretion disc into its corona. Particles are set on escaping trajectories and some of them attain relativistic velocity. The case of charged particles differs from charged dust grains, which are relevant further out from the black hole (above the sublimation radius), but the acceleration process operates in a similar manner. The chaotic dynamics controls the outflow and it enables the formation of near-horizon escape zones. We employ the technique of recurrence plots to characterize the onset of chaos in the outflowing medium. We show the location and the extent of the escape zones. The effects of black hole spin and the magnetic field strength on the formation of the escape zones and the onset of chaos is also examined.

We conclude that the effect of magnetic field triggers the chaos near the black hole. Chaotic trajectories escape from the equatorial disk, while the regular ones remain oscillating near the equatorial plane. This explains why the escape zone may only form close to the black hole, where the system is non-integrable.

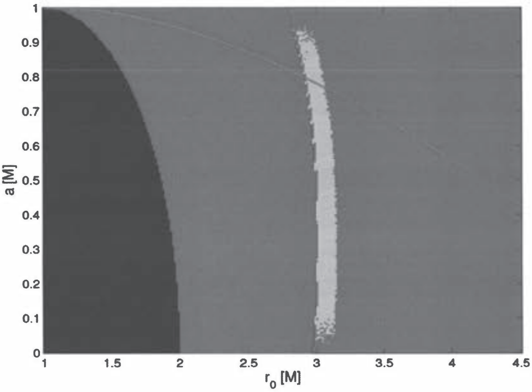

Figure 1. Behavior of charged particles escaping from stable circular orbits in the magnetized Kerr spacetime. Black color denotes the horizon region. Depending on the spin a and the initial radius r_0, the particles may fall directly onto the horizon (blue), remain oscillating in the equatorial plane (red) or escape along the symmetry axis (yellow). The innermost stable circular orbit (ISCO) is indicated by the green line.

References

[1] Karas V., Vokrouhlický D., "Chaotic motion of test particles in the Ernst space-time", General Relativity and Gravitation, 24 (1992), 729.

[2] Kopáček O., Karas V., "Inducing chaos by breaking axial symmetry in a black hole magnetosphere", The Astrophysical Journal, 787 (2014), 117.

[3] —, "Near-horizon structure of escape zones of electrically charged particles around weakly magnetized rotating black hole", The Astrophysical Journal, 853 (2018), 53.

Imaging Event Horizon Scale Structure in Nearby Active Galactic Nuclei with mm-VLBI

Johann Anton Zensus

Max-Planck-Institut für Radioastronomie Bonn, Germany

I will discuss the Event Horizon Telescope project, which is poised to deliver images from nearby active galactic nuclei on event horizon scales. Such observations (accompanyed by results obtained with the Global Millimeter VLBI Array) have been performed in earnest since 2017. The long-awaited first imaging results should become available later in 2019.

The central light-year of the Milky Way: How stars and gas live in a relativistic environment of a super-massive black hole

Andreas Eckart

I. Physikalisches Institut, University of Cologne
and
Max-Planck-Institute for Radio Astronomy, Bonn

The central region of our Milky Way is an extremely active region. It harbors the closest galactic nucleus that is accessible to us allowing us to study it in fine detail. Here we present most recent results obtained with state of the art instruments providing sensitive measurements at their highest angular resolution. The central star cluster harbors a small cusp of high velocity mostly young and dusty stars that are in orbit around the 4 million solar mass super massive black hole (SMBH) Sagittarius~A* (SgrA*). Molecular and atomic gas is streaming towards this region in the form of a spiral connecting it to the Circum Nuclear Ring. Using the Large Atacama Millimeter Array (ALMA) we investigated the kinematics and composition of this material in detail highlighting signatures of star formation and the interaction with a wind emerging form the direction of SgrA*. Using results from the Very Large Telescope (VLT) we will highlight the dynamics of the ultra-fast stars and present theories on their origin. We demonstrate that one of the innermost stars shows clear signs of relativistic motion in the deep potential well of the SMBH.

The interaction of plasma with SgrA* reveals that matter is orbiting and is being accreted onto the SMBH to produce powerful flares. These are detectable all across the electromagnetic spectrum and help us to understand the region close to the event horizon of SgrA* which is currently under investigation using the Event Horizon Telescope (EHT).

References

[1] Mossoux, E., Eckart, A., 2018, MNRAS 474, 3787
[2] Gravity Collaboration, et al, 2018, A&A 618, L10
[3] Gravity Collaboration, et al., 2018, A&A 615, L15
[4] Parsa, M., Eckart, A., et al., 2017, ApJ 845, 22
[5] Karssen, G. D.; et al., et al., 2017, MNRAS 472, 4422
[6] Moser, L., et al., 2017, A&A 603, 68

On accretion flows on exotic compact objects

L. Rezzolla

Institute for Theoretical Physics, Frankfurt am Main, Germany

Numerical simulations of magnetised accretion flows have long since been thought to be the ideal tool to understand the properties of matter in strong gravitational fields and to explain the phenomenology of accreting supermassive and stellar-mass black holes. I will review the recent progress made in modeling these flows not only onto rotating black holes in general relativity, but also on other more exotic compact objects. These comprise black holes in alternative theories of gravity, but also horizonless compact objects with and without a surface.

Polarized gravitational waves from early universe hydromagnetic turbulence

A. Brandenburg[123], **T. Kahniashvili**[34], **A. Kosowsky**[5], **S. Mandal**[3], **A. R. Pol**[2]
[1]Nordita, KTH Royal Institute of Technology and Stockholm University, Sweden
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In the early universe, primordial magnetic fields might have had energy densities that are a sizable fraction of the radiation energy density [1] and are needed to explain the lower limits on intergalactic magnetic field strengths today [2]. The resulting Maxwell stress would constitute a significant source of gravitational waves (GWs) [3, 4]. GWs can also be produced during inflation [5] and by bubble collision during the electroweak phase transition (EWPT) [6, 7]. The detection and spectro-polarimetric analysis of GWs with future space interferometers such as the Laser Interferometer Space Antenna (LISA) would allow physical insights into the very earliest moments of the universe [8]. We present the results of a novel approach to calculating these waves from direct numerical simulations (DNS) of early universe turbulent magnetic fields. This allows for the first time accurate modeling of turbulence-generated GWs compared to earlier analytic approximations. We show that early universe hydromagnetic turbulence with energy densities of up to 10% of the radiation energy density, can produce gravitational waves (GWs) with energy densities of about 10^{-10} times the critical energy density of the Friedmann universe today. Their characteristic strain today is about 10^{-20} and should be observable with the Laser Interferometer Space Antenna (LISA) in the mHz range. The GWs have positive (negative) circular polarization if the magnetic field has positive (negative) magnetic helicity. The GW energy reaches a constant value after the turbulent energy (kinetic or magnetic) has reached its maximum. Compressive modes are found to produce about 10 times stronger GWs than solenoidal ones. After a fraction of the Hubble time, a new shallow low frequency tail develops, which is not an artifact of a finite domain size.

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Accreting tori sequences: Ringed Accretion Disks

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Galactic cores and active galactic nuclei (**AGNs**) provide a rich scenario to observe super-massive black holes (**SMBHs**) interacting with their galactic environments. Chaotical, discontinuous accretion episodes may leave traces in the form of matter remnants orbiting the central attractor and produce sequences of orbiting toroidal structures with strongly different features as, for example, different rotation orientations with respect to the central Kerr **BH** where corotating and counterrotating accretion stages can be mixed. Motivated by these facts, ringed accretion disks (**RADs**) model structured toroidal disks which may be formed during several accretion regimes occurred in the lifetime of non-isolated Kerr **BHs**. First introduced in **[1]** and then detailed in **[2-8]**, **RAD** features a system made up by several axis-symmetrical matter configurations orbiting in the equatorial plane of a single central Kerr **SMBH**. Both corotating and counterrotating tori are constituents of the ringed disk. The number of the instability points is generally limited to n=2 and depends on the dimensionless spin of the rotating attractor. The model strongly binds the fluid and **BH** characteristics providing indications on the situations where to search for **RADs** observational evidences. Obscuring and screening tori, possibly evident as traces (screening) in x-ray spectrum emission, are also strongly constrained. The phenomenology associated with these toroidal complex structures may be indeed very wide, this complex scenario can enable to re-interpret the phenomena analyzed so far in the single-torus framework. More generally, observational evidence is expected by the spectral features of **AGNs** X-ray emission shape, due to X-ray obscuration and absorption by one of the tori, providing a **RAD** fingerprint as a radially stratified emission profile.

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Accretion disks in axially symmetric space-times

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For axially symmetric space-times we present the general analytic theory of thick accretion disks (Polish doughnuts) based on an ideal fluid which also can be charged. Based on that, accretion disks can be constructed and can be characterized in terms of an effective gravitational potential, shape, mass density and pressure. The results are used to estimate the effects of various neutral and charged Black Hole space-times on the accretion disks. First steps in order to extend this approach to a viscous fluid are presented.

Perturbation of a Schwarzschild black hole by a rotating thin disc

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Motivated by disc accretion on black holes and trying to incorporate, analytically, the effect of rotation, we consider a linear (first-order) perturbation of the Schwarzschild black hole due to a slowly rotating concentric finite thin disc. Inspired by Will [1] who calculated a perturbation due to an infinitesimally thin ring, we express in closed form the Green functions (for metric functions representing gravitational potential and rotational dragging), given in his paper as series in orthogonal polynomials. The closed form uses elliptic integrals and is more practical for numerical evaluation, but mainly for studying extended sources when the Green functions have to be integrated over the source volume. We illustrate the method on linear perturbation due to a simple thin disc existing between two finite radii and having constant Newtonian density.

After finding the two crucial metric functions, we calculate mass and angular momentum of the system and check its other properties, namely those which reveal how the disc gravity influences geometry of the black-hole horizon and those of circular equatorial geodesics (specifically, radii of the photon, marginally bound and marginally stable orbits). We also confirm that, in the linear order, no ergosphere occurs and the central singularity remains point-like. Finally, we consider what the usual physical requirements (energy conditions and subluminal restriction on orbital speed) imply for a single-stream as well as counter-rotating double-stream interpretations of the disc.

A more thorough introduction and details are given in our papers [2,3].

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Equilibrium configurations of charged fluids in strong gravity

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The strong gravity regime close to black holes and neutron stars provides an excellent laboratory to explore our understanding of General Relativity and its possible limitations. Accretion disks probe deep into this strong gravity regime, reaching up to horizon scales. For supercritical accretion rates the disk is believed to be geometrically thick close to the compact object. A simple analytical model of such geometrically thick configurations are fluid tori in hydrostatic equilibrium, also called polish doughnuts. Here we discuss a generalisation of this classical model to charged fluids interacting with electromagnetic test fields, which may be external, like the galactic magnetic field, or internally connected to the central compact object. After introducing a general construction method we will discuss specific examples, which give rise to new features of the fluid configurations and highlight the influence of charge.

Testing Theories of Gravity via Shadow Images of a Magnetized Accretion Flow onto a Black Hole

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Upcoming sub-millimeter Very Long Baseline Interferometry (VLBI) images of Sgr A* and M87 carried out by the Event Horizon Telescope Collaboration (EHT) are expected to provide critical evidence for the existence of this supermassive black hole. In this work we assess our present ability to use EHT images to determine if they correspond to a Kerr black hole as predicted by Einstein's theory of general relativity or to a black hole in alternative theories of gravity. To this end, we perform GRMHD simulations and use GRRT calculations to generate synthetic shadow images of a magnetized accretion flow onto a Kerr black hole and a non-rotating dilaton BH, which we take as a representative solution of an alternative theory of gravity. Taking into account the VLBI configuration of the 2017 EHT observation, we find that it could be difficult to distinguish between black holes from different theories of gravity, unless additional information were available.

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Telling black holes and boson stars apart using strong field images

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High-resolution radio-astronomical observations of the supermassive black-hole candidates Sgr A* and M87 will soon offer the possibility to test different models for these compact objects. Studies based on semi-analytic models and strong-field images of stationary plasma configurations around boson stars have stressed the difficulty to distinguish them from black holes. We here report on general-relativistic magnetohydrodynamic simulations of accretion onto a nonrotating boson star and employ general-relativistic radiative-transfer calculations to revisit the appearance of an accreting boson star. We find that the absence of an event horizon in a boson star leads to important differences in the dynamics of the accretion and results in both the formation of a small torus in the interior of the boson star and in the absence of an evacuated highly magnetized funnel in the polar regions. Synthetic reconstructed images considering realistic astronomical observing conditions show that differences in the appearance of the two compact object can be large enough to be detectable. These results, which also apply to other horizonless compact objects, strengthen confidence in the ability to determine the presence of an event horizon via radio observations and highlight the importance of self-consistent multidimensional simulations in the study of supermassive compact objects.

Simulations of accretion processes onto boson stars.

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Solutions of the Einstein's equations when coupled with a complex scalar field, compact Boson Stars (BS), if existent, would present no hard surface nor event horizon. Therefore, they provide a compelling scenario for astrophysical phenomena such as accretion flows, for which simulations play a crucial role in gaining a deeper understanding due to its rather rich complexities. The study of accretion processes can, for instance, reveal the presence of instabilities on analytical models, hint the origins of viscous momentum transport and predict the spectrum of emission of astrophysical sources. Indeed, through simulations, accretion onto BS have been shown to have different features from those onto black holes, for its peculiar effective gravitational potential gives rise to interesting structures regarding accretion dynamics [1,2,3]. Although intriguing, the BS in these previously reported simulations were mainly limited to ultra compact solutions that qualify them as black hole mimickers. Thus, we revisit the problem in our project, with a broader approach regarding the parameters of the BS (e.g. core density and and rotational quantum integer *k*). As preliminary tests we investigate the disruption of clouds near mini BS with various masses, simulating the evolution of ideal magnetohydrodynamics on a 2D grid. Furthermore we aim to do the same with rotating BS and implement different initial conditions to investigate the formation of discs and the final configurations of the plasma in the vicinity of such compact objects. The simulations are being accomplished using the Black Hole Accretion Code (BHAC) [4]. Although our project is in a preliminary stage we are looking forward to discuss our early results.

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Towards Understanding Black Hole Accretion and Jet Launching

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One and three millimeter Very Long Baseline Interferometry experiments are constructing the first ever images of the event horizon and the plasma flow in the immediate vicinity of the supermassive black holes at the centers of Milky Way and M87 galaxies. Hence, a detailed theoretical understanding of black hole astrophysics is now very crucial and timely to interpret these observations. In particular, high performance numerical simulations give us insight into how these black hole inflows and outflows work and look like. In this talk, I will present recent general relativistic magnetohydrodynamics simulations of black hole accretion flows with jets. My focus will be on modeling polarimetric properties of light produced in synchrotron processes in very strong gravitational field near the black hole event horizon. This polarized component of light gives us insights into the magnetic field geometry and dynamics at the event horizon, which are important keys to understand the jet launching process.

Magnetized accretion disks around Kerr black holes with scalar hair

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Testing the true nature of black holes – the no-hair hypothesis – will become increasingly more precise in the next few years as new observational data is collected in both the gravitational wave channel and the electromagnetic channel. In this work we consider numerically generated space- times of Kerr black holes with synchronised scalar hair and build stationary models of magnetized thick disks (or tori) around them. Our approach assumes that the disks are not self-gravitating, they obey a polytropic equation of state, the distribution of their specific angular momentum is constant, and they are marginally stable, i.e. the disks completely fill their Roche lobe. Moreover, contrary to existing approaches in the literature, our models are thermodinamically relativist, as the specific enthalpy of the fluid can adopt values significantly larger than unity. We study the dependence of the morphology and properties of the accretion tori on the type of black hole considered, from purely Kerr black holes with varying degrees of spin parameter, namely from a Schwarzschild black hole to a nearly extremal Kerr case, to Kerr black holes with scalar hair with different ADM mass and horizon angular velocity. Comparisons between the disk properties for both types of black holes are presented. The sequences of magnetized, equilibrium disks models discussed in this study can be used as initial data for numerical relativity codes to investigate their dynamical (non-linear) stability and used in tandem with ray-tracing codes to obtain synthetic images of black holes (i.e. shadows) in astrophysically relevant situations where the light source is provided by an emitting accretion disk.

Non-linear evolution of magnetized-torus-BH: Comparison between magnetic field approaches

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The magnetized tori-black hole system is the most studied scenario in relativistic astrophysics since is widely accepted as a result from binary neutron star merger. This astrophysical scenario is accepted as a possible engine to generate high energy events as jet propagation, gamma-ray, and X-ray emissions. There are very well known analytic solutions for a pure hydrodynamics (Abramowicz et al 1978, Daigne & Font 2004). Furthermore, the magnetized disc has been constructed by Komissarov 2006 with a toroidal magnetic field, however, this is not a unique solution.
In this talk, we will present and discuss a different way to construct the initial data and evolution of a magnetized tori around a black hole with high spin, a=0.99. We use three different prescriptions to construct a thick disc, in the first achieve we take a pure hydro solution a seed a toroidal magnetic field, the second recipe is using the Komissarov solution and the last one is a modified version of Komissarov solution recently presented in Gimeno-Soler et al 2018, where a generalized equation of state for fluid pressure is assuming a relativistic fluid. We will show the initial profiles of the disc exploring the magnetization parameter. And the resulting morphology after 100 orbital period's evolution, accretion rates and angular momentum distribution.

Magnetised self-gravitating disks around black holes

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Geometrically thick disks formed following the gravitational collapse of massive stars or the merger of compact binaries may reach high-enough masses to make necessary to account for their self-gravity for a correct description of their equilibrium structure and dynamics. This talk discusses a numerical procedure to build equilibrium sequences of self-gravitating and magnetised, stationary disks around rotating black holes within the so-called puncture framework. The Einstein equations for a self-gravitating, magnetized matter source are integrated numerically using an iterative procedure and assuming a stationary and axisymmetric spacetime.

Similarity solutions for self-gravitating accretion disks

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It is a widely accepted paradigm that almost any large galaxy hosts a supermassive black hole in its center. Recent observations of high redshift Quasars indicate that – at least some, but maybe much more of these – supermassive black holes already exist in the early universe at about 1 Gyr after the big bang [3]. On the other hand there is no observational evidence for massive primordial black holes [4]. Thus a fundamental question is, how do the supermassive black holes grow within such a short period. Currently there are three major theories which try to explain supermassive black hole growth: (i) direct collapse [5], (ii) black hole merger [6], and (iii) accretion disks [7].
In the first part of the talk I will shortly review the basic concepts and introduce the classical non-relativistic 1+1D model for geometrically thin disks and discuss some known analytical solutions and their limitations. These models are extended to account for self-gravity using the monopole approximation which leads to a self-consistent treatment of black hole growth [1,2]. The proposed non-linear advection-diffusion equation is invariant with respect to a one parameter Lie group of scaling transformations. This admits the construction of time-dependent self-similar solutions. The surface density and angular velocity of the disk derived from these similarity solutions show approximately a broken power law dependency on radial distance to the center. The fundamental parameter of the model is the power law exponent of the angular velocity distribution at large radii. It is shown that accretion disks with flatter rotation laws yield higher accretion rates which may even increase with time. Thus fully self-gravitating disks are found to evolve faster than nearly Keplerian disks. I will finally comment on the effects of different viscosity prescriptions on self-similar accretion disk models.

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Tilted Disks Around Black Holes: Investigating the Alignment Mechanism

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When matter orbits around a black hole obliquely with respect to the hole's spin axis, a relativistic torque causes the orbits to precess at a rate declining sharply with radius. Astrophysicists have long expected that in an orbiting accretion disk, the orbital angular momentum at small radii should align with the mass's spin. The location of the alignment front should be determined by a balance between the torque, the resulting differential precession, and warp-induced inward mixing of misaligned angular momentum from the outer to the inner disk. We are investigating the physics of this process through MHD and hydrodynamic simulations of mis-aligned disks. Our approach has been to use a semi-Newtonian method, in which the only relativistic effect retained is the lowest-order post-Newtonian term describing the torque. Through this approach, we have demonstrated a sound-speed dependence on the location of the alignment front, and the relative independence of the process from degree of black hole tilt. We also consider the effects of black hole tilt on accretion disk alignment, studying three initial black hole tilts, 6, 12, and 24 degrees. In a number of ways, but not all, the dynamics are homologous in the sense that the alignment fronts resulting from different initial tilts are very similar when analyzed in terms of the fraction of the initial tilt angle. Even when the initial misalignment is 24 degrees, which, for the sound speed studied, is 4 vertical scale heights at the disk fiducial radius, the surface density remains a smooth function of radius; i.e., we find no examples in which the disk inner aligned and outer misaligned regions separate, or ``break".

Abstracts of Posters

(in alphabetical order)

Accretion Disks in a Blon

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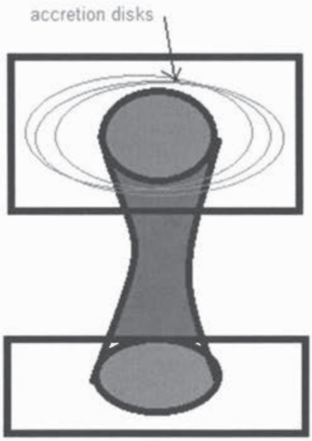
In this research, we will show that most accretion disks emerge around Blons. Blons [1] are systems which are constructed from two branes which are connected by a wormhole. In one end of the Blon, gravity leads to the emergence of disks that go towards the center. In the other end of the Blon, anti-gravity leads to the emergence of disks that go away from the center. This is because particles are absorbed from one end, go through the wormhole, emerge and are then repelled by the other end.



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A numerical study of MRI driven dynamo in radiatively inefficient accretion flows

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The most successful model of accretion disc proposed by Shakura and Sunyaev (1973) assume that an emergent turbulent viscosity is responsible for the outward angular momentum transport. However, a convincing source of turbulence was unknown until Balbus and Hawley (1991) drew attention to a weak field instability, namely, magneto-rotational instability (MRI). While linear MRI guarantees outward angular momentum transport, its study in the non-linear regime is essential to explain observed luminosity, time variability, jets etc. We study of MRI driven turbulence in geometrically thick ($H/R \sim 0.5$) radiatively inefficient accretion flows (RIAFs) using 3D global ideal MHD simulations and a pseudo-Newtonian gravity. In saturation, we observe dynamo-generated large-scale magnetic fields, a necessary component to produce jets. The dynamo cycles observed in the geometrically thick RIAFs are intermittent (see Fig. 1), unlike the very regular cycles seen in the global thin disc ($H/R \ll 1$) simulations. The irregularity is due to the sub-Keplerian nature of the angular velocity (for which the shear parameter $q = 1.7$). We find signatures of two kinds of dynamos– one is the direct dynamo close to the mid-plane, and another being a Parker-type dynamo away from the mid-plane. Away from the mid-plane, the back reaction of the Lorentz force plays an important role in causing the suppression of kinetic helicity by the magnetic helicity of a similar magnitude. The effects of dynamical quenching are shown explicitly for the first time in global simulations of accretion flows.

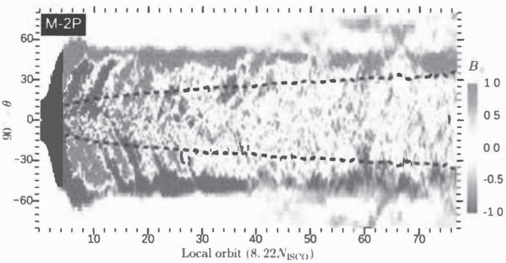

Fig.1 *Butterfly diagram: Spatio (latitude)-temporal variation of mean toroidal magnetic field at a radius r=20. Time is expressed in units of local orbit at that radius.*

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Numerical oversteepening in self-gravitating accretion disks

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Self-gravitating accretion disks with rapid cooling show fragmentation within the gas. In simulations of these disks non-convergence is a known problem. It leads to clumps in disks that cool slower, while moving to ever higher resolutions. Both, physical and numerical explanations exist in order to explain this behavior.

We show that the numerical setup has a strong and resolution-dependent impact on fragmentation in these disks [1]. Small errors that are induced by shock-capturing mechanisms in shallow regions are scaled up by self-gravity. Assigning the latter to a well-known effect called oversteeping yields a coherent picture of these conditions. Starting from deviations in linear theory, we show that our predictions hold even in the non-linear regime.

Finally, we present more recent simulations at highest resolutions, which fit into the previous results. Here, careful treatment of the initial conditions need to be taken into account in order to yield meaningful results.

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A toy model of viscous relativistic geometrically thick disk in Schwarzschild geometry

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In this work we study relativistic geometrically thick accretion disks, commonly known as Polish doughnuts in Schwarzschild spacetime, in the presence of dissipative effects generated as a consequence of differential rotation of the fluid within the disk around a given black hole. We therefore aim to study quasi-stationary solutions of the disk using causal Navier-Stokes equation proposed in Israel-Stewart formalism and later reformulated by Romatschke et.al. In this work, we focus only on shear viscous effects and the bulk viscosity is not taken into consideration. The viscosity is introduced as perturbations to the ideal fluid configuration of the disk and we categorically investigate effects of both shear viscosity and curvature of the Schwarzschild black hole on the shape of the geometrically thick disk. As a simplifying assumption, the heat flow which may arise as a result of viscosity within the fluid, is assumed to be small and consequently the heat flux is neglected in our study.

Properties of disk sources of the Kerr and Tomimatsu-Sato spacetimes

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For the disk sources matched to the exact vacuum Kerr and Tomimatsu-Sato spacetimes we analyze two models of the matter forming these disks: Rotating massive rings with pressure and counter-rotating streams of particles in circular geodesic motion. We discuss how the dragging effects present in such spacetimes prevent the construction of highly compact sources made of realistic matter. We also illustrate various properties of the disks and the parametric separation between disks with realistic properties and those where pathologies such as closed timelike curves exist.

eXtreme gravity with X-rays: a study into the nature of compact objects using X-ray reflection spectroscopy

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Einstein's theory of gravity is the prevailing theory to describe the gravitational effects in our universe. Although largely successful, there are some important deficiencies, e.g., dark matter, dark energy, curvature singularities, lack of a unified theory of gravity and quantum mechanics, and the hierarchy problem, which have led to several alternative theories. These alternative theories differ from Einstein's theory primarily in the strong field regime. With technological progress, tests in the strong gravity regime are rapidly becoming an important paradigm in physics.

X-ray spectroscopy of energetic black holes is a promising technique for testing predictions of alternative theories. It is based on the disk-corona model. [1] It is the standard technique to measure black hole spins in the X-ray astronomy community. [2] In this talk, I will describe the framework we have developed for analyzing the nature of black holes with X-ray reflection spectroscopy. [3] I will discuss results obtained until now and outline future prospects.

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Topic : "Black hole accretion and its variability"

Title : **"Effects of adiabatic index on transonic solution of low angular momentum accretion flow."**

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Study of standing and oscillating shocks in accretion flows has become very important since it is recognized that the spectral states of black holes as well as Quasi-Periodic Oscillations (QPOs) observed in light curves of black hole candidates are directly related to the radiative transfer properties of a compact Comptonizing region close to a black hole. More recently, the shock existence was found for the disc-like structure in hydrostatic equilibrium with low angular momentum both in pseudo-Newtonian potential and in full relativistic approach . Thus shocks play a significant role in governing the overall dynamical and radiative processes taking place in accreting matter. I will present the study of gamma dependence of shock waves of slightly rotating accretion flows onto black holes for a more accurate explanation for QPOs observed in light curves of black hole.

First-principle modelling of particle dynamics in black hole accretion disks

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Black holes provide us with an astrophysical laboratory which we can use to study exceptional physical conditions. Astrophysical black holes are often surrounded by an accretion disk, consisting of orbiting material emitting high-energy outflows. The macroscopic dynamics of black holes and their environment is typically described by general relativistic magnetohydrodynamics (GRMHD), coupling the fluid of charged particles to electromagnetic fields. This framework explains many observed plasma-phenomena in the Universe on the global scale, such as accretion onto and outflows from compact objects. Despite outstanding results achieved with GRMHD, state-of-the-art studies are affected by a lack of information on microscopic plasma dynamics. The accretion disk plasma shows complex behavior that can only be reflected by kinetic particle theory, self-consistently describing electromagnetic fields, gravitational fields, photon dynamics, particle acceleration and the emission of observable radiation. To bridge the gap between GRMHD and kinetic particle models, we developed a general relativistic particle module in the Black Hole Accretion Code (BHAC) [1]; [2]; [3]. In our test particle approach the GRMHD evolution captures the interaction of the plasma with electromagnetic and gravitational fields; Whereas the charged particles are guided by the fields obtained from GRMHD. The kinetic back-reaction of the particles on the electromagnetic fields is ignored in the test particle method. This is a valid assumption when there is only a small number of nonthermal particles with a minor contribution to the global energetics such that gravitational and electromagnetic fields dominate the evolution. The algorithm is developed such that it is also capable of fully consistently capturing the nonlinear kinetic interaction between particles and electromagnetic fields in the plasma without assuming the GRMHD approximation. First-principle modelling of particle dynamics in black hole accretion disks is essential to explain nonthermal flaring radiation as recently observed by the GRAVITY mission [4].

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The Role of Electric Charge in Relativistic Accretion

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The presented work is dedicated to examine the role of electric charge in relativistic accretion onto compact objects. To do so two different scenarios are employed. In both scenarios the discussion is proceeded as far as possible analytically.

First, the accretion process of hydrogen plasma onto a black hole with a realistically small electric charge is examined. An analytical model describes a stationary accretion process of plasma onto a rotating and charged black hole. The plasma particle motion is described within the test-particle approach. It could be shown, that even very small black hole charges may have a non-negligible effect onto accretion processes, as long as the electromagnetic field of the plasma is negligible.

The second scenario concerns charged thick accretion discs around spinning compact objects, which are affected by an external magnetic dipole field. The situation is described in an idealized way by the Kerr metric and a magnetic dipole "test-field" in Kerr spacetime. Pressure equations describe the charged fluid structures. The self-consistency of the model and integrability conditions of the pressure equations lead to restrictions on the fluid conductivity and the charge distribution in the structures. The focus lies on the influence of the central object's spin on the existence and locations of the charged structures. Frame dragging effects result in the existence of rigidly rotating polar clouds, which do not exist in the non-rotating case and in a preference for counter-rotating equatorial tori.

Equilibrium of charged perfect fluid near black hole

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Studies of equilibrium of toroidal structures of a perfect fluid are important to understand the physics of accretion disks in active galactic nuclei – AGN. Our interest is about equilibrium of electrically charged-perfect fluid surrounding a rotating or non rotating compact object, embedded in magnetic field. The vertical and radial structure of the torus are influenced by the balance between the gravitational and the magnetic force. Previous study of rotating charged test fluid around a non rotating black hole showed that according to the spin of the black hole the existence of such structures change. We focus on orbiting structures in the equatorial plane, as single or double tori, and structures above as levitating tori. Our interest is about their existence, shape and how the various forces (electromagnetic, centrifugal and gravitational) influence their physics.

Constraints on parameters of alternative gravity theories with observations of the Galactic Center

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Now there are two basic observational techniques to investigate a gravitational potential at the Galactic Center to prove a presence of a supermassive black hole, namely, (a) monitoring the orbits of bright stars near the Galactic Center with the largest telescopes; (b) measuring the size and shape of shadows around black hole giving an alternative possibility to evaluate black hole parameters with the Event Horizon Telescope. We discuss opportunities to test gravity theories with observations of bright stars at the Galactic Center. Recently, the joint LIGO – Virgo team not only discovered gravitational waves and binary black holes but also found an upper limit on graviton mass $m_g < 1.2 \times 10^{-22}$ eV (Abbott et al. 2016). We show that an analysis of bright star trajectories could constrain graviton mass with a comparable accuracy. We discuss opportunities to improve current estimates of graviton mass significantly with subsequent observations of Keck, VLT, GRAVITY, E-ELT and TMT and to reach a graviton mass estimate as low as $m_g < 5 \times 10^{-23}$ eV. We discuss recent GRAVITY results about gravitational redshift for S2 star near the pericenter passage. These results confirmed GR predictions for the Galactic Center. Therefore, such an analysis gives an opportunity to treat observations of bright stars near the Galactic Center as a useful tool to obtain constraints on the fundamental gravity law. We showed that in the future graviton mass estimates obtained with analysis of trajectories of bright stars would be better than current LIGO bounds on the value, therefore, based on a potential reconstruction at the Galactic Center we obtain bounds on a graviton mass and these bounds are comparable with LIGO constraints. Similarly, we could constrain a tidal charge for the black hole. Analyzing size of shadows around the supermassive black hole at the Galactic Center (or/and in the center of M87) one could constrain parameters of different alternative theories of gravity as well.

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Complete solution and visualization of the Oppenheimer-Snyder collapse

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The Oppenheimer and Snyder (OS) solution of the Einstein equations describes the collapse of a homogeneous dust star at the parabolic velocity of dust particles in the Schwarzschild coordinates. On the hypersurfaces of simultaneity *t=const.* the density appears as inhomogeneous. A detailed derivation of the parabolic OS solution [1] and solutions for hyperbolic and elliptic velocities [2] are presented. The plots of the proper time rate and particle trajectories r(t,R) in different layers visualize the structure of the dust star (Fig. 1). At large t, not only the surface quickly freezes outside the gravitational radius, asymptotically approaching it, but the particles in the internal layers also freeze at certain distances from the center, and their worldlines approach their own asymptotes, rapidly becoming almost parallel to the worldlines of particles at the center and on the surface. This shows that in the OS model the frozen star picture refers not only to the surface, but also to the structure of the collapsed dust star as a whole. Thus, at any finite moment of cosmological time the collapsed OS dust star appears as not a black hole, but as a frozar, an object by practically totally frozen internal structure.

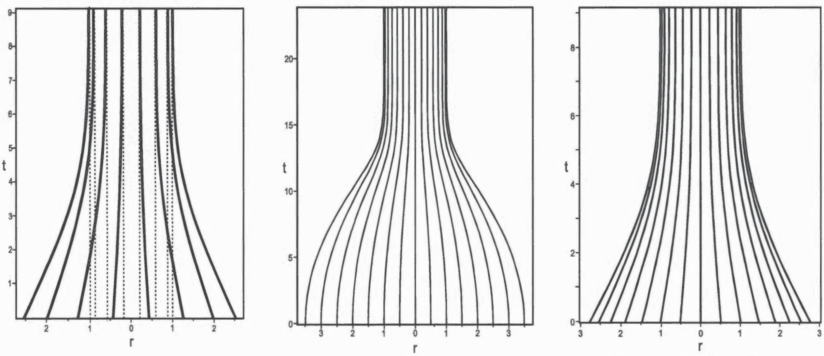

Fig. 1. The worldlines of the homogeneous dust star's particles along the star's diameter for the velocities: (*a*) parabolic, $k=0$, (*b*) elliptic, $k=+1$, (*c*) hyperbolic, $k=-1$. Here $R_b = 3.5$ (in units $2m$) at $\tau = 0$.

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