ICRANet-Minsk report 2024

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  - Pauli blocking effects on pair creation in strong electric field
- Charged particle motion near black holes
  - Electromagnetic field of a charge asymptotically approaching a spherically symmetric black hole

2 Participants

2.1 ICRANet-Minsk participants

- Sergei Kilin (director)
- Alexander Gorbatsievich (senior researcher)
- Mikalai Prakapenia (senior researcher)
- Stanislav Komarov (senior researcher)
- Aksana Kurguzava (graduate student)

2.2 Ongoing collaborations

- Alexey Aksenov (ICAD, RAS, Russia)
- Damien Begue (Bar-Ilan University, Israel)
- Alexander Fedotov (Belarusian State University, Belarus)
- David Melon Fuksman (Max Planck Institute for Astronomy, Germany)
- Alexander Garkun (Institute of Applied Physics of NASB, Belarus)
- Ian Korobov (Institute of Nuclear Problems of BSU, Belarus)
- George Krylov (Belarusian State University, Belarus)
- Dmitry Mogilevtsev (B.I. Stepanov Institute of Physics, NASB, Belarus)
- Yuri Petrov (Belarusian State University, Belarus)
- Oleg Romanov (Belarusian State University, Belarus)

- Alexei Shaplov (Institute of Applied Physics of NASB, Belarus)
- Leonid Simonchik (B.I. Stepanov Institute of Physics, NASB, Belarus)
- Igor Timoshchenko (Belarusian State University, Belarus)
- Gregory Vereshchagin (ICRANet, Italy)
- Maxim Usachenok (B.I. Stepanov Institute of Physics, NASB, Belarus)
- Yu Wang (ICRANet, Italy)

3 ICRANet-Minsk center

ICRANet-Minsk center was established in 2017 following the agreement between ICRANet and the National Academy of Sciences of Republic of Belarus. It operates in areas of Relativistic Astrophysics and Cosmology, in the theoretical and observational fields, in line with ICRANet activities.

The activity of the ICRANet-Minsk includes organization of schools, courses, workshops, and conferences in areas of competence of the ICRANet-Minsk combined with an active visiting program. In particular, it supports organization of the Zeldovich meetings series.

Currently the ICRANet-Minsk Center receives funding from three joint project BRFFR-ICRANet-2023:

- Kinetic processes and radiation transfer in relativistic plasma in external electric and magnetic fields (Belarusian PI: Mikalai Prakapenia, NASB; ICRANet PI: Gregory Vereshchagin)
- Electromagnetic field of a system of charges moving near spherically symmetric and magnetized black holes (Belarusian PI: Alexander Gorbatsievich, NASB; ICRANet PI: Gregory Vereshchagin)
- New effects in interaction of electromagnetic radiation with astrophysical plasma resulting from lower permittivity and density of states as compared to vacuum (Belarusian PI: Oleg Romanov, BSU; ICRANet PI: Gregory Vereshchagin)

The process of accession of the Republic of Belarus to ICRANet has been initiated by the National Academy of Sciences of Belarus and approved by the Steering Committee of ICRANet.

4 Scientific activities

Scientific activities of ICRANet-Minsk include research in radiation transfer in relativistic plasma, kinetics of relativistic plasma, motion of charged particles in the vicinity of black holes, effects in interaction of electromagnetic radiation with astrophysical plasma resulting from lower permittivity and density of states as compared to vacuum.

4.1 Kinetics of relativistic plasma

Binary interactions in relativistic plasma, such as Coulomb and Compton scattering as well as pair creation and annihilation are well known and studied in detail. Triple interactions, namely, relativistic bremsstrahlung, double Compton scattering, radiative pair production, and triple pair production and their inverse processes, are usually considered as emission processes in astrophysical problems, as well as in laboratory plasmas. Their role in plasma kinetics is fundamental [A. G. Aksenov et al., Phys. Rev. Lett. 99, 125003 (2007)]. We developed a new conservative scheme for computation of the Uehling-Uhlenbeck collision integral for all triple interactions in relativistic plasma based on direct integration of exact QED matrix elements [M. Prakapenia, I.A. Siutsou and G.V. Vereshchagin, Physics of Plasmas 27, 113302 (2020)], for an extensive review see [Gregory Vereshchagin and Mikalai Prakapenia, "Kinetics of Degenerate Electron–Positron Plasmas" Universe, 8 (2022) id.473].

4.2 Strong fields in astrophysics

Despite strong efforts the Schwinger process is not yet reachable in laboratory conditions. However, one may look for this process in some extreme astrophysical environments. Various kinetic effects in strong electromagnetic

fields are discussed in the book G.V. Vereshchagin and A.G. Aksenov "Relativistic kinetic theory", Cambridge University Press, 2017. We focus on physical processes in strong electric field such as pair production and their evolution in external fields, which may be probed by astrophysical observations.

4.2.1 Pair production in hot electrospheres of compact astrophysical objects

In this work we revisited pair production in compact astrophysical objects endowed with strong electric field on their surface. The region with overcritical $E > E_c$ electric field in these objects is called *electrosphere*.

Our kinetic simulation reveals two physical effects in hot electrosphere, which were ignored in previous analyses. The first effect is the inflation of electrosphere due thermal evaporation of electrons, leading to its spatial extension to distances much larger than the electrostatic solution implies. The second effect is enhancement of the rate of pair creation due to pair simultaneous acceleration by the electric field, first established in [A. Benedetti, W.-B. Han, R. Ruffini and G. V. Vereshchagin, Phys. Lett. B698 (2011) 75]. The latter effect can operate at electric fields values up to $E \lesssim 127E_c$. Both effects are crucial for estimation of pair creation rate, especially at low temperatures with strongly degenerate electrons, where analytical formulas fail to reproduce numerical rates.

The main conclusion is that the rate of pair creation in electrosphere is largely (be almost two orders of magnitude) underestimated in the literature. Moreover, the luminosity in pairs is determined not only by the temperature, but by the acceleration provided by the electric field. We find that the luminosity in pairs can be as large as

$$L_{\pm} \simeq 1.3 \times 10^{52}\ \mathrm{erg/s} \left(\frac{E}{5 \times 10^{17} \mathrm{V/cm}} \right)^3 .$$

In this estimate the typical value of electric field $E = 30E_c$ obtained from electrostatic configurations is used.

This work is supported within the joint BRFFR-ICRANet-2023 funding programme within the Grant **No. F23ICR-001**. The results are presented in several meetings and published in the Astrophysical Journal, 2024.

4.2.2 Radial electromagnetic perturbation of a compact astrophysical object

Another mechanism of energy deposition on the surface of a compact object with electrosphere is the deformation of the surface, e.g. radial displacement. Electrons and quarks respond differently to such a deformation (due to different fundamental interactions involved). Then such mechanical deformation will result in electrodynamical perturbation. We model such a perturbation as electric current. This is an alternative mechanism to heating, which, as we show, may also result in pair creation in the perturbed electrosphere.

We study relaxation of such perturbations in a microscopic scale for different parameters, characterizing the problem. With this goal relativistic kinetic equations with both source term describing the Schwinger pair production and collisional term describing relaxation accounted for are solved numerically together with the Maxwell equations.

This work is supported within the joint BRFFR-ICRANet-2023 funding programme within the Grant **No. F23ICR-001**. The results are presented in several meetings and submitted for publication to Physical Review D, 2024.

4.3 Charged particle motion near black holes

This year we continued the project dedicated to the motion of charged particles near black holes, supported by the joint ICRANet-BRFFR program. The purpose of the work is determination of electromagnetic field of a test charge moving in the vicinity of a black hole, as well as determination of its observational characteristics and application of obtained results to astrophysical problems of radiation in the vicinity of black holes. It is proposed to use the general covariant approach to calculate the retarded potentials of the electromagnetic field of a particle moving in the vicinity of a black hole.

4.3.1 Electromagnetic Field and Radiation of Charged Particles in the Vicinity of Schwarzschild Black Hole

The dynamics of electromagnetic fields and electromagnetic radiation of charged particles moving in the vicinity of a black hole are relevant in many astrophysical problems, and they are involved in the description of active galactic nuclei, X-ray binaries, and microquasars. Recently, the interest in

this subject has been revived due to the realization that magnetized black holes may accelerate particles and thus produce strong electromagnetic signals. This is an important subject for models of energy extraction from black holes.

Given the fact that the problem under consideration is quite involved, the solution is approached in steps. The first step is the determination of the electromagnetic field of a static charge outside the black hole. Then, the dynamical problem is addressed with the motion of a charge without radiation. Next, the problem of a charge (mass) emitting electromagnetic (gravitational) radiation is considered. Finally, the radiation reaction on the motion of the charge is taken into account. We prepared a review of the historic developments and recent results obtained in the study of this problem. Our main goal was to highlight the basic assumptions and limitations of various techniques and point out the main conclusions of these studies.

This work is supported within the joint BRFFR-ICRANet-2023 funding programme within the Grant **No. F23ICR-003**.

These results are published in Particles 2025, 8, 1.

5 Conferences and seminars

- Talk by Mikalai Prakapenia ”Schwinger process in hot electrosphere of strange stars”, The 2024 Annual Meeting of the Division of Gravitation and Relativistic Astrophysics of the Chinese Physical Society, April 19, 2024 - April 24, 2024, Hengyang, China.
- Talk by Mikalai Prakapenia ”Kinetics of pair creation in strong electric field”, International summer conference on theoretical physics 2024, 17-21 June 2024, Saint-Petersburg, Russia.
- Talk by Mikalai Prakapenia ”Numerical scheme for relativistic Boltzmann equation with spherical geometry”, Mathematical Modeling and Computational Physics 2024, 20-25 October 2024, Yerevan, Armenia.
- Talk by Mikalai Prakapenia ”Electron-positron plasma creation in strong electric field of astrophysical compact objects”, the XV Belarusian-Serbian symposium ”Physics and diagnostics of laboratory and astrophysical plasmas, September 09–14, 2024, Minsk, Belarus.
- Talk by Mikalai Prakapenia ”Electron-positron plasma creation in strong electric field of astrophysical compact objects”, XIV Serbian-Bulgarian Astronomical Conference (XIV SBAC) 23rd – 27th September 2024, Vrnjačka Banja, Serbia.
- Talk by Stanislav Komarov ”Electric and magnetic fields of a charged ring in the vicinity of Kerr black hole”, The 17th Marcel Grossmann Meeting, July 9, 2024, Pescara, Italy.
- Talk by Stanislav Komarov ”Electromagnetic field of a charged particle, asymptotically approaching Schwarzschild black hole”, The 17th Marcel Grossmann Meeting, July 9, 2024, Pescara, Italy.
- Talk by Aksana Kurhuzava ”Diffusion spectra and equitemporal surfaces of ultrarelativistic shell radiation as applied to gamma-ray

bursts", The 17th Marcel Grossmann Meeting, July 9, 2024, Pescara, Italy.

- Invited talk by Gregory Vereshchagin "On pair creation in electrosphere of compact astrophysical objects", Looking AHEAD to soft gamma-ray Astrophysics: prospects and challenges, February 14 – 16, 2024, Ferrara, Italy.
- Talk by Gregory Vereshchagin "Schwinger process in hot electrospheres of strange stars", The 17th Marcel Grossmann Meeting, July 9, 2024, Pescara, Italy.
- Talk by Gregory Vereshchagin "Magnetically dominated outflow in GRB 080916C?", The 17th Marcel Grossmann Meeting, July 9, 2024, Pescara, Italy.
- Talk by Gregory Vereshchagin "Electron-positron pair creation in electrosphere of compact astrophysical objects", High Energy Astrophysics and Cosmology in the era of all-sky surveys, Yerevan, Armenia, October 7 – 11, 2024.
- Seminar by Gregory Vereshchagin "Electron-positron pair creation in electrosphere of compact astrophysical objects" at the Astronomical Observatory of Belgrade, December 11, 2024, Belgrade, Serbia.

6 Teaching and outreach

6.1 Lecture course ≪Relativistic astrophysics≫ for graduate students of the Department of theoretical physics and astrophysics of the Belarusian State University (50 hours)

Lecturer: Dr. Mikalai Prakapenia

The course is delivered to undergraduate students of the 4th year.

Topics of the course:

1. Stars and protostars

Masses, luminosities and radii of stars. Spectral classes. Gravitational instability and isothermal collapse of a spherical cloud. Jeans criterion.

2. Nuclear reactions in stars

Thermonuclear reactions in stellar nuclei. The system of equations for the evolution of spherically symmetric stars. Example of the calculation for the Sun.

3. Stellar equilibrium

Polytropic equation of state and stellar equilibrium in nonrelativistic case. Chandrasekhar limit. Evolution of stars on the main sequence and final product of the evolution.

4. Neutron stars

Oppenheimer-Volkoff equation and the maximum mass of the neutron star. The mass-radius relation. The structure of the neutron star. Baym-Bethe-Pethick equation of state. Neutron star cooling.

5. Particle acceleration and radiative mechanisms.

Cosmic rays. Fermi acceleration mechanisms. Landau-Romer theory. Basic radiation processes. Interaction with the cosmic backgrounds. GZK cut-off.

6. Pulsars

The structure of magnetosphere. Giulian-Goldreich model. Energy losses. Starquakes.

7. Supernovae

Supernovae types. Explosion mechanisms. Shock waves and neutrino. Supernova remnants.

8. Accretion on a black hole

Spherically symmetric Bondi accretion. Shakura-Sunyaev accretion disc. Luminosity and spectrum of the disc. Eddington luminosity. Stellar wind.

9. Accretion on a neutron star

Spherically symmetric and disc accretion on a neutron star. Accretion column.

10. Binary systems.

Roche lobe in a binary. Hyperaccretion. Binary systems evolution.

11. Gravitational waves

Mechanisms of gravitational waves emission. The intensity averaged over binary period. Rotation period decrease.

Recommended topics for colloquia:

1. Thermodynamic and gravitational equilibrium in stars: nuclear reactions in stars, the system of equations for evolution of spherically symmetric stars; equation of state.

2. Neutron stars, radiative mechanisms, pulsars: the structure of a neutron star, neutron star cooling; Compton scattering, bremsstrahlung, neutrino transport; magnetosphere structure.

Topics for the seminars:

Binary systems: structure and evolution of a binary system. Roche approximation in modeling of binary systems.

6.2 Lecture course ≪Relativistic kinetics≫ for graduate students of the Department of theoretical physics and astrophysics of the Belarusian State University (108 hours)

Lecturer: Dr. Mikalai Prakapenia

The course is delivered to undergraduate students of the 5th year.

Topics of the course:

1. Nonrelativistic kinetics and relativistic kinetic theory

Hierarchy of kinetic equations. Binary correlations and collision integral. Boltzmann kinetic equation. Landau and Vlasov equations. Quantum kinetic equations. Uehling–Uhlenbeck equation. H-theorem. Relativistic Maxwell distribution. Relativistic Bogolyubov hierarchy. Vlasov-Maxwell system. General relativistic kinetic theory. Einstein-Vlasov system.

2. Radiative transfer theory

Kinetic equaitons in the form of radiative transfer. Moments of radiative transfer equation. Source function. Formal solution. Radiative transfer in a scattering atmosphere. Isotropic scattering. Plane-parallel case. Spherically symmetric case. Radiative equilibrium. Local thermodynamic equilibrium. Rosseland average. Opacity. Emission and absorption coefficients. Kramers formulae. Saha equation.

3. Radiative processes in astrophysics

Boltzmann equation for Compton scattering. Kompaneets equation and its properties. Sunyaev-Zeldovich effect. Comptonization in a static medium. Zeldovich-Levich solution. Bose condensation. Relativistic bremsstrahlung. Electron-positron pair creation and annihilation. Kinetics of pulsar magnetosphere. Radiation spectrum of accretion disc. Weak interactions in neutron stars. UCRA processes. Neutrino transport. Supernova models.

4. Thermalization of relativistic plasma

Pair plasma in astrophysics and cosmology. Plasma parameters. Collision integrals for binary and triple processes. Kinetic equilibrium. Reaction rates. Svensson formulae. Relaxation time. Thermalization process. Relativistic degeneracy and reaction rates. Creation of pairs in a strong electric field.

5. Kinetic theory of selfgravitating systems

Bogolyubov hierarchy. Jeans equatons. General relativistic treatment. Linearized Vlasov equation. Jeans length. Collisionless relaxation. Isothermal sphere. Spherically-symmetric acctetion. Cosmological perturbations. Microwave background radiation anisotropy.

Recommended topics for colloquia:

1. Radiative transfer theory: plane-parallel atmosphere, radiative equilibrium, local thermodynamic equilibrium.

2. Radiative processes in astrophysics: Comptonization in a static medium, synchrotron radiation, the spectrum of an accretion disc.

List of topics for in-depth study:

1. Non-relativistic and relativistic kinetic theory: one-particle distribution function, detailed equilibrium, Boltzmann kinetic equation. Uehling–Uhlenbeck equation

2. Thermalization of relativistic plasma: kinetic and thermodynamic equilibrium in opaque plasma of electrons, positrons and protons. Collision integrals with quantum corrections.
3. Kinetics of self-gravitating systems: Distribution functions and Boltzmann equation in curved space-time. Equations for scalar perturbations. Evolution of perturbations for neutrinos.

6.3 Public outreach

This year a special issue of "Science and Innovations" journal published by the National Academy of Sciences of Belarus from April 2024 (number 4(253) 2024) was prepared by the members of ICRANet-Minsk and invited renowned astrophysicists. The papers include:

- Gregory Vereshchagin, Astronomy: history and perspectives.
- Gennady Bisnovatyi-Kogan, Dark matter and dark energy: early and late Universe, the problem of the Hubble parameter.
- Yuri Vyblyi, Cosmology: past and future.
- Ivan Rybak, Towards the high energy physics on gravitational waves. Precision cosmology and observational data.
- Sergey Cherkas and Vladimir Kalashnikov, Archeology of the Universe: from plasma era to microwave radiation.
- Stanislav Komarov, Curvature of spacetime: what black holes images tell us.
- Evgeny Derishev, Gamma-ray bursts - the brightest flashes in the Universe.
- Mikalai Prakapenia, How to extract energy from rotating black hole.
- Oleg Boyarkin and Viktor Makhnach, Oscillations of solar neutrinos.

This special issue can be found at: http://innosfera.by/taxonomy/term/2429

7 Publications 2024

1. M. A. Prakapenia and G. V. Vereshchagin, “Pair creation in hot electrosphere of compact astrophysical objects”, ApJ 963 (2024) 149.

   The mechanism of pair creation in electrosphere of compact astrophysical objects such as quark stars or neutron stars is revisited, paying attention to evaporation of electrons and acceleration of electrons and positrons, previously not addressed in the literature. We perform a series of numerical simulations using the Vlasov-Maxwell equations. The rate of pair creation strongly depends on electric field strength in the electrosphere. Despite Pauli blocking is explicitly taken into account, we find no exponential suppression of the pair creation rate at low temperatures. The luminosity in pairs increases with temperature and it may reach up to $L_\pm\sim 10^{52}$ erg/s, much larger than previously assumed.

2. S. O. Komarov and G. V. Vereshchagin, ”Electromagnetic Field and Radiation of Charged Particles in the Vicinity of Schwarzschild Black Hole”, Particles 2025, 8, 1.

   We provide a concise review of the problem of calculating the electromagnetic field and radiation of a charged particle in the vicinity of a black hole. The interest in this problem has been revived due to recent progress in multimessenger observations. Many astrophysical models of energy extraction from a black hole involve consideration of such motion and radiation. Our main goal is to highlight the basic assumptions and limitations of various techniques and point out the main conclusions of these studies.

3. Mikalai Prakapenia and Gregory Vereshchagin, “Pair creation from radial electromagnetic perturbation of a compact astrophysical object”, submitted to Phys. Rev. D, 2024.

   Recently Usov’s mechanism of pair creation on the surface of compact astrophysical objects has been revisited [1] with a conclusion that the pair creation rate was previously underestimated in the literature by nearly two orders of

magnitude. Here we consider an alternative hypothesis of pair creation due to a perturbation of the surface of a compact object. Radial perturbation is induced in hydrodynamic velocity resulting in a microscopic displacement of the negatively charged component with respect to the positively charged one. The result depends on the ratio between the spatial scale of the perturbation $\lambda$and the mean free path l. When $\lambda \sim l$the perturbation energy is converted into a burst of electron-positron pairs which are created in collisionless plasma oscillations at the surface; after energy excess is dissipated electrosphere returns to its electrostatic configuration. When instead $\lambda \gg l$, the perturbation is thermalized, its energy is transformed into heat, and pairs are created continuously by the heated electrosphere. We discuss the relevant astrophysical scenarios.