Theoretical Astroparticle Physics

Contents

1 Topics

- Relativistic plasma
  - Pauli blocking effects on pair creation in strong electric field
- Strong fields in astrophysics
  - Pair production in hot electrospheres of compact astrophysical objects
- Charged particle motion near black holes
  - Electromagnetic field of a charge asymptotically approaching a spherically symmetric black hole

2 Participants

2.1 ICRANet participants

Gregory Vereshchagin

2.2 Ongoing collaborations

- Alexey Aksenov (ICAD, RAS, Russia)
- Alexander Garkun (Institute of Applied Physics of NAS of Belarus)
- Alexander Gorbatsievich (BSU, Belarus)
- Alexander Fedotov (MEPhI, Russia)
- Mikalai Prakapenia (ICRANet-Minsk and BSU, Belarus)
- Stanislav Komarov (ICRANet-Minsk and BSU, Belarus)
- Rahim Moradi (Institute of High Energy Physics, Chinese Academy of Sciences, China)
- Yu Wang (ICRA and ICRANet)

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 2024 we focused on electrodynamic part and pair creation, accounting for quantum statistics of particles.

3.2 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, for reviews see Ruffini et al. (2010); Vereshchagin and Prakapenia (2022). Various kinetic effects in strong electromagnetic fields are discussed in Vereshchagin and Aksenov (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.

3.2.1 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*. Electrospheres are predicted for such hypothetical objects as superheavy nuclei Migdal et al. (1976) and quark nuggets Forbes et al. (2010). The magnitude of electric field in electrosphere depends on the sharpness of the boundary of positively charged component Mishustin et al. (2010). Usov in his seminal paper Usov (1998) proposed that hot quark stars may be a source of pair winds, potentially observable at cosmological distances. The main parameter determining the wind is the temperature on the quark star surface T_S. Based on this work detailed study of particle interactions was performed by Aksenov et al. Aksenov et al. (2004, 2005) predicting observed properties of hot quark stars. Usov's rate is used in many publications since then.

In our paper Prakapenia and Vereshchagin (2024) we reconsider Usov's mechanism of pair creation in electrosphere of compact objects. First, we show that the reasoning under Usov's results contain some flaws. Then, we provide new arguments how pair creation can operate, and derive the rate of pair creation together with pair luminosity for electrosphere of a compact astrophysical object. Finally we perform self-consistent simulations for electron-positron pair creation and electric field evolution in electrosphere using Vlasov-Boltrzmann equations, describing distribution functions of electrons and positrons, and Maxwell equations describing time and space evolution of electric field. Our results indicate that hot electrosphere indeed is a source of strong pair wind.

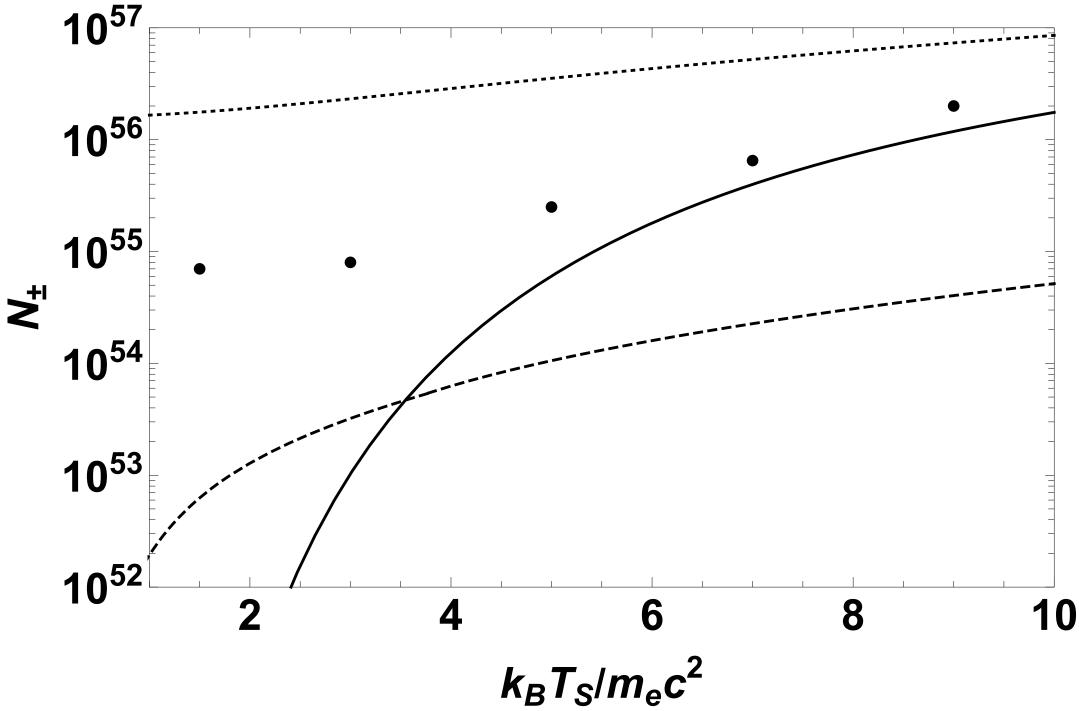
In particular, our kinetic simulation reveals two physical effects in hot electrosphere, which were ignored in previous analyses. The first effect is the inflation of electrosphere due thermal evaporation of electrons, leading to its spatial extension to distances much larger than the electrostatic solution implies. The second effect is enhancement of the rate of pair creation due to pair simultaneous acceleration by the electric field, first established in Benedetti et al. (2011). The latter effect can operate at electric fields values up to $E \lesssim 127 E_c$. 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, see Fig. 3.1.

Numerical simulations show that, as expected, the Schwinger process operates for nonzero temperature T_S. Positrons are accelerated in the Coulomb barrier and move outward. The total outward flux is approximately neutral due ability of electrons to overcome the Coulomb barrier. The distribution of the electric field and electron density is quasi static, and pair creation does not back react on the electrosphere. As a result electrons do not occupy all empty states and the process operates continuously.

Our results are summarized in Fig. 3.1. Usov's original prediction is shown by dashed curve. The rate obtained from the high field approximation $E \gg E_c$ to the Schwinger formula neglecting Pauli blocking factors is shown by dotted curve. The rate obtained from the Schwinger formula with Pauli blocking factors is shown by solid curve. Dots represent numerical results from solution of the Vlasov-Maxwell equations.

Initial conditions are chosen from electrostatic solution to the Maxwell-Vlasov system, neglecting pair creation. We recall that electrostatic solution of the the full Maxwell equations exists only in the case $T_S = 0$, that is for fully degenerate electrons. Only in this case the chemical potential $\mu = e\varphi$ equals Fermi energy, which means that there are no electrons with energies exceeding the Coulomb barrier. However, when the surface temperature is non-zero $T_S > 0$ there is a small part of electrons with energies larger than the Coulomb barrier. These electrons move outward the surface increasing

Figure 3.1: Pair creation rate in the electrosphere $\dot{N}_{\pm}$ according to Usov (dashed curve), ignoring Pauli blocking (dotted curve) and taking into account Pauli blocking but neglecting pair acceleration (solid curve). Dots represent numerical results.



the electric field outside the surface of the compact object, leading to electrosphere inflation.

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.

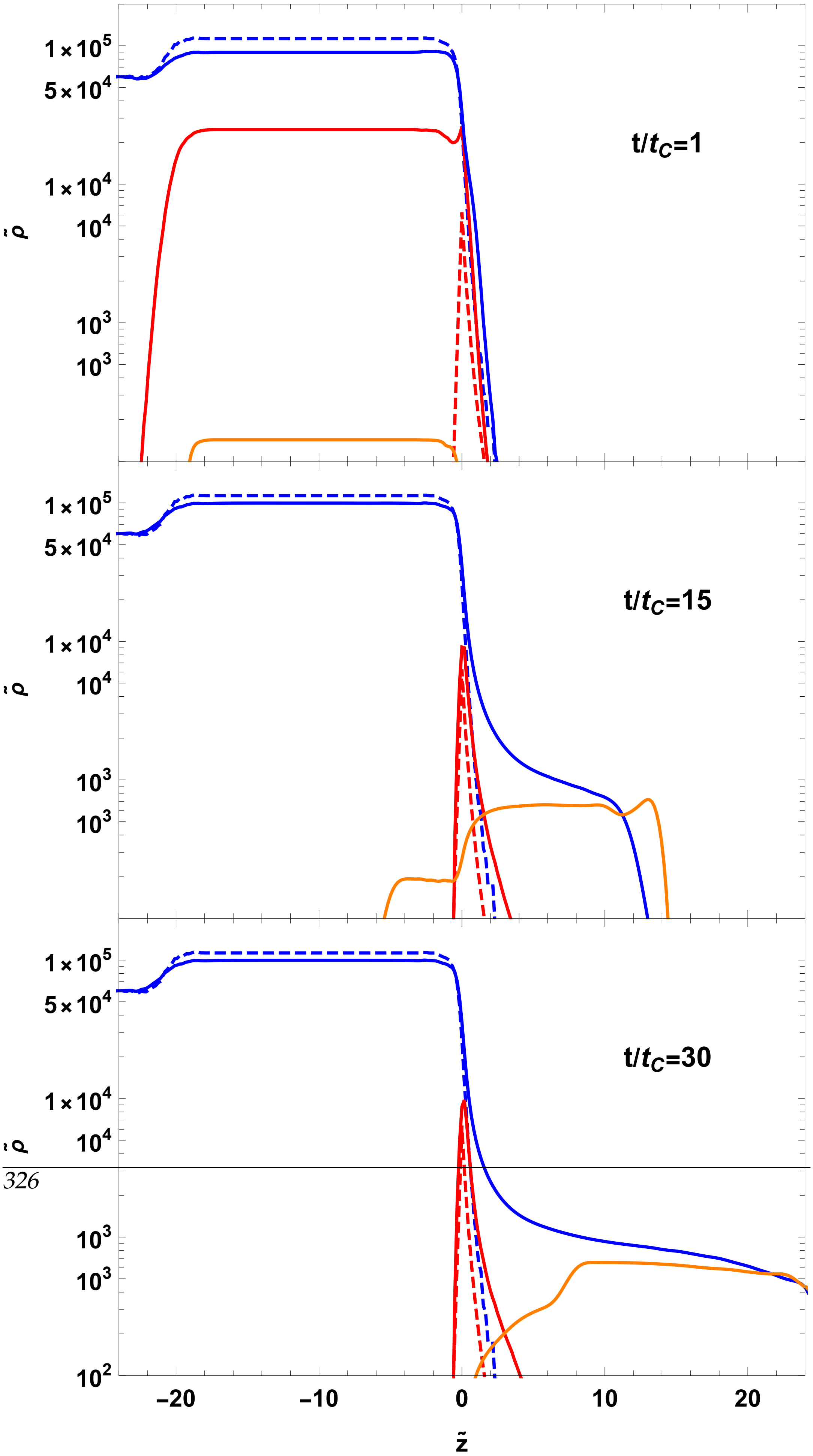
This work is supported within the joint BRFFR-ICRANet-2023 funding programme within the Grant **No. F23ICR-001**. The results are presented in several meetings and published in the Astrophysical Journal, 2024.

3.2.2 Radial electromagnetic perturbation of a compact astrophysical object

We also considered another mechanism of energy deposition on the surface of a compact object with electrosphere: the deformation of the surface, e.g. radial displacement with respect to the electrostatic solution. Electrons and quarks respond differently to such a deformation (due to different fundamental interactions involved). Then such mechanical deformation will result in electrodynamical perturbation. We model such a perturbation as electric current. This is an alternative mechanism to heating, which, as we show, may also result in pair creation in the perturbed electrosphere.

We study relaxation of such perturbations in a microscopic scale for different parameters, characterizing the problem. With this goal relativistic kinetic equations with both source term describing the Schwinger pair production and collisional term describing relaxation accounted for are solved numerically together with the Maxwell equations.

Our results are shown in Fig. 3.2, where energy density evolution in all components (electrons, positrons and electric field) are shown for a perturbation extended on a spatial scale much larger than the mean free path for Coulumb collisions. At the time moment $t = 1t_c$ electrons move outside the surface in accordance with its initial velocity, but energy excess is not dissolved yet. The perturbation in fact is a form of electric current which acts to increase the electric field within the surface of the compact object, leading to electron-positron creation in that region. The integral energy in different components is shown in Fig. 3.2. One can see that the increase of the electric energy occurs simultaneously with the decrease of the energy of electrons. Then at the time moment $t = 15t_c$ after a few oscillations, which are visible in Fig. 3.2, electric field decreases down to its electrostatic values, and a flux of electron-positron pairs forms outside the surface of the star. At this point pairs are created in the electrosphere with nearly a constant rate, as can be seen also from Fig. 3.2, where the energy of positrons grows monotonically. This pair creation process is caused by thermalization of perturbed electrons. Finally, at the time moment $t = 30t_c$ there is a steady approximately electrically neutral pair flux outside the surface.


t/t_C=1
t/t_C=15
t/t_C=30
1×10^5
5×10^4
1×10^4
10^4
10^3
10^2
$\tilde{\rho}$
-20
-10
0
10
20
$\tilde{z}$

Our simulations imply that the necessary condition for steady pair creation to occur is that the spatial scale of perturbation exceeds the mean free path, so that the electromagnetic perturbation is not dissipated, but its energy is converted into thermal energy, which in turn leads to opening up of the phase space for electrons and the corresponding possibility for prolific pair creation due to the Schwinger process. When this condition is not satisfied, pairs are created only in a short burst due to plasma oscillations, which quickly dissipate due to collisions. The mechanism of pair creation in this case is different from the thermal one: it is due to plasma oscillations, and not due to heating.

This work is supported within the joint BRFFR-ICRANet-2023 funding programme within the Grant **No. F23ICR-001**. The results are presented in several meetings and submitted for publication to Physical Review D, 2024.

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.

3.3.1 Electromagnetic field of a charge asymptotically approaching a spherically symmetric black hole

The dynamics of electromagnetic fields and electromagnetic radiation of charged particles moving in the vicinity of a black hole are relevant in many astrophysical problems, and they are involved in the description of active galactic nuclei, X-ray binaries, and microquasars. Recently, the interest in this subject has been revived due to the realization that magnetized black holes may accelerate particles and thus produce strong electromagnetic signals. This is an important subject for models of energy extraction from black holes.

We prepared an extensive review of the main works dedicated to this topic, published last year Komarov and Vereshchagin (2025).

Given the fact that the problem under consideration is quite involved, the solution is approached in steps. The first step is the determination of the electromagnetic field of a static charge outside the black hole. Then, the dynamical problem is addressed with the motion of a charge without radiation. Next, the problem of a charge (mass) emitting electromagnetic (gravitational) radiation is considered. Finally, the radiation reaction on the motion of the charge is taken into account. We prepared a review of the historic developments and recent results obtained in the study of this problem. Our main goal was to highlight the basic assumptions and limitations of various techniques and point out the main conclusions of these studies.

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

These results are published in Particles 2025, 8, 1.

4 Publications

4.1 Refereed papers

1. M. A. Prakapenia and G. V. Vereshchagin, "Pair creation in hot electrosphere of compact astrophysical objects", ApJ 963 (2024) 149.

   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.

2. S. O. Komarov and G. V. Vereshchagin, "Electromagnetic Field and Radiation of Charged Particles in the Vicinity of Schwarzschild Black Hole", Particles 2025, 8, 1.

   We provide a concise review of the problem of calculating the electromagnetic field and radiation of a charged particle in the vicinity of a black hole. The interest in this problem has been revived due to recent progress in multimessenger observations. Many astrophysical models of energy extraction from a black hole involve consideration of such motion and radiation. Our main goal is to highlight the basic assumptions and limitations of various techniques and point out the main conclusions of these studies.

3. Mikalai Prakapenia and Gregory Vereshchagin, "Pair creation from radial electromagnetic perturbation of a compact astrophysical object", submitted to Phys. Rev. D, 2024.

Recently Usov's mechanism of pair creation on the surface of compact astrophysical objects has been revisited [1] with a conclusion that the pair creation rate was previously underestimated in the literature by nearly two orders of magnitude. Here we consider an alternative hypothesis of pair creation due to a perturbation of the surface of a compact object. Radial perturbation is induced in hydrodynamic velocity resulting in a microscopic displacement of the negatively charged component with respect to the positively charged one. The result depends on the ratio between the spatial scale of the perturbation $\lambda$and the mean free path l. When $\lambda \sim l$the perturbation energy is converted into a burst of electron-positron pairs which are created in collisionless plasma oscillations at the surface; after energy excess is dissipated electrosphere returns to its electrostatic configuration. When instead $\lambda \gg l$, the perturbation is thermalized, its energy is transformed into heat, and pairs are created continuously by the heated electrosphere. We discuss the relevant astrophysical scenarios.

4.2 Invited talks at international conferences

- Invited talk by Gregory Vereshchagin "On pair creation in electrosphere of compact astrophysical objects", Looking AHEAD to soft gamma-ray Astrophysics: prospects and challenges, February 14 – 16, 2024, Ferrara, Italy.
- Talk by Gregory Vereshchagin "Schwinger process in hot electrospheres of strange stars", The 17th Marcel Grossmann Meeting, July 9, 2024, Pescara, Italy.
- Talk by Gregory Vereshchagin "Magnetically dominated outflow in GRB 080916C?", The 17th Marcel Grossmann Meeting, July 9, 2024, Pescara, Italy.
- Talk by Gregory Vereshchagin "Electron-positron pair creation in electrosphere of compact astrophysical objects", High Energy Astrophysics and Cosmology in the era of all-sky surveys, Yerevan, Armenia, October 7 – 11, 2024.
- Seminar by Gregory Vereshchagin "Electron-positron pair creation in electrosphere of compact astrophysical objects" at the Astronomical Observatory of Belgrade, December 11, 2024, Belgrade, Serbia.

Bibliography

AKSENOV, A.G., MILGROM, M. AND USOV, V.V.
Structure of Pair Winds from Compact Objects with Application to Emission from Hot Bare Strange Stars.
Astrophysical Journal, **609**, pp. 363–377 (2004).
doi:10.1086/421006.

AKSENOV, A.G., MILGROM, M. AND USOV, V.V.
Pair Winds in Schwarzschild Spacetime with Application to Hot Bare Strange Stars.
ApJ , **632**, pp. 567–575 (2005).
doi:10.1086/432905.

BENEDETTI, A., HAN, W.B., RUFFINI, R. AND VERESHCHAGIN, G.V.
On the frequency of oscillations in the pair plasma generated by a strong electric field.
Physics Letters B, **698**, pp. 75–79 (2011).
doi:10.1016/j.physletb.2011.02.050.

FORBES, M.M., LAWSON, K. AND ZHITNITSKY, A.R.
Electrosphere of macroscopic "quark nuclei": A source for diffuse MeV emissions from dark matter.
Phys. Rev. D, **82(8)**, 083510 (2010).
doi:10.1103/PhysRevD.82.083510.

KOMAROV, S. AND VERESHCHAGIN, G.
Electromagnetic field and radiation of charged particles in the vicinity of schwarzschild black hole.
Particles, **8(1)** (2025).
ISSN 2571-712X.
doi:10.3390/particles8010001.

MIGDAL, A.B., VOSKRESENSKIĬ, D.N. AND POPOV, V.S.

Distribution of vacuum charge near supercharged nuclei.
Soviet Journal of Experimental and Theoretical Physics Letters, **24**, p. 163 (1976).

MISHUSTIN, I.N., EBEL, C. AND GREINER, W.
Strong electric fields induced on a sharp stellar boundary.
Journal of Physics G Nuclear Physics, **37(7)**, 075201 (2010).
doi:10.1088/0954-3899/37/7/075201.

PRAKAPENIA, M. AND VERESHCHAGIN, G.
Pair Creation in Hot Electrosphere of Compact Astrophysical Objects.
ApJ , **963(2)**, 149 (2024).
doi:10.3847/1538-4357/ad24ee.

RUFFINI, R., VERESHCHAGIN, G. AND XUE, S.S.
Electron-positron pairs in physics and astrophysics: From heavy nuclei to black holes.
Phys. Rep. , **487**, pp. 1–140 (2010).
doi:10.1016/j.physrep.2009.10.004.

USOV, V.V.
Bare Quark Matter Surfaces of Strange Stars and e^+e^- Emission.
Physical Review Letters, **80**, pp. 230–233 (1998).

VERESHCHAGIN, G. AND PRAKAPENIA, M.
Kinetics of Degenerate Electron–Positron Plasmas.
Universe, **8(9)**, p. 473 (2022).
doi:10.3390/universe8090473.

VERESHCHAGIN, G. AND AKSENOV, A.
Relativistic Kinetic Theory: With Applications in Astrophysics and Cosmology (Cambridge University Press, 2017).
ISBN 9781107048225.