# ICRANet-Minsk report 2020

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- Kinetics of relativistic plasma
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- Effects of gravity in light interaction with quantum systems

# 2 Participants

## 2.1 ICRANet-Minsk participants

- Sergei Kilin (director)
- Ivan Siutsou (from January to August – senior research fellow)
- Mikalai Prakapenia (research fellow)
- Stanislav Komarov (research fellow)
- 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). Announced scientific visits of I. Siutsou and M. Prakapenia were cancelled due to COVID-19 pandemic.

Within the framework of the joint project BRFFR-ICRANet-2019, a unique workstation was created at the Institute of Physics that uses general-purpose computations on graphics processors with a peak performance of 14 teraflops of double precision.

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, mechanical and optical evolution of different objects in the vicinity of black hole and effects of gravity in light interaction with quantum systems.

## 4.1 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)]. In the paper of Physics of Plasmas 27, 113302 (2020) we present 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. Reaction rates for thermal distributions are compared, where possible, with the corresponding analytic expressions, showing good agreement, with relative errors in the calculations not exceeding few percent, except for the case of relativistic bremsstrahlung where the error can reach up to 20%. The convergence of interaction rates with increasing grid resolution is demonstrated. The new kinetic code, which computes binary and triple interactions in relativistic plasma out of first principles has wide applications in astrophysics, as well as for the description of plasmas generated in a laboratory. Our results are relevant for quantitative description of relativistic plasmas out of equilibrium, both under astrophysical and laboratory conditions. These results were reported at the 4th Zeldovich virtual meeting in September 2020.

The results of investigations of Pauli blocking effects in thermalization process were published in Physics Letters A. Vol. 384, 27. P. 126679 (2020). The influence of Pauli exclusion principle on thermalization of relativistic plasma was studied for the first time in the framework of relativistic Uehling-Uhlenbeck equations. The collision integral contained all binary and triple quantum electrodynamical processes. It was shown that fully degenerate pair state without photons corresponds to the values of degeneracy parameter $D \gtrsim 1$. Therefore to reach small values of degeneracy parameter $D \ll 1$ initial state should contain a large amount of photons. Energy density and particle density should satisfy the following conditions: $\rho_{\pm} \gg \rho\gamma$ and $n_{\pm} \ll n_{\gamma}$. As it was expected pair annihilation process cancels initial degeneracy and thermalization of degenerate electron-positron pair plasma with zero electric charge has regular character. But it the case of nonzero electric charge the influence of pair annihilation can be suppressed and Pauli blocking effects thermalization process. It was shown that initial state with degenerate electrons and photons but without positrons evolves regularly. Initial degeneracy leads to suppression of reaction rates so that basic thermodynamic quantities does not change in time. And when Compton scattering process transfers electrons to higher energies so that degeneracy is decreased thermalization process has fast avalanche behaviour.

In the article of Monthly Notices of the Royal Astronomical Society, Volume 494, Issue 1, May 2020, Pages 1463–1469 it was shown that photospheric emission may originate from relativistic outflows in two qualitatively different regimes: last scattering of photons inside the outflow at the photospheric radius, or radiative diffusion to the boundary of the outflow. In this work the measurement of temperature and flux of the thermal component in the early afterglows of several gamma-ray bursts (GRBs) along with the total flux in the prompt phase are used to determine initial radii of the outflow as well as its Lorentz factors. The results indicate that in several cases (GRBs 060218, 111225A and 150727A) the inferred Lorentz factors are relatively small, $\Gamma < 10$, while in other cases (GRBs 090618, 131030A and 151027A) the inferred Lorentz factors are larger, $\Gamma > 10$. Such differences suggest two possible sources of the thermal component: mildly relativistic cocoons or highly relativistic jets. This is valid only for those cases, where inferred Lorentz factor is relatively small, below few tens.

## 4.2 Reconstruction of relative motion of a binary star in the vicinity of black hole by its redshift

The theoretical researches of motion of binary stars in the vicinity of the Galactic Center in Belarusian State University was started in 2010 by A. Gorbatsievich, A. Bobrik and A. Tarasenko. In 2015-2020 S. Komarov continued work on this topic.

The problem of calculating of radiation characteristics of a source that moves in external gravitational field of Schwarzschild or Kerr black hole has important place in the study of motion of stars in the neighbourhood of the Galactic Center and for testing theories of gravity. In [S. Komarov and A. Gorbatsievich, Int. J. Mod. Phys. A, 35, 2040052 (2020)] the method of reconstruction of motion of a binary star in the vicinity of supermassive black hole by time dependence of redshift of spectrum was proposed. The presented approach gives possibilities to take into account effects of strong external gravitational field. Due to this it is possible to use the approach for study of binary stars that moves on short distances from the Galactic Center ($100M$ — $100000M$, where $M$ is mass of supermassive black hole in the Galactic Center in geometrical units). It is shown in the paper that the redshift $z$ of a star in binary system, that moves in external gravitational field, as a function of time of observation can be expressed from the redshift for a single star by the formula:

$$z(\tau) = (1 + z_0(\tau)) \left(1 - \frac{1}{c}\frac{\partial}{\partial\tau}(n_{(\alpha)}X^{(\alpha)})\right) - 1 + \mathrm{O}\left(\frac{X^2}{M^2}, \frac{v^2}{c^2}\right), \qquad (4.2.1)$$

where $z_0(\tau)$ is the redshift of light of the imagine source that is located in the center of mass of the binary, $\tau$ is the proper time of the center of mass of the binary, $n^{(\alpha)} = k^{(\alpha)}/\sqrt{k_{(\beta)}k^{(\beta)}}$ is the normalised 3-wave vector of the light ray in the point of radiation, $X^{(\alpha)}$ are Fermi coordinates of the relative position of the stars, $v$ — their relative velocity.

The presented approach is tested on the model numerical problem. The possibility of reconstruction of the trajectory of motion of components open a prospect for investigation of such characteristic of relative motion as precession relative to the inertial reference frame due to the influence of external gravitational field. Or precession and deformation of the orbit of relative motion of the stars due to the gravitational interactions with external gravitational field. All these effects can be estimate using the reconstructed parameters of the orbit for different intervals of time of observation. These results were reported at the 4th Zeldovich virtual meeting in September 2020.

## 4.3 Gravitationally induced dephasing in multilevel atomic systems

The researches of quantum decoherence due to gravity was started in 2019 by Vlad Stefanov and Ivan Siutsou together with Dmitriy Mogilevtsev of Center of Quantum Optics and Quantum Information of B.I. Stepanov Institute of Physics (National Academy of Sciences of Belarus). In 2020 Vlad Stefanov continued that topic and provided analises for multi-level atoms.

In [Phys. Rev. D, 101, No. 4, 044042] was found that a photon absorbed by the stationary system of randomly placed stationary atoms is no more spontaneously emitted in the direction of the impinging photon. The influence of gravity leads to broadening of the angular distribution of emission. The spread of wave-vectors around the wave-vector of the impinging photon is defined by the quantity $a\nu/\Gamma$, distribution of $k_z$ being

$$G_{k_z} = \frac{-i}{a\nu} \exp\left[-(k_{0z} - k_z)\frac{\Gamma}{a\nu}\right] \Theta[k_{0z} - k_z], \tag{4.3.1}$$

where $\vec{k}_0$ is the vector of initial photon and $\Theta[k_{0z} - k_z]$ is the Heaviside step function.

An analogous result is obtained for the three-level system with cascade scheme of transitions:

$$\begin{aligned} G_{k_z+k'_z} = &\frac{i}{a\left((\nu_2 + i\Gamma_2/2)\omega_{\mathbf{k}'} - (\nu_1 + i\Gamma_1/2)(\omega_{\mathbf{k}} + \omega_{\mathbf{k}'})\right)} \times \\ &\times \exp\left[i(k_{0z} - k_z - k'_z)(2/a + Z)\right] \times \\ \times \Bigg(\exp\left[-(k_{0z} - k_z - k'_z)\frac{\Gamma_2 - 2i\nu_2}{a(\omega_{\mathbf{k}} + \omega_{\mathbf{k}'})}\right] &- \exp\left[-(k_{0z} - k_z - k'_z)\frac{\Gamma_1 - 2i\nu_1}{a\omega_{\mathbf{k}'}}\right]\Bigg) \times \\ &\times \Theta[k_{0z} - k_z - k'_z]. \end{aligned} \tag{4.3.2}$$

It seemed interesting to model the situation in which one of two spontaneously emitted photons is detected with subsequent averaging of the wave vector. In that case the wave function coincides in zero order with expression obtained for the vacuum case. The obtained results could seem obvious because all intermediate calculations were made for corrections linear in a and the zero term of the expansion should coincide with the unperturbed one. However, the loss of phase matching appears namely in the zero term because the expansion in a becomes erratic due to the arising delta functions. The nontriviality of the zero order results only from effects associated with the time dilation of atoms at various heights. Therefore, it could be shown that the influence of the change in the time rate will dominate in further calculations. The results showed that this was not so and that all corrections linear in a should be taken into account to describe the effect of a weak gravitational field on the spectral line width.

An analogous result could also be obtained for any multilevel system because only the uncertainty of the wave vector of one of the photons is essential to the calculation. The range of emission frequencies or lifetime of atomic levels was not indicated in describing the disappearance of the zero-order gravitational effect after averaging the state of one of the emitted photons. This suggested that nullification also occurred for an unobserved transition. These results were reported at the 4th Zeldovich virtual meeting in September 2020.

# 5 Teaching and outreach

ICRANet-Minsk stuff performs teaching activities. Mikalai Prakapenia is a lecturer in theoretical mechanics and electrodynamics in the Belarusian State University, while Ivan Siutsou gives lectures on nonlinear physics, astrophysics and physical kinetics for master students of the Graduate School of the National Academy of Sciences of Belarus.

Also Vlad Stefanov, Ivan Siutsou and Mikalai Prakapenia are scientific consultants of the school team (gymnasium No. 61 in Minsk) in the "International Young Physicists' Tournament".

ICRANet-Minsk is active in popularization of physics and astrophysics. The open lecture by prof. Vereshchagin "Nobel Prize in Physics 2020: laureates and their results" was organized by the Belarusian Physical Society.

Stanislav Komarov, Mikalai Prakapenia and Vlad Stefanov defended their Ph.D. theses and received degrees in September (Stanislav Komarov) and in November (Mikalai Prakapenia and Vlad Stefanov) 2020.

# 6 Publications 2020

1. M.A. Prakapenia, "Pauli blocking effects in thermalization of relativistic plasma"/M. A. Prakapenia, G. V. Vereshchagin // Physics Letters A. – 2020. – Vol. 384. – P. 126679

   We investigate the effects of Pauli blocking on thermalization process of relativistic plasma by solving relativistic Uehling-Uhlenbeck equations with QED collision integral for all binary and triple processes. With this purpose we consider nonequilibrium initial state of plasma to be strongly degenerate. We found that when electron-positron annihilation is active, initial plasma degeneracy is quickly destroyed. As a result in a wide range of final temperatures ranging from nonrelativistic to mildly relativistic $0.1 m_e c^2 \leqslant k_B T \leqslant 10 m_e c^2$ thermalization is not affected by Pauli blocking. Conversely, when electron-positron annihilation process is inactive, thermalization process in such degenerate plasma is strongly affected by Pauli blocking. This is possible either in a nonrelativistic plasma, with equilibrium temperature $k_B T \leqslant 0.3 m_e c^2$, or in photon-electron plasma. In these cases all reaction rates are strongly suppressed by Pauli blocking and thermalization does not occur until electrons can populate energy states above the Fermi energy. Soon after this happens thermalization proceeds suddenly in an avalanche-like process.

2. M.A.Prakapenia, "Numerical scheme for evaluating the collision integrals for triple interactions in relativistic plasma"/ Prakapenia M. A., Siutsou I. A., Vereshchagin G. V. // Physics of Plasmas. – 2020. – Vol. 27. – No. 11. – P. 113302.

   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 present 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. Reaction rates for thermal distributions are compared, where possible, with the corresponding analytic expressions, showing good agreement. Our results are relevant for quantitative description of relativistic plasmas out of equilibrium, both under astrophysical and laboratory conditions.

3. S. Komarov, “Reconstruction of relative motion of a binary star in the vicinity of black hole by its redshift”/ S. Komarov, A. Gorbatsievich // International Journal of Modern Physics A. – 2020.– Vol. 35.– P. 2040052

   The redshift of the spectral lines of electromagnetic radiation of a binary star that moves in the vicinity of a supermassive black hole is considered. An approach for the reconstruction of the relative motion of the components of the binary using observational data of redshift is proposed.

4. V. Stefanov, “Conditional Disappearance of Gravitational Dephasing in Multilevel Atomic Systems”// Journal of Applied Spectroscopy – 2020. – Vol. 87. – No. 4. – P. 641-646

   The state of an ensemble of three-level atoms after absorption of a single photon and subsequent spontaneous decays in the presence of a weak gravitational field is shown to lose the phase matching of the emitted photons with the wave vector of the absorbed photon, similar to the case of an ensemble of two-level atoms. However, the spatial distribution of a second photon coincides with the result for a space without a gravitational field when averaging over the state of one of the emitted photons.