ICRANet-Minsk report 2023

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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)
- Vladislav Stefanov (scientific secretary of the Center)

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. Members of ICRANet-Minsk actively participated in the 5th Zeldovich meeting held on 12-17 June, 2023 in Yerevan, Armenia.

Currently the ICRANet-Minsk Center receives funding from two 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. Currently the internal procedure in the Government of Belarus is ongoing.

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. New topic has been added recently, namely the study of 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)]. Recently we presented 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)]. We also completed an extensive review [Gregory Vereshchagin and Mikalai Prakapenia, "Kinetics of Degenerate Electron–Positron Plasmas" Universe, 8 (2022) id.473].

4.1.1 Pauli blocking effects on pair creation in strong electric field

In this work we use classical kinetic equations with the source term due to the Schwinger process, as well as Maxwell equations to describe electron-positron pair plasma and electric field evolution. We consider kinetic evolution of pair plasma with initially non-vacuum states.

Main result in this work is the demonstration how quantum exclusion principle suppresses pair creation in overcritical uniform electric field, which in turn modifies the back reaction dynamics. We studied electron-positron pair creation and oscillations with initial vacuum state as well as with electron-positron plasma initially present. Two cases can be distinguished. 1) When the energy in electric field dominates that in pairs oscillations are induced, which leads to opening up of the phase space and consequent prolific pair creation. 2) In the opposite case, when pairs dominate energetically over electric field, plasma oscillations do occur with much higher frequency, since electric field is unable to displace them significantly in momentum space: as a consequence pair creation remains strongly suppressed.

This work is supported within the joint BRFFR-ICRANet-2023 funding programme within the Grant **No. F23ICR-001**.

Results of this work were reported at the 5th Zeldovich meeting held in Yerevan, Armenia on June 12-17, 2023. These results are published in Phys. Rev. D 108, 013002 (2023). This work has been selected as Top-10 results from 2023 at the National Academy of Sciences of Belarus.

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 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**. It is submitted for publication in the Astrophysical Journal.

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 of a charge asymptotically approaching a spherically symmetric black hole

The problem of finding the electromagnetic field of a charge in a gravitational field within general relativity has a long history. While the basic results for the total radiated energy and the spectrum of the radiation of a charged particle in the vicinity of a black hole have been established, the question remains as to the fate of the electromagnetic field of the charged particle as it approaches the horizon of the black hole. Obviously, the particle cannot be at rest in the external gravitational field without an external force. Much more interesting from a physical point of view is the problem of the electromagnetic field produced by a free-falling charged particle in the external gravitational field of a Schwarzschild black hole.

The equations describing the electromagnetic field appeared to coincide with the Regge-Wheeler equations describing small perturbations of a black hole. It is well known that this equation mathematically coincides with the stationary Schrodinger equation for a particle in a potential barrier. The simplest way to obtain approximate analytic solution of this equation is to represent such a barrier with the Dirac delta function located in the maximum of the potential. For the particle that is approaching asymptotically the black hole event horizon ($t \to +\infty$) we find that all multipole components of electromagnetic field except for the monopole tend to zero exponentially, when $t \to +\infty$. This result is independent on the equation of motion of a particle. It is valid also when external electromagnetic field as well as radiation reaction are present.

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

Results of this work were reported at the 5th Zeldovich meeting held in Yerevan, Armenia on June 12-17, 2023. These results are published in Phys. Rev. D 108 (2023) 104056.

5 Teaching and outreach

5.1 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.

5.2 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 Publications 2023

1. M. A. Prakapenia and G. V. Vereshchagin, “Pauli blocking effects on pair creation in strong electric field”, Phys. Rev. D 108, 013002 (2023).

   The process of electron-positron pair creation and oscillation in a uniform electric field is studied, taking into account the Pauli exclusion principle. Generally, we find that pair creation is suppressed; hence, coherent oscillations occur on longer timescales. Considering pair creation in already existing electron-positron plasma, we find that the dynamics depends on pair distribution function. We considered Fermi-Dirac distribution of pairs and found that for small temperatures pair creation is suppressed, while for small chemical potentials it increases: heating leads to enhancement of pair creation.

2. M. A. Prakapenia and G. V. Vereshchagin, “Pair creation in hot electrosphere of compact astrophysical objects”, submitted to ApJ (2023).

   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.

3. Komarov, S. O. ; Gorbatsievich, A. K. ; Vereshchagin, G. V., ”Electromagnetic field of a charge asymptotically approaching a spherically symmetric black hole”, Phys. Rev. D 108 (2023) 104056.

   We consider a test charged particle falling onto a Schwarzschild black hole and evaluate its electromagnetic field. The Regge-Wheeler equation is solved analytically by approximating the potential barrier with Dirac delta function and rectangular barrier. We show that for asymptotically large times measured by a distant observer the electromagnetic field approaches the spherically symmetric electrostatic field. This implies that in the region accessible to a distant observer the initial state of separated charge and the electromagnetic field outside the event horizon of Schwarzschild black hole becomes asymptotically indistinguishable from the Reisnner-Nordström solution. The implications of this result for some astrophysical models of black holes accreting charged particles are discussed.

4. S. O. Komarov, A. K. Gorbatsievich, A. S. Garkun, and G. V. Vereshchagin, "Electromagnetic Radiation and Electromagnetic Self-Force of a Point Charge in the Vicinity of the Schwarzschild Black Hole", Nonlinear Phenomena in Complex Systems, 26 (2023), pp.77 - 82.

   A point charge, radially moving in the vicinity of a black hole is considered. Electromagnetic field in a wave zone and in the small neighbourhood of the charge is calculated. Numerical results of the calculation of the spectrum of electromagnetic radiation of the point charge are presented. Covariant approach for the calculation of the electromagnetic self-force is used for the case of the slowly moving charge. Numerical results for the self-force in the case of the slow motion of a particle are obtained and compared to the results in literature.