Report on habilitation thesis **“Charged particle dynamics in black hole magnetosphere”** by **Martin Kološ.**

Presented thesis summarizes author’s research in several specific areas concerned with motion of test particles in the vicinity of black hole potentially immersed in magnetic field. The situation is investigated using both analytical and numerical methods.

The first chapter is devoted to overview of possible configurations of electromagnetic field that are treated as a test fields on the background of Kerr black hole whose basic properties are explained as well. Since plasma environment can be assumed around astrophysical objects the solutions for magnetospheres are classified based on the importance of plasma effects into vacuum, force-free electrodynamics, and numerical ones like GRMHD or Particle-in-Cell. Selected analytical solutions are then discussed and plotted concentrating on Wald solution and solutions with distributional sources often motivated by effective description of numerical results.

In the second chapter, motion of a test charged particle in the background of Kerr or Schwarzschild geometry and under the influence of the previously discussed magnetospheres (mostly Wald solution) is investigated. The motions are classified based on values of parameters influencing qualitative character of trajectories and effective potential description is discussed. Notable examples of motion are illustrated, e.g. particles escaping along the magnetic field from the vicinity of black hole. Additionally, a radiation reaction of these accelerated charged particles is added into the picture.

In the third chapter, astrophysical applications of the aforementioned studies are discussed concentrating on the appearance of charged particles. The proposed source is an accretion disk surrounding the black hole where ionization can take place due to collisions or irradiation. Subsequently, the trajectories of these pairs of charged particles are followed and the effects on the accretion disk analyzed. Next, the Penrose process and its modifications are investigated as a potential source of high-energy cosmic rays. Finally, epicyclic frequencies of perturbed circular trajectories are analyzed as a potential explanation for quasiperiodic oscillations observed in certain sources.

The last chapter provides overview of author’s research worldline and lists open problems that are planned to be tackled in the future. This represents less orthodox, but very useful part of this thesis.

Overall the thesis provides thorough overview of authors research and its connection to real astrophysical phenomena. It does not delve unnecessarily into details and provides plenty of figures to help with understanding basic structures of the fields and particle motions. At the same time it shows that the research is clearly internationally competitive as the number of publications in impacted journals demonstrates. Based on the above I deem the thesis and the research it exposes to be on a high level of expertise and recommend its acceptance as a habilitation thesis.

The quality of the text might have been improved by further reading, but occasional typos do not distract from the qualities of the thesis.

Potential questions for the defense hearing:

1) The figure 2.5 shows escaping trajectories of charged particles. How high velocities or energies can such escaping particles achieve asymptotically in realistic scenarios?

2) In figure 2.7 the plots of numerical errors in middle and right panels exhibit sharp constant upper and lower cut-offs for the oscillations. What is the reason behind this behavior?

3) In figure 3.9 the nature of motion of charged particles after ionization in the disk evidently leads to charge separation. Can one expect that this will have significant effect on the structure of the magnetic field in the vicinity of the disk?

4) Are the conditions for radiative Penrose process described in section 3.6 realistic or does one need to assume low probability situation for combined system of particle and emitted radiation?

In Prague 30.4.2025

doc. RNDr. Otakar Svítek, PhD

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Referee report on the habilitation thesis of Dr. Martin Kološ

Dear Professor Karas, dear members of the committee,

it is my pleasure to provide in the following a report on the habilitation thesis presented by Dr. Martin Kološ, entitled „Charged particle dynamics in black hole magnetosphere". The author is well known to me from his publications, scientific presentations, and discussions in the framework of scientific conferences. There are however no joint publications or joint funding of research projects. The presented thesis is based on the scientific work of Dr. Kološ in the area of theoretical physics and astrophysics. It comprises four original research articles published in the most respected professional journals of the field, among them the Astrophysical Journal, representing the scientific work of the author during the last decade.

The thesis is situated at the intersection of general relativity, high-energy astrophysics, and plasma physics, focusing on the extreme physical conditions in the vicinity of black holes. In this regime, the interplay between strong gravitational fields and intense electromagnetic forces gives rise to a rich spectrum of energetic phenomena. The thesis addresses fundamental questions about how charged particles behave and radiate near black holes, how energy can be extracted from rotating black holes, and how chaotic dynamics emerge in such environments. By exploring these processes in curved spacetime, the work contributes to our theoretical understanding of multi-messenger signals from astrophysical sources, including relativistic jets, ultra-high-energy cosmic rays, and quasi-periodic oscillations in accretion disks. These investigations aim to clarify the mechanisms underlying some of the most energetic and enigmatic phenomena observed in the universe. Dr. Kološ's scientific work, presented in this thesis and in 46 peer reviewed publications and several conference proceedings since 2010, significantly contributes to these open questions.

The scientific questions addressed in the thesis correspond to the evolving research interests of Dr. Kološ, from analytical modeling of idealized systems toward increasingly realistic and complex descriptions of plasma dynamics in black hole environments. A particularly interesting point are investigations of natural ionization processes as triggers for charged particle acceleration, leading to models of relativistic jet formation and ultra-high-energy cosmic ray production via mechanisms such as the magnetic and radiative Penrose processes. Alongside this theoretical development, Dr. Kološ engaged deeply with observational data and nonlinear analysis techniques. More recently, he expanded his methodological repertoire to include general relativistic magnetohydrodynamic (GRMHD) simulations, enabling the study of complex plasma structures such as double-torus accretion flows and more realistic BH magnetospheres, reflecting a mature and integrative approach to the open problems in high-energy astrophysics.

The research directions outlined above are reflected in the candidate's contributions to the selected publications and are summarized in a concise overview (50 pages plus references), which includes a summary and a brief but valuable outline of future research plans. The scientific results presented in the thesis are very impressive, and provide a strong foundation for a wide spectrum of future investigations. Particularly interesting directions include the study of radiation belt formation in black hole magnetospheres, the collective effects of radiation reaction and especially the radiative Penrose process in many-particle systems, and the extension of these methods to gravitational radiation reaction in extreme mass ratio inspirals. From the perspective of dynamical systems, further applications of recurrence quantification analysis to diverse astrophysical observational data seems to be an impactful research direction.

The thesis provides a detailed discussion of black hole charging resulting from the interaction between rotation and the surrounding magnetosphere, as originally described by Wald. It would be highly valuable to hear the candidate's extended perspective on the significance of this process in light of recent developments, such as the studies by Komissarov (*MNRAS* 521, 2022) and King & Pringle (*ApJ Letters* 918, 2021). A reflection on these contributions and their implications during the habilitation lecture would enrich the broader context of the work.

Finally, besides the original research and the scientific results exhibited in the papers and included in this thesis, it seems that Dr. Kološ has been very active in regular teaching duties at the university. Moreover, he acts as a principal investigator in a research programme funded by the Czech Science Foundation, and leads a team of three experienced researchers and two students.

I conclude that Dr. Kološ clearly demonstrates the expertise and readiness to undertake the responsibilities associated with the Habilitation at the Silesian University in Opava. I therefore recommend that the submitted thesis be accepted and the qualification be awarded.

Please feel free to contact me if any further clarification is needed.

Yours faithfully

Eva Hackmann

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August 25, 2025

Review of the Habilitation thesis by Dr. Martin Kološ

In this Habilitation thesis, the author presents a clear and comprehensive overview of more than a decade of research on the motion of charged matter in the vicinity of magnetized black holes. This substantial body of work, documented in over 40 peer-reviewed publications in leading physics journals such as *Physical Review D*, *Journal of Cosmology and Astroparticle Physics*, *Monthly Notices of the Royal Astronomical Society*, or *Classical and Quantum Gravity*, aims to advance our understanding of key high-energy astrophysical phenomena, including quasi-periodic oscillations in microquasars, ultra-high-energy cosmic rays, and relativistic jets.

The thesis is organized into four parts:

Chapter 1 provides a thorough review of black hole magnetosphere models, including Wald's asymptotically uniform magnetic field, as well as the split monopole, dipole, and parabolic magnetic configurations. All these fields are solutions of the linear Maxwell equations on a Kerr background, neglecting the backreaction on the metric, and so they can be superposed to construct more complex magnetic field structures.

Chapter 2 focuses on the dynamics of charged particles within these magnetospheres, primarily employing effective potential methods derived from the Hamiltonian formulation of the Lorentz force equation. While many results rely on numerical computations due to the complexity of the system, the analysis is clearly presented, carefully interpreted, and extended to include higher-order effects such as radiation reaction.

Chapter 3 highlights astrophysical applications of charged particle dynamics. Recognizing that a full description of accretion flows requires general relativistic magnetohydrodynamics, the author convincingly demonstrates how single-particle dynamics remains a powerful tool to interpret black hole observations, particularly in ionized environments. This section explores particle acceleration as a source of ultra-high-energy cosmic rays, the radiative Penrose process, quasi-periodic oscillations, and the dynamics of hot spots near black holes.

Chapter 4 summarizes the author's research contributions and lays out ambitious yet realistic plans for future investigations. These include developing analytic and numerical models of black hole and neutron star magnetospheres (including radiation belt structures), extending radiation reaction studies to multi-particle and gravitational wave scenarios, investigating multipolar electromagnetic fields and spinning or magnetized particles, analyzing string loop stability, and applying advanced nonlinear dynamics techniques (such as recurrence quantification analysis) to blazars, pulsars, and gravitational wave data to uncover signatures of chaos.

Overall, this thesis demonstrates the author's strong expertise and significant contributions to the field of relativistic astrophysics. The work is clearly written, well-organized, and supported by extensive and relevant references. The proposed research directions are promising and build naturally on the author's substantial achievements to date.

On a personal note, I have had the opportunity to meet and interact scientifically with the author. I find him to be an engaging speaker and a thoughtful, enthusiastic interlocutor, consistently contributing original ideas.

For these reasons, I strongly recommend the author for appointment as **Associate Professor**.

Best regards,

José Natário
(Full Professor)

Hodnocení habilitační práce Martina Kološe

CHARGED PARTICLE DYNAMICS IN BLACK HOLE MAGNETOSPHERE

Obsah práce je přesně vystižen jejím názvem. V okolí černých děr, jehož geometrie je popsána Einsteinovou obecnou teorií relativity, dochází k zajímavým procesům spojeným s vlivem magnetosféry na pohyb nabitých částic. Autor se zabývá hlavně rotujícími černými děrami, jejichž geometrii popisuje Kerrovo řešení. Téma pohybu nabitých částic v magnetosféře zpracoval v recenzovaných článcích v kvalitních časopisech (čtyři jsou přiloženy k habilitaci). Výsledky, připravené ve spolupráci s kolegy, jsou interpretovány v širším astrofyzikálním a relativistickém kontextu. Autor také naznačil směry dalšího rozvíjení tématu.

Práce je rozdělena do čtyř kapitol.

První kapitola nejprve rekapituluje poznatky o geometrii prostoročasu vytvářeného černými děrami. I když pro popis geometrie se lze obvykle spokojit s Einsteinovými gravitačními rovnicemi, při velkých poměrech nábojů a hmotností částic může být magnetosféra pohybem částic podstatně ovlivněna. Je proto třeba použít i Maxwellových rovnic pro magnetické pole na pozadí černé díry. Jednoduché a obecně přijímané řešení zde neexistuje a autorova práce nemá ambice řešit problém magnetosféry obecně, rozebírá však a dopracovává vybrané modely, které lze považovat za fyzikálně relevantní. Kapitola je sama o sobě jakousi stručnou monografií o Kerrově řešení a o možnostech jeho navázání na magnetosféru.

Ve druhé kapitole autor využívá modelů magnetosféry k popisu pohybu nabitých částic v ní. K rovnicím určujícím geodetický pohyb se tu připojují rovnice pro Lorentzovu sílu. Velké výhody při řešení problému a kvalitativním hodnocení výsledků zde přináší použití Hamiltonova formalismu, které umožňuje efektivně pracovat se zákony zachování. Řada úloh vyžaduje numerické postupy; autor přitom nejen zohledňuje nepřesnosti výpočtů, ale i pečlivě sleduje možné ztráty kvalitativních vlastností řešení. Ukazuje, jak lze dospět k výsledkům srovnatelným s realitou i bez explicitního řešení pohybových rovnic. Cenným přínosem této kapitoly je názorná demonstrace možností hamiltonovské mechaniky.

Zatímco první dvě kapitoly jsou věnovány hlavně matematickým problémům, třetí kapitola přistupuje k jejich astrofyzikálním aplikacím. Při vysokém měrném náboji částic může i slabé magnetické pole mít výrazný vliv na astrofyzikální procesy, jako je poloha vnitřního okraje akrečního disku, frekvence epicyklických pohybů částic okolo černých děr či vznik a urychlování relativistických jetů. Autor ukazuje, jak tyto jevy souvisí s jeho výsledky. Zvláště pozoruhodným přínosem práce je prokázání možnosti existence Penroseova radiačního procesu, kdy jediná nabitá částice je schopna vynést energii z černé díry. Tento proces nepodléhá omezením, která vedla k pochybnostem o realitě původního Penroseova efektu.

Čtvrtá kapitola je stručná, ale pro čtenáře poutavá tím, jak v ní autor nastínil cestu, na níž vznikal a dotvářel se jeho zájem o astrofyzikální problémy. Významnou roli v tom sehrál již jeho středoškolský učitel. Představuje také další perspektivy svého výzkumu. Je pěkně vidět, jak důležitá je pro mladého vědce týmová spolupráce s kolegy doma i v zahraničí. Autor píše o svých dalších tvůrčích záměrech. Které počítají i s širší mezinárodní spoluprací.

Dále práce obsahuje seznam literatury (přibližně 100 položek), přehled používaných zkratek a přílohu se čtyřmi publikovanými pracemi.

Považuji hodnocenou práci za shrnutí nových a významných příspěvků k poznání fyzikálních procesů v okolí černých děr. Těmito příspěvky i jejich zpracováním autor prokázal hluboké znalosti problematiky. Mimořádná je jeho schopnost spojovat a plodně využívat analytické i numerické metody a kriticky hodnotit vztah dosažených teoretických závěrů k realitě. Své výsledky dovede autor přehledně uspořádat a srozumitelně vyložit. Velmi oceňuji grafickou stránku díla, která si vyžádala mnoho pečlivé práce. Je z ní vidět a ukazuje, jak obrázky a grafy mohou mnohdy povědět více než pouhé formule. Obrázků a grafů je několik stovek a působí někdy až estetický zážitek.

Pokud bych měl vyslovit určitou připomínku, řekl bych, že porovnání autorových výsledků s pozorovanými jevy, které se v práci na řadě míst objevuje, by si zasloužilo na vhodném místě souhrnný přehled. Bylo by proto vhodné, aby se k této otázce autor podrobněji vyjádřil při obhajobě.

Nepochybuji o tom, že práce Martina Kološe ve všech ohledech splňuje požadavky kladené na habilitační práci, a doporučuji, aby byla jako taková uznána.

V Brně 30. 8. 2025

Prof. RNDr. Jan Novotný, CSc.