ICRANet-Minsk report 2021

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1 Topics

- Kinetics of relativistic plasma
  - Numerical scheme for evaluating the collision integrals for triple interactions in relativistic plasma
  - Interaction rates in relativistic plasma with baryons
  - Correlations in relativistic plasma

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)
- Gregory Vereshchagin (ICRANet-Pescara, visiting)
- Dmitry Mogilevtsev (B.I. Stepanov Institute of Physics, NASB)

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 include 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, the 4th meeting was held in September 2020 (in virtual format). The proceedings of this meeting were published in Astronomy Reports in October 2021.

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 particlein the vicinity of black hole.

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 performed calculations of nonequilibrium reaction rates for all triple interactions in relativistic plasma including: relativistic bremsstrahlung, double Compton scattering, radiative pair production, triple pair production/annihilation and their inverse processes. Reaction rates are computed out of first principles, numerically integrating exact QED matrix elements over the phase space of particles. Example is given for photon emission by hot thermal electron-positron pairs. These results were reported at the 107 SIF National Congress, 13-17 September 2021, online, and published in Astronomy Reports, volume 65 (2021), pp. 1011–1014.

Within the joint project supported by BRFFR-ICRANet grant we started the work on two additional topics.

4.1.1 Interaction rates in relativistic plasma with baryons

In addition to interactions between electrons, positrons and photons we are considering electromagnetic interaction with baryons. The presence of baryons modifies kinetics in non-equilibrium relativistic plasma, with respect to the pure leptonic case. Instead of approximate expressions for reaction rates, used previously, we compute interaction rates out of first principles. We are also developing a new numerical code capable of solving relativistic kinetic equations for spherically symmetric case. This code will be used to study thermalization and transport in optically thick plasmas composed of electrons, positrons and photons.

4.1.2 Correlations in relativistic plasma

The relativistic Boltzmann equation is traditionally derived out of quantum field theory when particle correlations are neglected. We are reconsidering this derivation with the focus on conditions which can be used to derive kinetic equations for particle correlations. Such correlation analysis is important for establishment of validity conditions of relativistic Boltzmann equation, as well as to the study of non-equilibrium kinetics for strongly correlated relativistic plasmas.

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 given 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 given 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 2021

1. M. A. Prakapenia and G. V. Vereshchagin, “Numerical scheme for evaluating the collision integrals for triple interactions in relativistic plasma”, Astronomy Reports, volume 65 (2021), pp. 1011–1014.

   We perform calculations of nonequilibrium reaction rates for all triple interactions in relativistic plasma including: relativistic bremsstrahlung, double Compton scattering, radiative pair production, triple pair production/annihilation and their inverse processes. Reaction rates are computed out of first principles, numerically integrating exact QED matrix elements over the phase space of particles. Example is given for photon emission by hot thermal electron-positron pairs.