Theoretical Astroparticle Physics

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1 Topics

- Relativistic plasma
  - Degeneracy effects in relativistic plasma
- Photospheric emission
  - Is magnetically dominated outflow required to explain GRBs?
- Charged particle motion near black holes
  - The motion and radiation of a test charged particle in the vicinity of a black hole

2 Participants

2.1 ICRANet participants

- Liang Li
- Remo Ruffini
- Gregory Vereshchagin

2.2 Ongoing collaborations

- Alexey Aksenov (ICAD, RAS, Russia)
- Damien Begue (Bar Ilan University, Israel)
- Alexander Garkun (Institute of Applied Physics of NAS of Belarus)
- Alexander Gorbatsievich (BSU, Belarus)
- Mikalai Prakapenia (ICRANet-Minsk and BSU, Belarus)
- Stanislav Komarov (ICRANet-Minsk and BSU, Belarus)

3 Brief description

Astroparticle physics is a new field of research emerging at the intersection of particle physics, astrophysics and cosmology. Theoretical development in these fields is mainly triggered by the growing amount of experimental data of unprecedented accuracy, coming both from the ground based laboratories and from the dedicated space missions.

3.1 Relativistic plasma

Electron-positron plasma is of interest in many fields of physics and astrophysics, e.g. in the early universe, active galactic nuclei, the center of our Galaxy, compact astrophysical objects such as hypothetical quark stars, neutron stars and gamma-ray bursts sources. It is also relevant for the physics of ultraintense lasers and thermonuclear reactions. We study physical properties of dense and hot electron-positron plasmas. In particular, we are interested in the issues of its creation and relaxation, its kinetic properties and hydrodynamic description, baryon loading and radiation from such plasmas.

Two different states exist for electron-positron plasma: optically thin and optically thick. Optically thin pair plasma may exist in active galactic nuclei and in X-ray binaries. The theory of relativistic optically thin nonmagnetic plasma and especially its equilibrium configurations was established in the 80s by Svensson, Lightman, Gould, Haug and others. It was shown that relaxation of the plasma to some equilibrium state is determined by a dominant reaction, e.g. Compton scattering or bremsstrahlung.

Developments in the theory of gamma ray bursts from one side, and observational data from the other side, unambiguously point out on existence of optically thick pair dominated non-steady phase in the beginning of formation of GRBs. The spectrum of radiation from optically thick plasma is usually assumed to be thermal.

Experiments with high intensity laser beams interacting with each other as well as with solid targets aim at creation of relativistic plasmas and their study in laboratory conditions. The goal of such experiments is reproduction of astrophysical plasmas in controlled environment.

In a series of publications we consider kinetic, electrodynamic, hydrodynamic and observational properties of relativistic plasma.

In 2022 in collaboration with the Universe journal we launched a Special Issue of this journal dedicated to relativistic kinetic theory. The goal of this Special Issue is to cover the recent developments in kinetic theory, with particular attention to relativistic plasma, neutrino transport, self-gravitating systems and dark matter, radiative transfer in relativistic flows and other new and emergent topics in kinetic theory. Altogether we received six contributions:

- ”A Multidimensional Multicomponent Gas Dynamic with the Neutrino Transfer in Gravitational Collapse” by Alexey G. Aksenov,
- ”Field-Theoretical Representation of Interactions between Particles: Classical Relativistic Probability-Free Kinetic Theory” by Anatoly Yu. Zakharov and Victor V. Zubkov,
- ”Post-Newtonian Jeans Equation for Stationary and Spherically Symmetrical Self-Gravitating Systems” by Gilberto Medeiros Kremer,
- ”The Principle of Maximum Entropy and the Distribution of Mass in Galaxies” by Jorge Sanchez Almeida,
- ”The secular dressed diffusion equation” by Pierre-Henri Chavanis
- ”Kinetics of Degenerate Electron–Positron Plasmas” by Gregory Vereshchagin and Mikalai Prakapenia.

3.1.1 Kinetics of Degenerate Electron–Positron Plasmas

One of the contributions to the Special Issue of the Universe journal is our review ”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.

The review starts with the formulation of conditions for formation of relativistic degenerate plasma both in astrophysical systems as well as in laboratory. In particular, the role of strong electromagnetic fields in compact astrophysical objects and the ultraintense lasers is discussed. Relativistic kinetic equations with quantum corrections are derived from the quantum kinetic theory. Collision integrals for binary and triple interactions of quantum electrodynamics are presented. The relation between kinetic and thermal equilibria is pointed out. Numerical examples of degenerate plasma are given, which illustrate new phenomena: 1) Bose condensation of photons in relativistic plasma and 2) avalanche thermalization of strongly degenerate fermions.

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, see Vereshchagin and Prakapenia (2022).

3.2 Photospheric emission

Emission from optically thick stationary plasma is an important topic in astrophysics. Such plasma confined by the gravitational field constitutes stars, accretion disks and other objects. The light from these systems is coming from the photosphere defined as a region where the optical depth computed from the interior of the optically thick plasma outwards reaches unity.

There are also dynamical sources where bulk velocities of plasma reach ultrarelativistic values such as microquasars, active galactic nuclei and gamma-ray bursts (GRBs). While in the former two objects there is clear evidence for jets which contain optically thin plasma, in the latter objects the issue of jets is controversial, and the source is required to be optically thick. This observational fact poses a new problem: the emission from (spherically) expanding plasma which initially is optically thick. Such plasma eventually becomes optically thin during its expansion, and initially trapped photons should be released. We have developed a new theory of photospheric emission in GRBs, reviewed in Vereshchagin (2014) and recently applied it also to the emission observed in their early afterglows Vereshchagin and Siutsou (2020).

This year we focused in the implications of observed photospheric emission on the composition of relativistic outflows producing GRBs.

3.2.1 Is magnetically dominated outflow required to explain GRBs?

The composition of relativistic outflows producing gamma-ray bursts is a long standing open question. One of the main arguments in favor of magnetically dominated outflows is the absence of photospheric component in their broadband time resolved spectra, with such notable example as GRB 080916C Zhang and Pe'er (2009).

In this paper we present the new spectral analysis of GRB 080916C, and confirm the previous results on the presence of additional spectral component in the time resolved spectra Guiriec et al. (2015). By interpreting this spectral component as photospheric emission and by applying the method of ref. Pe'er et al. (2007) we estimate the Lorentz factor of the baryonic outflow, the nozzle radius and the photospheric radius of the outflow. Our results indicate that observations of GRB 080916C can be naturally accounted for in the standard baryonic fireball model, provided that the high energy emission, detected in this GRB originates not at the photosphere, but at larger radii. This is consistent with the earlier proposals of high energy emission emerging in the external shock. We argue that the main assumption behind the conclusions in Zhang and Pe'er (2009) is the origin of the broadband non-thermal emission in the same zone (one-zone approximation). This is clearly not required by the data, and cannot provide evidence for the outflow composition.

Results of this work were reported at the 6th Bego Rencontre Summer School, ICRANet Seat at Villa Ratti, Nice (France) and online, 4-14 July 2022.

These results are published in MNRAS, see Vereshchagin et al. (2022).

3.3 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. Specifically, the following is planned to be achieved:

- Obtain the equations of motion of a test charge in the curved spacetime and quantify the role of the curvature and reaction of electromagnetic radiation in the equations of motion and in the properties of electromagnetic radiation.
- Find analytic (or numerical) solutions of the equations of motion, describing test charge motion in the external gravitational field, as well as its electromagnetic radiation. Study in particular the case of a test charge moving in the vicinity of non-rotating black holes, including magnetized one.
- Apply the results to particular astrophysical problems, connected with radiation in the vicinity of black holes.

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

The problem of point charge motion in external gravitational field of a black hole is very important for the understanding of the mechanisms of plasma accretion e. g. within the recently proposed unified model of gamma-ray bursts and quasars Ruffini et al. (2018, 2019); Rueda and Ruffini (2020). There are many open questions about the electromagnetic radiation and the motion of such charges Shatskiy et al. (2013); Tursunov et al. (2018); Poisson et al.

(2011). The main difficulties emerge in the description of electromagnetic radiation reaction and in the description of the influence of external gravitational field on electromagnetic field distribution and on the motion of the charge.

In this work we consider electromagnetic field of point charge moving radially in the vicinity of a Schwarzschild black hole. By using the approach that is based on the papers Ruffini et al. (1972); Ruffini (1972) we study analytically and numerically electromagnetic spectrum of radiation of the charge in wave zone. Also we consider electromagnetic field and electromagnetic self-force for the charge. Using covariant formalism for the description of electromagnetic field from the paper Poisson et al. (2011) we obtain analytical formula for the self-force that can be used in vicinity of the event horizon of black hole. We obtain numerical results and compare it with those in the literature.

The main result of this work is the solution for the spectrum of the electromagnetic radiation of the charge falling into Schwarzschild black hole presented in compact form using the confluent Heun functions. For multipole components of the electromagnetic field vector A_k one has the following equation (for notation see Ruffini (1972))

$$\left[\left(1-\frac{2M}{r}\right)\tilde{b}_{lm,r}\right]_{,r}+\left(\frac{\omega^2}{1-2M/r}-\frac{l(l+1)}{r^2}\right)\tilde{b}_{lm}=a(r)\,,$$

where

$$a(r)=\frac{q}{2\pi}\frac{2l+1}{l(l+1)}e^{it(r)}\left[\frac{ME/r^2}{(E^2-1+2M/r)^{3/2}}-\frac{i\omega}{E^2-1+2M/r}\right].$$

The solution is

$$b_{lm}(r,\omega)=\frac{1}{W(r)(1-\frac{2M}{r})}\left[y_1(r)\int\limits_r^{+\infty}y_2(r')a(r')\mathrm{d}r'+y_2(r)\int\limits_{2M}^{r}y_1(r')a(r')\mathrm{d}r'\right],$$

where $y_1(r)$ and $y_2(r)$ are linear independent solutions of the homogeneous equation, where $W(r)=y_1(r)y_2'(r)-y_1'(r)y_2(r)$ is Wronskian. In order to satisfy boundary conditions it is necessary to choose solutions y_1 as ingoing wave at the event horizon, and y_2 as outgoing wave at the spatial infinity.

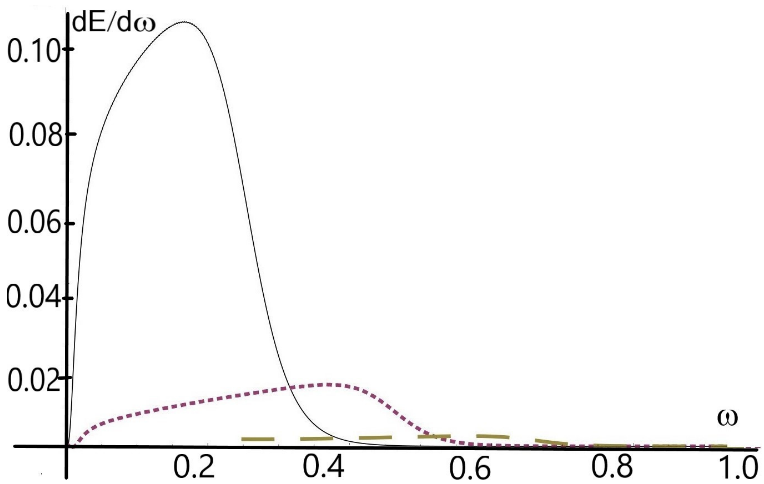

Figure 3.1: Spectrum of electromagnetic radiation of the particle, falling radially into the Schwarzschild black hole, for different multipole index l: for $l = 1$ (solid), for $l = 2$ (point), for $l = 3$ (dotted). Frequency is calculated in units of $1/M$.

First solution can be written by using confluent Heun functions for the variable $\xi = r/2M$:

$$y_1 = \xi^2(\xi - 1)^{-2i\omega} e^{-2i\omega\xi} H(\xi) \,. \tag{3.3.1}$$

The numerical solution for electromagnetic radiation spectrum integrated over time is shown in Fig. 3.1.

This work is supported within the joint BRFFR-ICRANet-2021 funding programme within the Grant **No. F21ICR-002**. These results are submitted for publication in NPCS, to appear in 2023 Komarov et al. (2022).

4 Publications

1. 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.

2. D. Begue, L. Li and G. V. Vereshchagin, "Is magnetically dominated outflow required to explain GRBs?", MNRAS 512 (2022) pp.4846-4851

   The composition of relativistic outflows producing gamma-ray bursts is a long standing open question. One of the main arguments in favor of magnetically dominated outflows is the absence of photospheric component in their broadband time resolved spectra, with such notable examples as GRB 080916C. Here we perform accurate analysis of time resolved spectra of this GRB and confirm the previous detection of additional spectral component in GRB 080916C. We show that this subdominant component is consistent with the photosphere of ultrarelativistic baryonic outflow, deep in the coasting regime. We argue that, contrary to previous statements, the magnetic dominance is not required for interpretation of observations of this GRB. Moreover, simultaneous detection of high energy emission in its prompt phase requires departure from a simple one-zone emission model.

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.

4.1 Invited talks at international conferences

1. "Kinetic effects in nonequilibrium electron-positron plasmas", Prof. Remo Ruffini Festschrift. A conference in celebration of Prof. Remo Ruffini 80th birthday, ICRANet Seat at Villa Ratti, Nice (France) and online, 16-18 May 2022.

2. "Photospheric emission from relativistic cocoons", the 6th Bego Rencontre Summer School, 4-14 July 2022, ICRANet Seat at Villa Ratti, Nice (France) and online.

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