Electron-positron pair creation in electrosphere of compact astrophysical objects

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Schwinger process

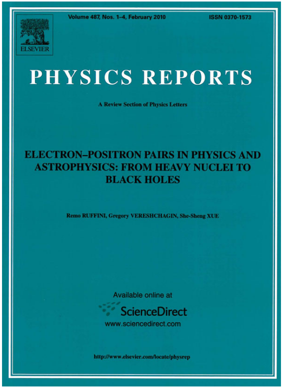
QED predicts the creation of $e^{\pm}$ pairs in strong electric field out of vacuum as a nonperturbative process when the field strength exceeds $E_c = m^2c^3/e\hbar \sim 10^{18}$ V/m. Predicted more than ninety years ago, but not yet observed in laboratory.

In *laboratory* attempts to create such a plasma are linked with the development of ultra-intense lasers within large projects, such as ELI, CoReLS and XCELS.

In *astrophysics* $e^{\pm}$ plasma is present is relativistic and transient high energy sources: gamma-ray bursts, soft gamma repeaters, in magnetospheres of compact objects.

The presence of pairs in plasma greatly enhances opacity. Short time-scales of variability of astrophysical sources and non-thermal spectra of observed radiation imply that such plasmas are not in thermal equilibrium: the description requires kinetic approach.

Literature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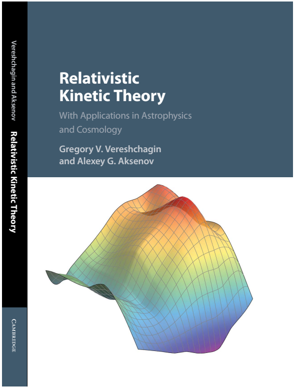
Vereshchagin and Aksenov
Relativistic Kinetic Theory
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Relativistic
Kinetic Theory
With Applications in Astrophysics
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Gregory V. Vereshchagin
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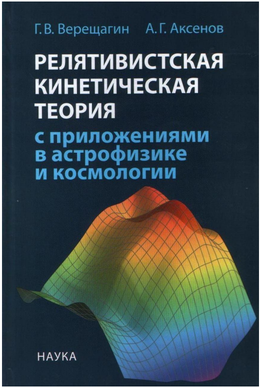
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Outline

In what follows I will present results of two recent works:

- Mikalai Prakapenia and Gregory Vereshchagin, ”Pair creation in hot electrosphere of compact astrophysical objects”, ApJ 963, 149 (2024).
- Mikalai Prakapenia and Gregory Vereshchagin, ”Pair creation from radial electromagnetic perturbation of a compact astrophysical object”, submitted to Phys. Rev. D (2024)

Electrosphere of compact objects

1. Strong electric fields may exist on bare surfaces of hypothetical quark stars (Alcock, 1986) or even neutron stars (e.g. Belvedere et al., 2012). The region with overcritical $E > E_c$ electric field in these objects is called *electrosphere*.
2. Electrosphere is formed because the sharpness of the quark (neutron) star surface is determined by the strong interactions, while degenerate electrons are bound to quarks by electromagnetic interactions. Thus electron spatial distribution extends to larger, yet microscopic, distances.
3. In vacuum such a field should produce electron-positron pairs, but this does not happen at small temperatures, due to the *Pauli blocking*.
4. To start the pair creation process empty electronic states must be present. This is possible when the compact object is just formed, with its surface temperature $k_B T_S \sim \varepsilon_F \sim 20$ MeV (Usov, 1998).

Usov's mechanism

1. All empty states below the pair creation threshold are instantly occupied by creating electrons and positrons;
2. the slower process of thermalization of electrons determines the appearance of new empty states for electrons;
3. positrons are ejected by the electric field; charge neutrality requires the outflow of electrons.

$$\dot{n}_\pm = \frac{\dot{N}_\pm}{S_R \Delta r_E} \simeq \Delta n_e / \tau_{ee}, \qquad \Delta n_e \simeq \frac{3 k_B T_S}{\varepsilon_F} n_e \exp\left(-\frac{2 m_e c^2}{k_B T_S}\right),$$

$$\tau_{ee}^{-1} \simeq \frac{3\alpha}{2\pi^{3/2}} \frac{(k_B T_S)^2}{\hbar \varepsilon_F} J(\zeta), \qquad \Delta r_E = \left(\frac{3\pi}{2\alpha}\right)^{1/2} \frac{m_e c^2}{e\varphi_0} \frac{\hbar}{m_e c}$$

$$J(\zeta) = \begin{cases} 51(1 - 19.5\zeta^{-1} + 296\zeta^{-2}), & \zeta > 20, \\ 0.23\zeta^{1.8}, & 1 < \zeta < 20, \\ (1/3)\zeta^3 \ln 2/\zeta, & \zeta < 1. \end{cases}$$

First principle simulations

We solve numerically the system of Vlasov-Boltzmann-Maxwell equations (reduced to Vlasov-Boltzmann-Ampere equations) self consistently, taking into account:

1. pair creation by the Schwinger process;
2. Pauli blocking;
3. particle collisions;
4. backreaction of pairs and electrons on the electric field.

Vlasov-Boltzmann-Ampere equations

The symmetry of the problem leaves only one spatial coordiate z, orthogonal to the surface boundary and two momentum coordinates: parallel $p_{||}$ and orthogonal $p_{\perp}$ to the electric field direction. The system of equations is

$$\frac{\partial f_{\pm}}{\partial \tilde{t}} + \frac{\tilde{p}_{||}}{\tilde{p}^0}\frac{\partial f_{\pm}}{\partial \tilde{z}} \mp \tilde{E}\frac{\partial f_{\pm}}{\partial \tilde{p}_{||}} = (1 - f_+ - f_-)S + \mathrm{St} f,$$

$$\frac{\partial E}{\partial t} = 2\alpha \int d^3\tilde{p}\,\frac{\tilde{p}}{\tilde{p}^0}(f_- - f_+) - 4\alpha\frac{1}{\tilde{E}}\int d^3\tilde{p}\tilde{p}_0(1 - f_+ - f_-)S,$$

$$S = -|\tilde{E}|\ln\left[1 - \exp\left(-\frac{\pi(1+\tilde{p}_{\perp}^2)}{|\tilde{E}|}\right)\right]\delta(\tilde{p}_{||}),$$

$$\mathrm{St} f = -\frac{f - f_0}{\tau}, \qquad \tau \simeq (\sigma_T n_e)^{-1}.$$

where $\tilde{t} = tm$, $\tilde{z} = zm$, $\tilde{p} = p/m$, $\tilde{E} = Ee/m_e^2$.

Static electrosphere

Electrons obey Fermi-Dirac statistics
$f_e = \left\{1 + \exp\left[\left(\sqrt{p^2 + m_e^2} - \mu\right)/T_S\right]\right\}^{-1}$. The chemical equilibrium condition for electrons is $\mu = e\varphi$, implying that electrons are bound by the electrosphere and also that their distribution function does not depend on time $\partial f_e/\partial t = 0$. The number density of electrons for $T_s \ll \mu$ is $n_e = \mu^3/3\pi^2 + \mu T_S^2/3$.
In ultrarelativistic approximation for electrons the Poisson equation

$$\frac{d^2\varphi}{dz^2} = -\frac{4\alpha}{3\pi}\left[e^2\varphi^3 + \pi^2 T_s^2 \varphi - n_q\right],$$

where $n_q(z<0) = (\alpha/3\pi^2)(e^2\varphi_q^3 + \pi^2 T_S \varphi_q)$ is the density of a positively charged core, z is spatial coordinate normal to electrosphere. The electric field $E(z)$ is defined from the electrostatic potential $\varphi(z)$ as $E(z) = -d\varphi/dz$.

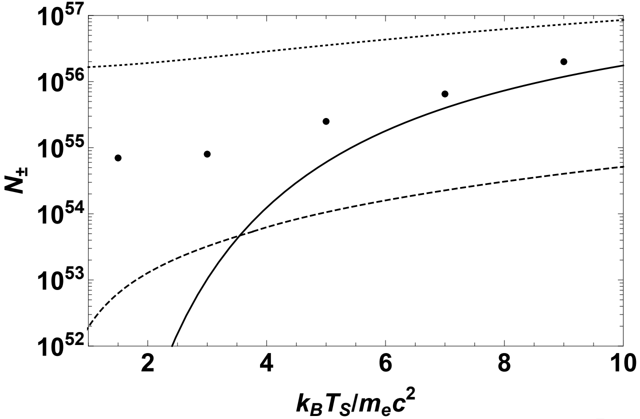
Revisiting Usov's mechanism

We identified crucial flaws in the original mechanism and found new phenomena ignored in previous analysis:

1. Thermalization is not fast enough, as electrons are *collisionless* in electrosphere;
2. electron evaporation at $T > 0$ leads to electrosphere *inflation*;
3. Pauli blocking is released due to *acceleration* of pairs by the electric field, simultaneous to pair creation.

The rate of pair creation as function of temperature

Figure: Pair creation rate in the electrosphere according to Usov (dashed), maximum (dotted), with Gatoff (1987) rate accounting for Pauli blocking (solid) and numerical results (dots).



Luminosity estimate

At high temperatures $T_S > \varepsilon_F$ Pauli blocking is negligible

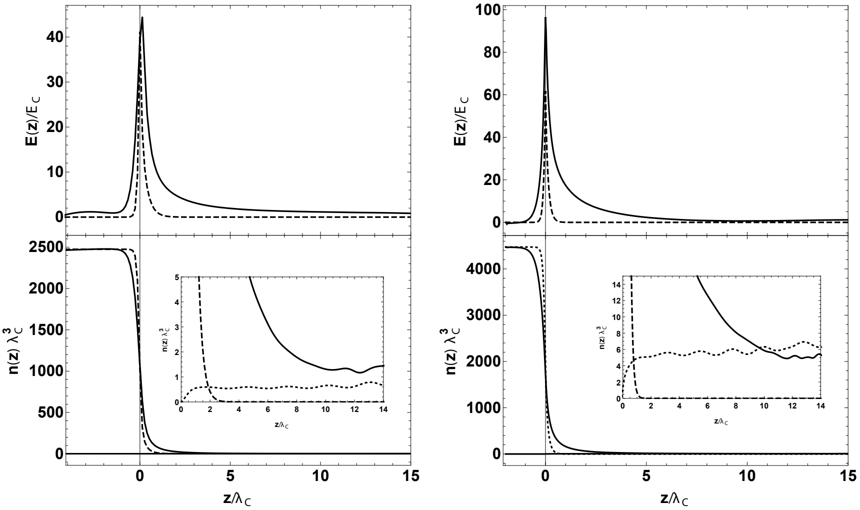
$$\dot{N}_{\pm} \simeq 4\pi R^2 \Delta r_E \frac{m_e^4}{4\pi^3} \left(\frac{E}{E_c}\right)^2 \simeq 4 \times 10^{56}\ \mathrm{s}^{-1} \left(\frac{E}{5 \times 10^{17} \mathrm{V/cm}}\right)^2 .$$

The luminosity in pairs is determined not by their temperature, but by the Lorentz factor of the outflow $\gamma \simeq E/E_c$. Electrons, while decelerated in the electrosphere, are dragged together with positrons. In fact, the flux of positrons reduces the Coulomb barrier thereby allowing more electrons to escape. This guarantees charge neutrality of the total outflow.

$$L_{\pm} \simeq 1.3 \times 10^{52}\ \mathrm{erg/s} \left(\frac{E}{5 \times 10^{17} \mathrm{V/cm}}\right)^3 .$$

Even very large isotropic luminosities of gamma-ray bursts (GRBs) of 10^{53} erg/s and higher are possible for electrosphere of compact objects, provided that $E \sim 80 E_c$ or higher at their surface.

Results: T=1.5 MeV and 3.5 MeV



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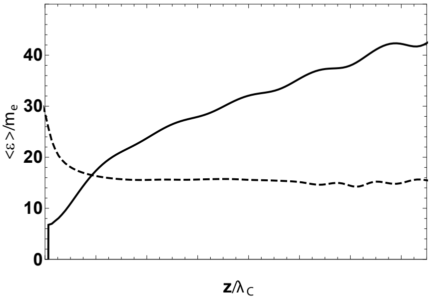
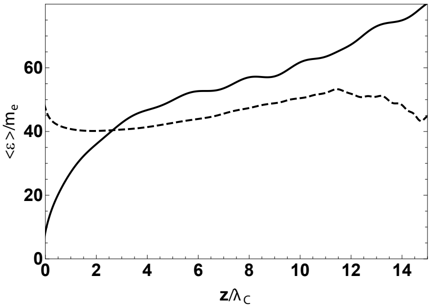
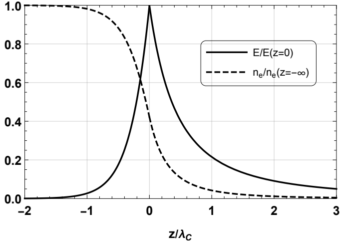
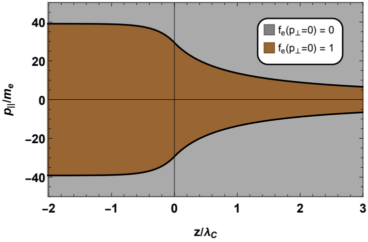
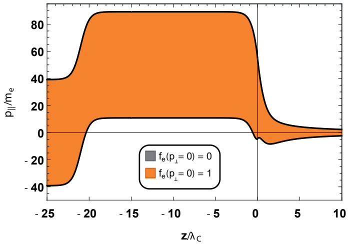




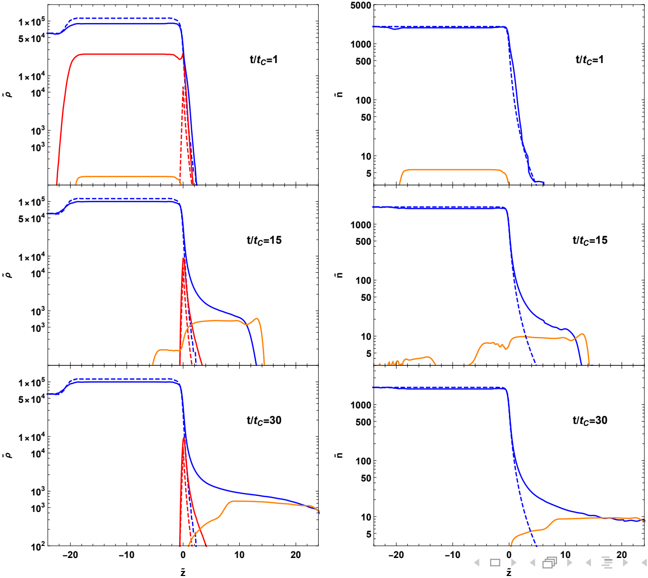
Initial conditions: radial perturbation







Results: radial perturbation



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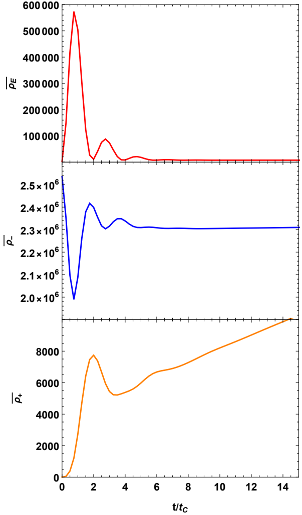

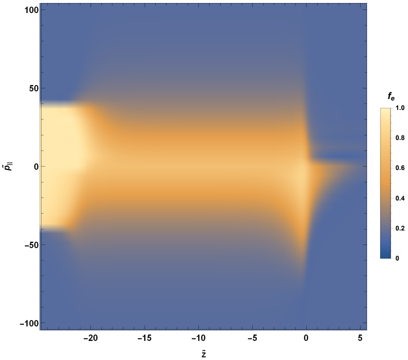

Conclusions

We revisited Usov's mechanism for pair creation in electrosphere of compact astrophysical objects, such as hypothetical quark stars or neutron stars.

1. Due to thermal evaporation of electrons electrosphere is inflated to much larger distances, than electrostatic solution implies: electrostatic energy increases.
2. In hot electrosphere Pauli blocking is reduced by simultaneous acceleration of pairs created by the Schwinger process.
3. Both these effects dramatically enhance pair creation rate, leading to luminosities that can be $> 10^{52}$ erg/s, much larger than previously derived.
4. Radial electromagnetic perturbation on spatial scales larger than the mean free path leads to electrosphere heating.