Brief information about the project

Name of the project	AP13067667 «General relativistic effects in the magnetospheres of astrophysical compact objects» (0122PK00072)
Relevance	The study of astrophysical compact objects is one of the main goals of relativistic astrophysics, which can be considered as a direct application of Einstein's theory of general relativity. In general, the concept of astrophysical compact objects includes all the objects that are small for their mass such as planet-like objects, stars, white dwarfs, neutron stars, other exotic dense stars, and black holes. In this project, we will focus on the study of white dwarfs for which it is expected that relativistic effects play an important role. In particular, we are interested in finding out how the quadrupole moment, which is a measure of the deviation of the object from spherical symmetry, affects the physical properties of compact objects. Moreover, we plan to analyze this problem by considering the entire spacetime, i.e., the interior and exterior spacetimes that are joined by using the C^3 matching procedure. The physical properties of white dwarfs, in turn, can be obtained from the integration of the conservation laws, which are interpreted as the conditions for hydrostatic equilibrium of the star. To our knowledge, the consideration of the quadrupole moment, as an additional parameter that explicitly enters the equilibrium equations and the geometry of spacetime, is new. In fact, most of the studies of equilibrium conditions in relativistic astrophysics are limited to the case of spherically symmetric sources. ***The novelty of the present project*** is the way we consider the quadrupole and the axial symmetry in the metrics that determine the geometric structure of spacetime. The study of relativistic compact objects and their physical properties is very important in order to better understand our Universe. Since the formulation of general relativity as a theory of the gravitational field, thousands of research projects have been dedicated to the study of compact objects. This is a proof of the importance of the present project in the context of astrophysics and science, in general.
Purpose	Analytical description and numerical simulation of charged particles dynamics inside the magnetospheres of compact objects and application of results to observable high-energy astrophysical phenomena, such as the quasi-periodic oscillations from X-ray microquasars and acceleration of relativistic jets and ultra-high-energy cosmic rays by black holes in active galactic nuclei.

Objectives	The project objectives are divided into three exact and closely connected tasks, corresponding to each year of the project implementation. ***Task 1:*** Investigation of the motion of charged particles around *spherically symmetric* compact objects immersed into external superposition magnetic fields. **1.1** Superposition of *uniform and split-monopole* magnetic field configurations in the *Schwarzschild* metric. **1.2** Superposition of *dipole and uniform* magnetic field configurations in the *Schwarzschild* spacetime. ***Task 2:*** Investigation of the motion of charged particles around *axially-symmetric* compact objects immersed into external combined magnetic fields. **2.1** Superposition of *uniform and split-monopole* magnetic field configurations in the *Kerr* spacetime metric. Investigation of the effect of corresponding induced charge. **2.2** Superposition of *dipole and uniform* magnetic field configurations in the *Kerr* spacetime metric. Comparison of the effects of induced charges from previous studies. ***Tasks 3:*** Applications of obtained results to observable high-energy astrophysical phenomena: **3.1** Construction and constraining the model of the *quasi-periodic oscillations* (QPOs) from X-ray microquasars containing black holes or neutron stars. **3.2** Modeling the *relativistic jets* and *ultra-high-energy cosmic rays*. *The 1st task includes*: Derivation of the dynamical equations of charged particles, analyses of stable and unstable orbits, calculation of frequencies of epicyclic oscillations, finding the particles' escape conditions and numerical simulations of particles' trajectories for various parameters of the system. Within the 1st year of the project implementation, we will also look through other combinations of electromagnetic field configurations, including the effects of the central charge of the compact object. *The 2nd task* is the generalization of the 1st task to the axially-symmetric spacetime, given by the rotating Kerr metric. The combination of the spacetime rotation with the external magnetic field sharing the symmetry of the background metric leads to the twisting of magnetic field lines and resulting induction of an electric field capable of accelerating charged particles. The impact of such induced electric fields in chosen magnetic field configurations on the dynamics of ionized matter will be investigated. *The 3rd task* is the astrophysical applications of the 1st and the 2nd tasks. For each task, we shall seek verifiable and/or observable predictions, which will be useful for the construction of particular models of astrophysical

	relevance, planned for the 3rd year of the project implementation. For constraining the models, we will use the available multi-wavelength and multi-messenger observational data.
Expected and achieved results	*Expected results:* 1. Formulation of a novel approach to the modeling of magnetosphere of compact object as a super-position of various magnetic field configurations. Derivation of charged particle's dynamical equations, conditions for stable and unstable orbits, frequencies of quasi-harmonic epicyclic oscillations. Effect of given superposition field on the charged particle's equations of motion, conditions for stable and unstable orbits, frequencies of quasi-harmonic epicyclic oscillations, escape conditions. Solving equations of the motion numerically, finding trajectories. Search for other combinations of electromagnetic field configurations. *Achieved results:* The motions of charged particles around spherically symmetrical compact objects located in an external combined magnetic field were studied. A new approach to modeling the magnetosphere of a compact object as a superposition of different magnetic field configurations was formulated. Equations for the dynamics of charged particles, conditions for stable and unstable orbits, and frequencies of quasi-harmonic epicyclic oscillations were derived. The effects of a given superposition field, the equations of motion of a charged particle, and the conditions for stable and unstable orbits were studied. Additionally, the frequencies of quasi-harmonic epicyclic oscillations and the conditions for the particle to go to infinity were calculated. A numerical solution to the equations of motion was obtained, and the trajectories of charged particles were determined. Furthermore, other combinations of electromagnetic fields in curved spacetime have been considered. *Expected results:* 2. Showing that the rotation of the compact object in chosen superposition magnetic field leads to induction of an electric field. It is expected that the induced electric field is capable of accelerating charged particles. Effect of chosen superposition magnetic field and spacetime on the charged particle dynamics. Effect of chosen superposition field on the charged particle's dynamical equations, conditions for stable and unstable orbits, escape-to-infinity conditions. Numerical simulation of charged particle trajectories in given configuration. Comparison with results of the tasks 1.2 and 2.1. *Achieved results:*

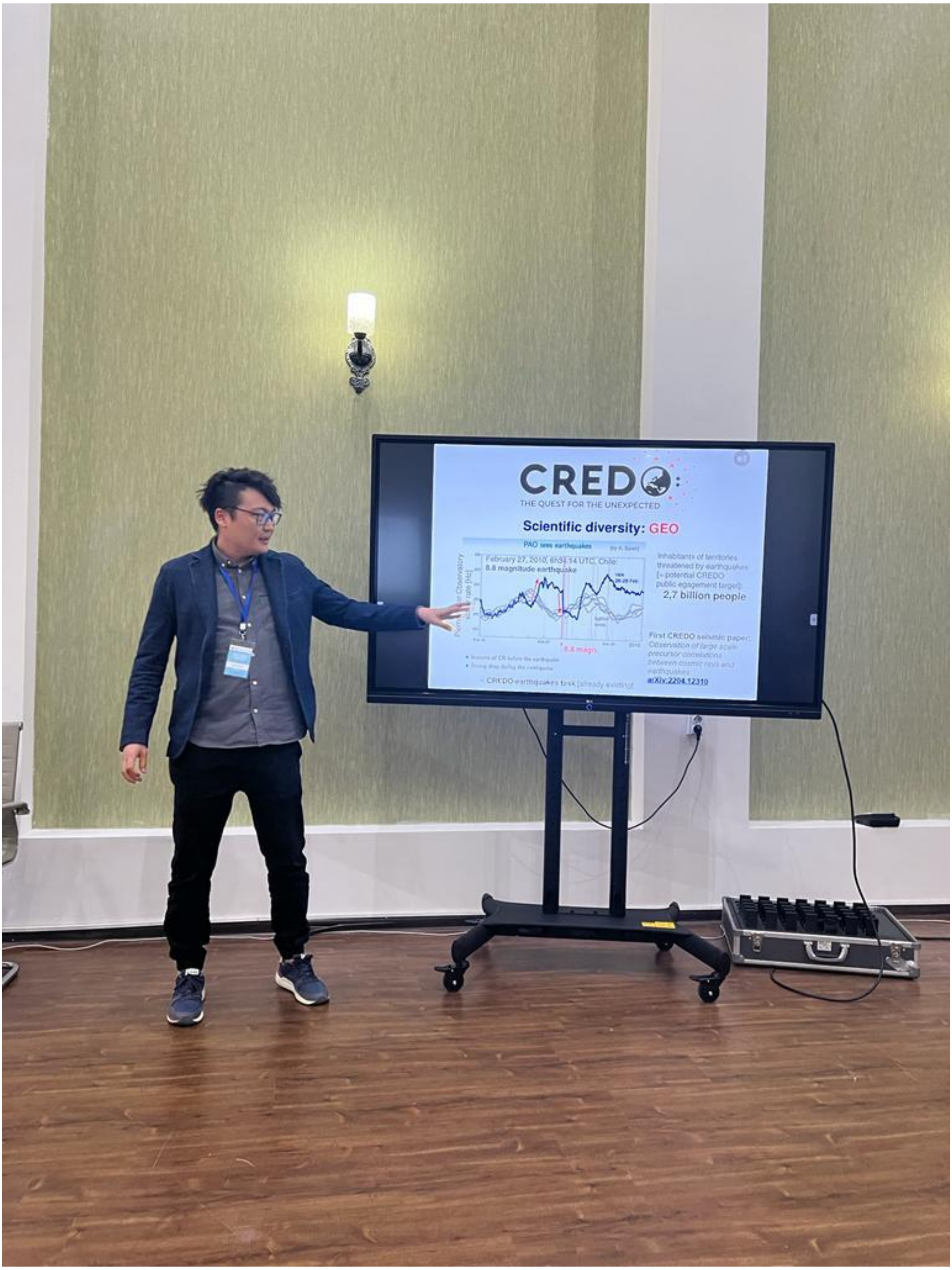
	In the course of the research, an analysis was carried out and conclusions were drawn that the rotation of a compact object in a given superposition magnetic field leads to the induction of an electric field. This induced electric field has been shown to accelerate charged particles. The influence of superposition magnetic field and space-time on the dynamics of charged particles was also studied. As part of the research carried out, the influence of a given superposition magnetic field on the dynamics equations of a charged particle was studied. The corresponding equations of motion were derived and analyzed, which made it possible to evaluate the conditions for the stability of the orbits of charged particles and the conditions for their exit to infinity in given magnetic fields. *Expected results (2024):* 3. Astrophysical application of the 1st and 2nd tasks suggesting the model of generation of quasi-periodic oscillations (QPOs) observed in X-ray microquasars and some AGNs. Correlation of the new model with observational data. Astrophysical application of the 1st and 2nd tasks suggesting the model of acceleration of ultra-high-energy cosmic rays with expected energy of protons of the order of 10^{20} eV. Probing relativistic jet acceleration, CZK-cutoff limit and the Hillas criterion within the new model.
Research team members with their identifiers (Scopus Author ID, Researcher ID, ORCID, if available) and links to relevant profiles	1. **Toktarbay Saken**, 39 years old, Education: Al-Farabi KazNU(Bachelor, 2009, Kazakhstan); Tomsk Polytechnic National Research University (Master, 2011, Russia); Al-Farabi KazNU (PhD, 2016, Kazakhstan). Degree: PhD in Theoretical Physics (2016). Work experience in the direction of the project more than 10 years (physics and astronomy). ScopusID: 56336189300, (Scopus h-index=3); WoS/PublonsID: B-3614-2012 , (WoS/Publons h-index=3); ORCID: 0000-0002-5699-4476; Position and role in the project: General management of the Project, coordination of the Project, development and testing of computer code, preparation of scientific articles, writing reports on the Project. 2. **Zhami Bakytzhan**, 31 years old, Education: Al-Farabi Kazakh National University (Bachelor, 2012, Kazakhstan); Al-Farabi Kazakh National University (Master, 2014, Kazakhstan); Al-Farabi Kazakh National University (PhD, 2020, Kazakhstan). Degree: PhD in Theoretical Physics (2020). Work experience in the direction of the project more than 7 years (physics and astronomy). Scopus ID: 56336051500, (Scopus h-index=3); WoS/PublonsID: P-7959-2014, (Scopus h-index=3); ORCID: 0000-0002-8132-5477;

	Position and role in the project: development and testing of computer code, preparation of scientific articles, writing reports on the project. 3. **Aldabergenov Yermek**, 31 years old, Education: Al-Farabi KazNU (Bachelor, 2012, Kazakhstan); Al-Farabi KazNU (Master, 2014, Kazakhstan); Tokyo Metropolitan University (PhD, 2018, Japan). Degree: PhD in Theoretical Physics (2018). Work experience in the direction of the project more than 8 years (physics and astronomy). ScopusID: 56743280800, (Scopus h-index=8); WoS/PublonsID: AAK-1668-2021, (Scopus h-index=8); ORCID: 0000-0001-6021-9707; Position and role in the project: development and testing of computer code, preparation of scientific articles, writing reports on the project. 4. **Talkhat Amankhan**, 26 years old, PhD Student, Al-Farabi KazNU; ScopusID: 57200368356; ORCID:0000-0002-0615-417X ; Position and role in the project: development and testing of computer code, preparation of scientific articles, writing reports on the project. 5. **Muratkhan Aray**, 33 years old, PhD Student, Al-Farabi KazNU; WoS/PublonsID: V-1168-2018; ORCID:0000-0001-9920-5193; Position and role in the project: Support in analytical calculations, participate in articles and reports writing on the Project. 6. **Balgimbekov Galymdin**, 33 years old, PhD student, Al-Farabi KazNU; ScopusID: WoS/PublonsID: ORCID: 0000-0002-2677-9070; Position and role in the project: Support in analytical calculations, participate in articles and reports writing on the Project.
List of publications with links to them	*Scopus u Web of Science.* *In press:* Black hole in a combined magnetic field: Ionized accretion disks in the jetlike and looplike configurations *by Saltanat Kenzhebayeva, Saken Toktarbay, Arman Tursunov, et al.(* Physical Review D. *2024).* *In a journal included in KOKSON MES RK* 1. Beissen, N., Abishev, M., Toktarbay, S., Yernazarov, T., Utepova, D., & Zhakipova, M. (2023). The Exploring nonlinear vacuum electrodynamics beyond Maxwell's Equations. International Journal of Mathematics and Physics, 14(1), 61–70. https://doi.org/10.26577/ijmph.2023.v14.i1.07 2. Muratkhan, A., Orazymbet, A., Zhakipova, M., Assylbek, M., & Toktarbay, S. (2023). A shadows from the static black hole mimickers. International Journal of

	Mathematics and Physics, 13(2), 44–49. https://doi.org/10.26577/ijmph.2022.v13.i2.06 *International conference* 1. Saken Toktarbay. The Influence of photon orbits on shadow creation by naked singularities. «Disks, tori, spheres. Accretion onto compact objects, 22-27 June 2023, Opava»// report (with certificate). https://indico.slu.cz/event/22/timetable/#20230626 2. Saken Toktarbay. Shadow formation and observational signatures from naked singularities. International Conference ABDILDIN READINGS (ACTUAL PROBLEMS OF MODERN PHYSICS), Al Farabi Kazakh National University, April 12–15, 2023, Almaty // report (with certificate)
Patents	-

Видео:

https://drive.google.com/file/d/1BjSubZj8bnGh27uM0s2acZgLGdVcbBwa/view?usp=drive_link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First CREDO seismic paper:
arXiv:2204.12310