ICRANet-Minsk report 2022

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- Kinetics of relativistic plasma
  - Kinetics of Degenerate Electron–Positron Plasmas
- Charged particle motion near black holes
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2 Participants

2.1 ICRANet-Minsk participants

- Sergei Kilin (director)
- 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)
- David Melon Fuksman (Max Planck Institute for Astronomy, Germany)
- Dmitry Mogilevtsev (B.I. Stepanov Institute of Physics, NASB)
- Gregory Vereshchagin (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 are actively participating in the organization of the the 5th Zeldovich meeting to be held in 2023 in Yerevan, Armenia.

Currently the ICRANet-Minsk Center receives funding from two joint project BRFFR-ICRANet-2021:

- Kinetics of nonuniform and (or) anisotropic relativistic plasma with correlations
- The motion and radiation of a test charged particle in the vicinity of a black hole

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.

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)].

This year we prepared an extensive review "Kinetics of Degenerate Electron–Positron Plasmas", which was published among the contributions to the Special Issue of the Universe journal dedicated to relativistic kinetic theory.

4.1.1 Kinetics of Degenerate Electron–Positron Plasmas

Relativistic plasma can be formed in strong electromagnetic or gravitational fields. Such conditions exist in compact astrophysical objects, such as white dwarfs and neutron stars, as well as in accretion discs around neutron stars and black holes. Relativistic plasma may also be produced in the laboratory during interactions of ultra-intense lasers with solid targets or laser beams between themselves. The process of thermalization in relativistic plasma can be affected by quantum degeneracy, as reaction rates are either suppressed by Pauli blocking or intensified by Bose enhancement. In addition, specific quantum phenomena, such as Bose–Einstein condensation, may occur in such plasma. In this review, the process of plasma thermalization is discussed and illustrated with several examples. The conditions for quantum condensation of photons are formulated. Similarly, the conditions for thermalization delay due to the quantum degeneracy of fermions are analyzed. Finally, the process of formation of such relativistic plasma originating from an overcritical electric field is discussed. All these results are relevant for relativistic astrophysics as well as for laboratory experiments with ultra-intense lasers.

This work is supported within the joint BRFFR-ICRANet-2021 funding programme within the Grant **No. F21ICR-003**.

Results of this work were reported at the conference in celebration of Prof. Remo Ruffini 80th birthday, ICRANet Seat at Villa Ratti, Nice (France) and online, 16-18 May 2022. These results are published in Universe, 2022.

4.2 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.

4.2.1 The motion and radiation of a test charged particle in the vicinity of a black hole

Point charge, radially moving in the vicinity of a black hole is considered. Electromagnetic field in 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 electromagnetic self-force is used for the case of the slowly moving charge. Numerical results for the self-force in the case of slow motion of the particle are obtained and compared to the results in literature.

This work is supported within the joint BRFFR-ICRANet-2021 funding programme within the Grant **No. F21ICR-002**.

These results are reported at the XXIX International Seminar Nonlinear Phenomena in Complex Systems, Minsk, Belarus June 21 -– 24, 2022. The paper is submitted for publication in NPCS, to appear in 2023.

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 perturbuations. Evolution of perturbations for neutrinos.

6 Publications 2022

1. V.P. Stefanov, V.N. Shatokhin, D.S. Mogilevtsev, and S.Ya. Kilin, "Key for a Hidden Quantum State", Physical Review Letters, Volume 129, Issue 8, article id.083603, 2022.

   Quantum trajectories are crucial to understanding the evolution of open systems. We consider an open cavity mode undergoing up and down multistate quantum jumps due to the emission and absorption of photons. We prove that among all subtrajectories, starting simultaneously from different photon number states, only one survives a long single-run evolution. A random Fock state terminating the subtrajectory becomes known for the ergodic case via the key—the processed record of the input and output photocounts, and the trajectory duration. Based on this result, we propose a robust protocol to infer the Fock state, a valuable resource for quantum applications.

2. G. V. Vereshchagin and M. A. Prakapenia, "Kinetics of Degenerate Electron–Positron Plasmas", Universe vol. 8 (2022) p. 473.

   Relativistic plasma can be formed in strong electromagnetic or gravitational fields. Such conditions exist in compact astrophysical objects, such as white dwarfs and neutron stars, as well as in accretion discs around neutron stars and black holes. Relativistic plasma may also be produced in the laboratory during interactions of ultra-intense lasers with solid targets or laser beams between themselves. The process of thermalization in relativistic plasma can be affected by quantum degeneracy, as reaction rates are either suppressed by Pauli blocking or intensified by Bose enhancement. In addition, specific quantum phenomena, such as Bose–Einstein condensation, may occur in such a plasma. In this review, the process of plasma thermalization is discussed and illustrated with several examples. The conditions for quantum condensation of photons are formulated. Similarly, the conditions for thermalization delay due to the quantum degeneracy of fermions are analyzed. Finally, the process of formation of such relativistic plasma originating from an overcritical electric field is discussed. All these results are relevant for relativistic astrophysics as well as for laboratory experiments with ultra-intense lasers.

3. Komarov, S. O. ; Gorbatsievich, A. K. ; Garkun, A. S. ; Vereshchagin, G. V., "Electromagnetic radiation and electromagnetic self-force of a point charge in the vicinity of Schwarzschild black hole", to appear in NPCS, 2023; arXiv:2211.04544.

   Point charge, radially moving in the vicinity of a black hole is considered. Electromagnetic field in 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 electromagnetic self-force is used for the case of the slowly moving charge. Numerical results for the self-force in the case of slow motion of the particle are obtained and compared to the results in literature.