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Research Article

Method of Generalized Mathematical Transfer for Modification and Solutions Visualization of the Nonlinear Navier-Stokes Equation for Describing Vysikaylo's Shock Waves of an Electric Field and Plasma Nozzles

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Abstract

Cumulation (self-focusing) of charged particles in non-uniform plasma (with current) is a universal property of cumulative-dissipative structures with characteristic sizes from 10^{-15} to 10^{26} m. These phenomena are observed from the femto- to the macroworld (non-uniform atmospheres and ionospheres of all planets of the Solar system, intergalactic lightning). Here we draw attention to the solution and visualization of this solution of the non-stationary nonlinear 3D equation of the Navier-Stokes type. We applied this equation to describe phenomena in a non-uniform plasma with current. In this paper, a more complete classification of 3D processes of ambipolar transport in plasma with current and a classification of non-uniform 3D profiles of plasma parameters are given. We verify the theoretical models by experiments on the study of non-uniform plasma, locally perturbed by a beam of fast electrons. This leads to self-formation of: 1) shock waves of the electric field (layer of positive volume charge), stopped for photography by pumping gas, and 2) transition 3D profiles and plasma 3D Vysikaylo's nozzles already in quasi-neutral inhomogeneous plasma. We have for the first time analytically, numerically and experimentally investigated 3D processes of nonlinear ambipolar transport caused by violation of electrical neutrality and 3D interaction of electric fields with matter (charged particles) in inhomogeneous plasma with current. For the first time it has been proven that the coefficients of ambipolar diffusion, due to violation of electroneutrality, are vectors determined by the vector of the electric field, related to the concentration of electrons (E/ne).

Keywords: Visualization of the Navier-Stokes Equation Solution; Vysikaylo's Cumulative-Dissipative Structures, Electric Field Shock Waves, Vysikaylo's Plasma Nozzles, Laval's Nozzle, Ambipolar Drift, Ambipolar Diffusion

1. Introduction

Cumulation (self-focusing) of charged particles in inhomogeneous media with electric fields is a universal property of a number of cumulative-dissipative structures (CDS) with characteristic sizes from 10^{-15} to 10^{26} m [1-3]. The main processes that form CDS in any media are focusing (cumulation) processes and dissipation processes (spraying of what does not cumulate into the structure). CDS in various media arise as a result of the action of external forces or potentials on these media. It turns out that 3D dissipation (spray, transfer, etc.) of external action (including various potentials and energy differences) in media can be co-organized with 3D convective focusing (cumulative) flows of energy, momentum, and mass (EMMP). The functional property of CDS is to most quickly dissipate external action (disperse disturbance, throw it to the periphery of the medium, etc.) on the medium through cumulative processes. For this purpose, cumulative (self-focusing) flows of EMMP [1] are realized in the medium. Taking into account pulsations in time, the description of non-stationary CDS becomes an 8D dimensional problem. Such dual 8D KDS are formed in the unity and struggle of opposites (cumulation and dissipation) in one structure (according to Hegel). The world is one, and the dynamics of cumulation and dissipation (acquisition and loss) rule in it. Usually, cumulation phenomena are studied by some scientists [4], and dissipation phenomena by others (see references in [1, 2]).

In case of coincidence of characteristic times of cumulation and dissipation it is possible to solve 8D problem in quasi-stationary mode and thus to significantly reduce the dimension of the problem. Thus the general problem of Kepler's radial pulsar can be reduced to the problem of uniform rotation of a body along a circle. Galileo already knew how to solve problems with uniform rotation of planets along a circle, but did not understand the elliptical nature of planetary motion according to Kepler's laws. If characteristic times of cumulation or dissipation processes differ significantly from each other, then it

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is possible to reduce 8D problem to 4D problem, taking into account roughly corresponding influence of one of opposite processes (by setting corresponding initial, boundary or inhomogeneous potentials of one or another nature for analysis of the second opposite). Thus in [3] the author solved the problem of studying the electron temperature profile in the entire heliosphere, setting the charge of the Sun at 1400 C. In this case he determined the charge of the Sun by the types of positive iron ions observed in the solar wind.

1.1. Definition of Cumulation

The most intelligible definition of cumulation is given in the preface to [4] by Ya. B. Zeldovich: "***cumulation is the concentration of force, energy or another physical quantity in a small volume."*** We will rely on this definition in the future, implying that we are talking about the cumulation of a certain parameter (dynamic or static order). When using this definition, it should be understood that during the cumulation of one parameter, "dissipation" (scattering, decrease, etc.) of another parameter can be observed. Thus, when a shock wave expands into the atmosphere, its speed increases due to a decrease in the density of the atmosphere with height, while the energy density decreases. In this case, we can talk about the cumulation of speed in the wave front, but there is no need to talk about the cumulation of energy. The main results of the study of the phenomenon of unlimited cumulation are presented in [4] in the form of separate problems.

The difference between Vysikaylo's CDS and dissipative structures (Kolmogorov-Turing-Prigogine and their followers) is the consideration of convective processes of focusing (cumulation) of energy-mass-pulse flows (EMPF) to points, lines or surfaces of cumulation [1-3, 5-14]. The CDS include neutral and charged structures such as neutrons, atomic nuclei, atoms, molecules, lightning, tornadoes, stars, galaxies, intergalactic lightning, states, ethnic groups, living organisms, etc. The analogy of a number of processes in the CDS allows us to apply the method of generalized mathematical transfer (MGMT) of the most complete mathematical models and their solutions to describe similar phenomena from well-studied areas of science in less thoroughly studied areas of natural science. When transferring mathematical models in this way, we must take into account the specifics of the phenomena being described.

MGMT has long been used and is still used to accelerate the development of philosophy and natural sciences in various areas of natural science. This method was used by:

1) Newton. He studied and generalized the description of gravitational forces on Earth and in Space. On March 29, 1696, Isaac Newton was appointed Warden (and from 1699, Director) of the London Mint. In this position, he saved England from chaos due to the debasement of money by counterfeiters;

2) Louis de Broglie to describe quantum phenomena using his hypothesis. He put forward the hypothesis: "Particles behave like waves" and received the Nobel Prize for developing this idea. He introduced the concept of de Broglie wave for particles;

3) Einstein to describe the photoelectric effect. He applied the opposite idea: "Electromagnetic waves behave like particles" and received the Nobel Prize for explaining the photoelectric effect;

4) Niels Bohr. He successfully applied the planetary model of Copernicus and his followers to describe electric potentials and electron orbits to explain the spectra of the hydrogen atom. In 1922, Niels Bohr was awarded the Nobel Prize "for his services to the study of the structure of atoms and the radiation emitted by them";

5) Schrödinger with Dirac. They created a new quantum (wave) theory that takes into account the wave statistical properties of an electron in a hydrogen atom and its wave passage through two slits. As a result, in 1933, Schrödinger and Dirac received the Nobel Prize "for the discovery of new productive forms of atomic theory" (and thus for the transfer of Bohr's theory to the status of a pseudoscientific theory);

6) Vysikaylo to the discovery and description of:

a) shock waves of an electric field and plasma nozzles (analogs of Laval nozzles) in a plasma with current (1985-2024). For this, he constructed the most complete theory of perturbations in a plasma with current and thus obtained a modified Navier-Stokes equation [6], which made it possible to analytical and numerically describe all the phenomena observed (in the experiments organized by him) in an inhomogeneous plasma with current (Fig.1) [1-3, 5-14];

b) 5 points of cumulation and libration for electrons in a system of two rotating positively charged Coulomb attractors (two atoms in a molecule). Here he took into account the generality of the laws of cumulation ~ 1/r in gravitational and Coulomb potentials. He related the number of electron cumulation points in a molecule with the valence of atoms [9];

c) points, lines and surfaces (charged strata – running and standing shock waves of the electric field) of libration and cumulation for free electrons between positively charged structures of plasma with current. He proved that Coulomb (electric) potentials in 4D space-time function similarly to gravitational potentials [9];

d) endoelectrons in fullerenes and, accordingly, all spectra of negatively charged fullerenes. He proved (based on a number of experiments, see references in [10]) the formation of symmetric de Broglie waves of electrons in *hollow* fullerenes and the corresponding degeneration of spectra in hollow fullerenes with respect to the principal quantum number *n* and *n*-1/2 [10]. Such similar cos-waves are formed (when drops fall into cylindrical glasses with liquid, when studying sonoluminescence phenomena, etc.) in ordinary hydrodynamics in *hollow* spherically and cylindrically symmetric resonators.

f) standing Vysikaylo's excitons formed in the area of chemical doping of diamonds with boron atoms. Here he modified the Wannier-Mott model (with a uniform value of the permittivity ε = const throughout the crystal) into a model that takes into account the polarization of crystals ($\varepsilon = \varepsilon(r)$) when a foreign atom is introduced into their crystal lattice. And thus he

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proposed a new method for determining the profile of the relative permittivity ε(r) from the distance to the center of a standing exciton using Raman spectra [11, 12];

e) the mechanism of Coulomb fractalization of meteoroids and small asteroids by a plasma tail behind them [14]. This mechanism was developed on the basis of a modification of the Vysikaylo model of lightning impulse propagation, see [13], observed in experiments by B.F.J. Shenland in 1934-1938. Shenland experimentally proved, using a Boyce chamber, that electrons, cumulating in lightning, run away from it forward (in the form of runaway electron jets) with an energy of up to 5 MeV; etc.

The MGMT goes back to the idea of Eratosthenes, which he applied (June 19, 240 BC) when calculating the length of the Earth's meridian (geometric structures are similar, various theorems can be applied to them, etc.). The method, founded by Eratosthenes, has long been successfully used on Earth and helps in the discovery and quantitative description of "mysterious" phenomena, including CDS.

In this work we use this general method (MGMT) to apply (transfer) the achievements of classical Mach's shock wave hydrodynamics to calculate the main parameters of the discharge in an experimental setup, to describe and photograph Vysikaylo's shock waves of the electric field and plasma nozzles in plasma with current.

Electrons are more mobile than ions due to their low mass compared to ions. Electrons leave plasma structures faster than positive ions, thereby charging them with a positive charge, the electric field of which returns some of the low-energy electrons back to the plasma positively charged cumulative-dissipative structures (+CDS). This is how dual (related, entangled, opposite) flows of charged particles arise in the +CDS region. The reverse electron flows focus (cumulate) +CDS. Returning electrons exert a dynamic pressure on the entire +CDS surface. This is how the dynamic surface tension of +CDS arises. This tension forms +CDS of various symmetries: spherical (cathode and anode spots, ball lightning, etc.), cylindrical (electric arcs, linear lightning, intergalactic lightning, etc.), conical, elliptical (bead lightning) or planar (striations). Taking into account the dynamic surface tension in +CDS and considering the distribution of the positive charge density in +CDS to be uniform, we come to the conclusion that the electric field strength E reaches its maximum value on the +CDS surface. The strength (an analogue of the droplet model of the atomic nucleus) of the electric field in +CDS increases toward its surface and then decreases with increasing distance to the +CDS surface. Usually, the ambipolar plasma drift is directed from small values of the E/N parameter to large values [1, 5-8]. If the particle number density is constant, then the parameter E/N also reaches its maximum value on the +CDS surface and here the ambipolar drifts collapse to the +CDS surface. From the classical theory of ordinary gas-dynamic Mach shock waves, only those parameter jumps (shock waves) survive whose disturbances are directed into the jump. If disturbances propagate in a certain region in opposite directions, then plasma nozzles (similar to Laval nozzles) are formed in this region. Also in gas-discharge plasma, if the ambipolar drift is directed to the +CDS surface, then a shock wave of the electric field or a diffusion jump can be formed on the +CDS surface, see the textbook [2].

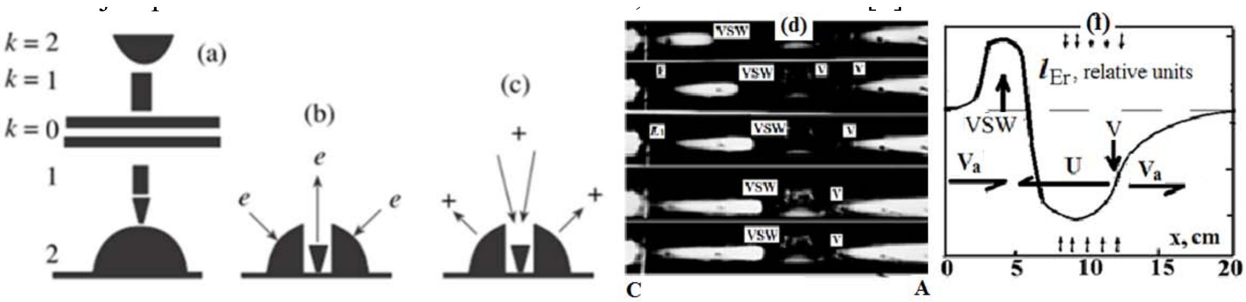

Figure 1: Examples of +CDS with different symmetry [1,2]: (*a*) Possible arrangement of structured plasmoids with different symmetry. *k*=0 – layers in a gas discharge, *k* = 1 – electric arcs, linear lightning and *k* = 2 – cathode and anode spots, ball lightning. (*b*) Arrows show the directions of cumulation of electron fluxes and electric field – *E/N* in the cathode spot area. Electrons – e appear in large quantities in the spot area, for example, due to preliminary ultraviolet ionization. (*c*) Scheme of cumulation of ion fluxes in the cathode spot. (*d*) Photographic evidence of formation of shock waves – VSW and Vysikaylo's plasma nozzles – V (in plasma with current). *P* = 15 torr, *U* = 40 m/s (from A to C), J*q* = 3 μA/cm², Current I varied from 0.33 mA/cm² to 1.52 mA/cm². F – Faraday dark space. L_1 – Vysikaylo's cumulation point for electrons between positively charged structures (cathode spot and positive column). (*f*) – diagram of the discharge radius dependence according to equation (5), determined by interference and diffraction of the electric field (by discharge glow) in plasma with current.

2. Vysikaylo's Model of Transport Processes of Charged Particles of Plasma without Magnetic Field. Modification of the Schottky's Model

This model includes equations for the balance of ion numbers:

$$\partial n_i/\partial t + \mathrm{div}(n_i(\boldsymbol{V}_i + \boldsymbol{U})) = I_i - R_i, \qquad (1)$$

Here n_i – concentration of positive (or negative, if present) ions; $V_i+U= \mu_i E +U$ – drift velocity of ions, which is a function of the parameter E/N. U – the rate of pumping of neutral gas, which entrains ions. It is constant and does not depend on the parameter E/N. The same way (as gas pumping or an external electric field) one can take into account any forces acting on certain components of the plasma, for example, gravitational forces acting on ions (gravitational forces acting on ions [2,6]), magnetic fields acting on electrons, etc. see references in [2,6,8]. I_i, R_i – ion sources and sinks. To equation (1) it is necessary to add the electrodynamic equations:

$$\text{rot}\,\boldsymbol{E} = 0 \text{ и } \text{div}\,\boldsymbol{E} = 4\pi\rho; \quad \rho = e(\sum_{\alpha=1}^{m} z_a n_a - n_e);, \tag{2}$$

Here z_α – ion charge; m – number of different types of ions.

Instead of the balance equation for electrons (as in the case of ions), we will take into account the total current density. To do this, we add the balance equations for electrons and all possible ions (multiplying them by the corresponding charge) and take into account that charged particles of different signs in the volume are born and die simultaneously, using (2), we get:

$\nabla \boldsymbol{j} = 0$. Here $\boldsymbol{j}/e = (\partial \boldsymbol{E}/\partial t)/(4\pi e) - n_e \boldsymbol{V}_e + \sum_{\alpha=1}^{m} z_a n_a \boldsymbol{V}_\alpha + \nabla(D_e n_e)\ldots$ D_e – electron diffusion coefficient, (… - denotes ion diffusion). Electrons and ions in plasma are born and die together, in the current continuity equation the sources and sinks are mutually compensated (as are the flows caused by the non-stationarity and non-uniformity of the plasma concentration and electric field strength, as well as the non-stationarity and non-uniformity of the electron velocity distribution function in the sources and sinks). From (2): $n_i = n_e + \nabla \boldsymbol{E}/(4\pi e) \sum_{\alpha=1}^{m-1} z_a n_a$, and, the equation for j taking into account the displacement current $-(\partial \boldsymbol{E}/\partial t)/(4\pi)$:

$$\boldsymbol{j}/e = 1/(4\pi e)\,(\partial \boldsymbol{E}/\partial t) - n_e \boldsymbol{V}_e + (\sum_{\alpha=1}^{m-1} z_a n_a \boldsymbol{V}_\alpha + z_i \boldsymbol{V}_i\,(n_e + \nabla \boldsymbol{E}/(4\pi e) - \sum_{\alpha=1}^{m-1} z_a n_a) + \nabla(D_e n_e)\ldots, \tag{3}$$

Here 5th member with $z_i V_i$ $\nabla E/(4\pi e)$ takes into account the influence of the violation of plasma electroneutrality on the modification of the internal electric field – E [2, 5].

2.1. Parameters of Perturbation Theory

Since electrons have a smaller mass, they are more mobile and the main current transfer is the electron drift in an external electric field. Therefore, the main assumption of Vysikaylo's perturbation theory for plasma with current is the smallness of the ion current compared to the electron current. Therefore, we will consider the ratio of $n_e V_e$ to the other terms in (3) to be small parameters:τ_M/τ, 1, $(\mu_i/\mu_J) l_E/L$, l_u/L ... Here τ is the characteristic time of charge change, $\tau_M = 1/(4\pi e\, \mu_J n_e)$ – Maxwellian time of neutralization of space charge,μ_J – effective plasma mobility, taking into account the mobility of ions and electrons, $l_{E0} = E_0/(4\pi e\, n_e)$ – vectorized characteristic size of the change in electric field strength. The system of equations (1) - (3) taking into account the violation of plasma electroneutrality (2) can be solved using Vysikaylo's perturbation theory, if the parameters: $\Omega\tau_M$, $(\mu_i/\mu_J) l_E/L$ and $l_u/L \ll 1$ [2,5-8]. The smallness of the parameter $(\mu_i/\mu_J) l_E/L \ll 1$ can be observed at $l_{E0}/L \gg 50$, since $\mu_i/\mu_J \approx \mu_i/\mu_e$. Within the framework of Vysikaylo's perturbation theory, it is possible to advance in zero order to a region with a significant violation of electroneutrality [2,5]. The zero approximation in Vysikaylo's perturbation theory splits into two approximations:

1) quasi-neutral or drift approximation, here: $l_{E0}/L \ll 1$ (see [2,5]) and
2) with a significant violation of plasma electroneutrality (Vysikaylo's approximation), when $l_{E0}/L \sim 1$ (or even when $l_{E0}/L \gg 50$, but $(\mu_i/\mu_J) l_E/L \ll 1$ (the main current is carried by electrons $\mu_J \approx \mu_e \gg \mu_i$ is the ion mobility).

2.2. Modification of the Schottky's Method. Ambipolar Schottky Diffusion

Schottky in 1924 presented (3) in the form $\boldsymbol{j}/e = - n_e \boldsymbol{V}_e + \nabla(D_e n_e) = n_e \mu_e \boldsymbol{E} + \nabla(D_e n_e)$ or

$$\boldsymbol{E} = \boldsymbol{E}_0 + \boldsymbol{E}_1 = \boldsymbol{j}/(e\, n_e \mu_e) + \nabla(D_e n_e)/(n_e \mu_e) \tag{4}$$

and substituting (4) into (1) he obtained for the first time the Schottky's ambipolar diffusion coefficient $D_a = \mu_i D_e/\mu_e$. According to section 2.1 [2,5,7,8], taking into account the electric field $\boldsymbol{E}_1$ is the first (or diffusion approximation) approximation of Vysikaylo's perturbation theory for a small parameter $l_u/L \ll 1$.

All processes in gas discharge plasma are determined by the parameter E/N. This was already known to Stoletov. Detailed experimental measurements of the profiles of the processes of birth, death, transfer of charged and excited plasma particles from the parameter E/N were obtained by Townsend and his followers, see references in [2, 5, 7, 8]. For this reason, the

Schottky's diffusion field – E_1 should be taken into account in all these processes. Such an account leads to a number of ambipolar drifts and ambipolar diffusions [2, 5, 7, 8]. This is the modification of the Schottky method. It was performed by Vysikaylo in 1987. According to this modification, the most significant term is the ambipolar drift, caused by taking into account the diffusion field $\boldsymbol{E}_1$ in the ion source $-\nu_i\nu_i^*(D_{e0}/\mu_{e0})\nabla n_e$. This term takes into account the non-uniformity of the electric field in the ionization term $(I_i = \nu_i n_e,\ \nu^*_{i0} = \partial ln\ \nu^*_{i0}/\partial ln\gamma,\ \gamma = E_0/N)$.

A similar account should be taken of the inhomogeneity of the electric field $(E = E_0 + E_1)$ in the Euler equation for momentum transfer (and taking into account the term with $V_{i,e}\nabla V_{i,e}$ as a small addition). This leads to the appearance of Vysikaylo-Euler's ambipolar diffusions for electrons and ions, see references in [2, 5, 7, 8].

Taking into account the displacement currents in (3) leads to the appearance of a perturbation of the electric field $E_1 = [1/(4\pi e)]\ (\partial E_0/\partial t)/(n_e\mu_{e0})$. This perturbation, when taken into account in equation (1) (using the Schottky method), leads to the appearance of mixed derivatives (the second derivative with respect to time and one with respect to coordinates) and the renormalization of all terms with mixed derivatives with respect to time and coordinates. This makes the problem quite complex and (given the importance of these processes) it requires complex equipment for photographing non-stationary structures in inhomogeneous plasma. We will restrict ourselves to the case of very small values of E_1 in (1). Displacement currents and the ambipolar plasma flows arising from them are significant at the initial stages of the discharge. Below we will focus on photographs of the quasi-stationary stage of a non-uniform discharge with profiles of electric field shock waves (here the Vysikaylo-Poisson's diffusion is important) and Vysikaylo's plasma nozzles (here the ambipolar drifts and gas pumping are important). The gas pressure in the experiments was 15 Torr, so we will neglect the displacement currents and the ambipolar Schottky's and Vysikaylo-Euler's diffusions. Thus, we will limit ourselves to ***the zero approximation*** in Vysikaylo's perturbation theory [2,7,8] and compare the theoretical results with photographs of the glow profiles of a *quasi-stationary* self-focusing inhomogeneous discharge.

3. Zeroth Approximation of Vysikaylo's Perturbation Theory

In this approximation, the drift velocity of electrons and ions is described by the relations: $V_{e0} = \mu_{e0}E_0$, $V_{i0} = \mu_{i0}E_0 + U$. Here the mobilities of electrons– μ_{e0} *и ионов* – μ_{i0} are presented respectively. From (1) and (3) in the zero approximation ($\mu_{j0}n_e\nabla\boldsymbol{E}_0 = -\boldsymbol{E}_0\nabla(\mu_{j0}n_e)$) we obtain a non-stationary 3D equation for simple plasma [2, 5-8]:

$$\partial n_e/\partial t - \partial[(\boldsymbol{l}_{E0}/\mu_{e0})\nabla](\mu_{e0}\, n_e)/\partial t + (\boldsymbol{j}/e)\nabla(\mu_{i0}/\mu_{e0}) + \boldsymbol{U}\nabla n_e - \nabla(\boldsymbol{U}(\boldsymbol{l}_{E0}/\mu_{e0})\nabla(\mu_{e0}n_e)) - \nabla\{\boldsymbol{l}_{E0}(\mu_{i0}\boldsymbol{E}_0/\mu_{e0}\nabla)(\mu_{e0}n_e)\} - \beta n_e(\boldsymbol{l}_{E0}/\mu_{e0})\nabla(\mu_{e0}\, n_e) + \mu_i m_i\,(\boldsymbol{g}/z_i e)\nabla n_i - (\mu_i\mu_e[\boldsymbol{E}\mathrm{x}\boldsymbol{H}]/c)\nabla n = I_{i0} - R_{i0}; \quad \boldsymbol{l}_{E0} = \boldsymbol{E}_0/(4\pi e n_e). \qquad (5)$$

The four-dimensional Vysikaylo's equation (5) is derived from (1) by modifying the ion concentration n_i by $n_e-(l_{E0}\nabla)(n_e\mu_{e0})/\mu_{e0}$. ***Equation (5) is the Navier-Stokes equation modified by Vysikaylo to account for the violation of plasma electroneutrality.*** The terms with the vector l_{e0} in (5) arise due to the violation of electroneutrality. The second term with mixed derivatives with respect to time and spatial coordinates has no analogues in hydrodynamics, the third term determines the ambipolar plasma drift due to different dependences of the electron and ion mobilities on the parameter *E/N*, the fourth term is determined by the gas pumping rate, and the fifth and sixth terms are similar to ambipolar diffusion, but with ***a vector diffusion coefficient***. The fifth term is determined by the gas pumping rate and the violation of electroneutrality. In the same way that gas pumping is taken into account, one can take into account the forces of gravity (acting on ions due to their greater weight) and the magnetic field (acting on electrons due to their greater speed). The eighth term takes into account the gravitational forces acting on the ions, the ninth term takes into account the magnetic field forces acting on the electrons, see [2, 6]. Vysikaylo's Equation (5) most fully describes the interference of the internal electric field of charged particles with charged particles of plasma in a plasma with current [2, 5-8]. The zeroth approximation in Vysikaylo's perturbation theory (or equation (5)) is valid for a significant violation of neutrality. The main point of this approximation is the smallness of the ion current compared to the electron current. We see that already in this approximation, when taking into account the violation of electroneutrality, ambipolar diffusion flows appear, caused by the violation of electroneutrality (or ***the interference of various forces***: gas pumping, gravitational forces, etc. ***with an electric field***) in an inhomogeneous plasma with a current [2, 5-8].

It should be noted that in the Schottky theory, ambipolar diffusion appears in the first (***diffusion***) approximation according to the Vysikaylo perturbation theory and is an important phenomenon only in the region of low neutral gas pressures. Vysikaylo's amphipolar diffusions, caused by the violation of plasma electroneutrality (taking into account the Poisson equation (2)) appear in the zero (***drift***) approximation according to the Vysikaylo's perturbation theory and are manifested in gas-discharge plasma, both at low neutral gas pressures and at high pressures.

In hydrodynamics (as established by Mach and his followers), the transition from convective to diffusion transfer is observed during the formation of shock waves discovered by Mach. The presence of a diffusion term in (5), caused by the violation

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of electroneutrality, allows us to assert, based on the method of generalized mathematical transfer, that in a plasma with current, one should expect the formation of electric field shock waves in the plasma [2, 5-8]. Vysikaylo's electric field shock waves in a gas discharge were predicted by Vysikaylo in 1985(based on MGMT), and discovered and visualized by Vysikaylo et al. in 1986-1987, see references in [2, 5, 8]. Photographs of the discharge glow (Fig.1*d*) qualitatively reflect the magnitude of the electric field voltage (parameter *E/N*) and the electron concentration profiles (n_e). This is due to the fact that from $\Delta_j = 0$ in the zero approximation of Vysikaylo's perturbation theory there follows a single-valued dependence of the electric field - *E* and the electron concentration - n_e in plasma with current on the current strength - *j.* The presence of the 2nd and 6th terms in (5) with a mixed derivative allows one to describe (in zero approximation according to the perturbation theory constructed by Vysikaylo [2, 5, 8]) stationary and running shock waves of the electric field - strata (pulsations of the parameter *E/N*) both in ordinary gas discharge plasma and in the ionosphere, heliosphere and when describing intergalactic lightning in the M 87 region, where global flows of inhomogeneous plasma with current clearly occur [2, 5, 8].

4. Ambipolar Drift in Plasma with Current

The impact of various external forces on the charged components of plasma leads to ambipolar drift of plasma and its +CDS as a whole [2-8]. External impacts allow controlling plasma flows, stopping shock waves, moving them in the desired direction, localizing energy disturbances, etc. Therefore, the study of ambipolar drifts, electric field shock waves and solutions of the modified Navier-Stokes equation (5) is of great practical and scientific value.

4.1. Ambipolar Plasma Drift Due to Different Dependence of Electron and Ion Mobilities on the Electric Field (E/N)

In the zero approximation of Vysikaylo's perturbation theory, the third term in (5) – $(j/e)\nabla(\mu_{+0}/\mu_{J0})$ is determined by the ambipolar drift velocity – $\boldsymbol{V}_a=\mu+(\mu+^{*}-\mu_e^{*})/(1+\mu_e^{*})E_0$ of the inhomogeneous plasma due to the different dependence of the electrons and positive ions mobilities even in a simple plasma. $\mu^* = \partial\ln\mu/\partial\ln(E/N)$. According to numerous experiments, see references in [2], in high-purity nitrogen plasma, and according to numerical calculations, the electron drift velocity is well described by a simple approximation $V_e = 1.83\cdot10^6\cdot\gamma^{0.75}$[m/s], here $\gamma = E/N$ [V/cm^2]10^{16} in the range of *E/N* from 1 Td to 240 Td. According to experiments, see references in [2], the reduced mobility of positive ions in molecular nitrogen is well approximated by μ[cm^2/(V·s)] = 2.97 (N+); 1.84 (N_2+); 2.26 (N_3+); 2.33 (N_4+) in the range of parameters of our experiments (1 <*E/N*[Td]< 60) and remains virtually unchanged. Therefore, the velocity of ambipolar drift is equal to $V_a = 1/3\mu(760/P)E$ and is directed from smaller values of the parameter *E/N* to larger values (from the Faraday dark space to the positive column. In the near-cathode region, it is directed from the Faraday dark space to the cathode, and in the near-anode region, from the positive column to the anode). In high-purity nitrogen, $\boldsymbol{V}_a$ reaches 70 m/s and depends significantly on the parameter *E/N* [2, 6].

In air, $\boldsymbol{V}_a$ is even greater [2].
Of particular interest are calculations of ambipolar plasma (with current) drift in the heliosphere and interstellar medium [6].

4.2. Ambipolar Drift Due to Neutral Gas Pumping

The simplest way to push the excited quasi-neutral plasma out of the discharge gap is to pump neutral gas (with the velocity –***U***) through the discharge gap. Since positive ions are entrained by the neutral gas (ions are frozen into the neutral gas), the effective velocity of the ambipolar plasma drift changes by the value of the gas pumping velocity – ***U***, i.e. a term with $\boldsymbol{U}\nabla n_e$ should be added to (1) or (5). Taking into account the violation of electroneutrality, this leads to the appearance in (5) of a number of transport processes due to gas pumping. This is how interference and diffraction of the electric field in an inhomogeneous plasma with current occurs, visualized in Fig.1*d*. By pumping gas, it is possible to stop the movement of plasma profiles due to the internal ambipolar drift and obtain photographs (Fig.1*d*) of solutions of the modified by Vysikaylo nonlinear Navier-Stokes equation – (5).

4.3 Law of Additivity of Ambipolar Drifts

We, see references in [1-5], have theoretically (5) and experimentally proven the law of additivity of ambipolar drifts caused by longitudinal (to current) pumping of gas, and internal ambipolar drift caused by different dependence of the electron and positive ion mobilities on the parameter *E/N* in a discharge in high-purity nitrogen with gas pumping from the cathode to the anode and from the anode to the cathode. These experiments and theoretical foundations provide grounds for applying the law of additivity of ambipolar flows when modeling the nonlinear interaction of an electric field with charged particles within the framework of the Vysikaylo's equation (5).

4.4. Ambipolar Plasma Drift Due to Violation of its Electroneutrality

The second term in (5) is non-zero in the case of non-stationarity of the l_{E0}/μ_{J0}. The non-stationarity of this term is determined mainly by the non-stationarity of the electric field – E_0 (or the parameter E_0/N). In this case, the ambipolar drift velocity is $V_E \sim \partial \boldsymbol{l}_{E0}/\partial t = \partial(\boldsymbol{E}_0/(4\pi e n_e))/\partial t$ [2, 5]. Taking this type of ambipolar drift into account, we explained the Pekarik's effect, see [2].

4.5. Ambipolar Drift and Plasma Polarization in a Gravitational Field

Gravitational forces act on positive ions m_i/m_e times stronger than on electrons. In this case, the gravitational force acting on ions should be substituted into the ambipolar drift velocity: $\boldsymbol{U}_g = \mu_i m_i \boldsymbol{g}/e$. $\boldsymbol{g}$ is the acceleration due to the action of gravity on positive ions. A. Pannekoek (1922) thought about taking into account the difference in gravitational forces acting on ions and electrons in solar plasma. The problem of violation of electrical neutrality of the Sun (with a charge of 1,400 C), the entire heliosphere and the generation of global eddy currents in the heliosphere can be found in more detail in [3]. The presence of global currents in the heliosphere and the violation of its electrical neutrality explains many phenomena of cumulative-dissipative structures in the ionosphere and heliosphere, in particular all parameters of the weak solar wind, [3] (as well as the appearance of plasma structures in the upper layers of the Earth's atmosphere at altitudes greater than 40 km). To do this, it is necessary to correctly calculate the electric field profiles in the heliosphere and take into account the role of runaway electrons and returning to the heliosphere [3].

5. Comparison of the Solution of the Vysikaylo's Equation (5) with Experiments

Ignition of a stationary discharge with longitudinal gas pumping in gas-discharge tubes occurs when a small cathode spot is formed on the cathode (Fig.1*d*, the glowing pea on the left), and behind it, due to the ambipolar drift – $\boldsymbol{V}_a$, a Faraday dark space – *F* is formed on the cathode (Fig. 1*d*, further than the cathode spot). Between the positively charged cathode spot and the positive column of homogeneous plasma, the Vysikaylo cumulation point – L_1 is formed (Fig.1*d*) [9]. The Vysikaylo's plasma flow cumulation point L_1 is an analogue of the libration point discovered (in 1767 in Russia) by Euler between two gravitational attractors. The issue of boundary conditions in a gas-discharge plasma with a cathode spot and a Faraday dark space is quite complex, see references in [2, 5-8]. Therefore, for the study in non-uniform plasma: 1) shock waves of the electric field (stopped by pumping gas – *U*) and 2) photographing quasi-stationary profiles (solutions of equation (5)) in the experiments of P.I. Vysikaylo, a method of quasi-stationary local perturbation of a small volume of previously homogeneous plasma in a gas-discharge tube by a beam of fast electrons (with an energy of 100 keV) was proposed. A beam of fast electrons with an energy of 100 keV and a current density of up to $j_q \sim 10\ \mu A/cm^2$ was introduced into a special window (with a Mylar film) measuring 2x2 cm^2 in the center of the gas-discharge tube. The setup was a glass tube with a cross-section of 3 cm^2 and a length of 45 cm. We used such tubes in experiments to directly prove the existence of ambipolar plasma drift – $\boldsymbol{V}_a$, caused by nonlinearity – the difference in the dependences of the electron and ion mobility on the field – *E*, or more precisely on the parameter *E/N*, see references in [2, 5-8]. The pumping speed *U* (at a gas pressure of nitrogen in the tube P = 15 Torr) could vary within 1-100 m/s. As a rule, the gas pumping rate was chosen so that the gas was not heated significantly (N ≈ const is the density of the number of gas particles in the tube), and the maximum value of V_a (in the positive plasma column) was somewhat greater than the gas pumping rate *U*. After the fast electron beam was introduced, the electron concentration in the discharge center and in the disturbance relaxation region increased sharply. Accordingly, the electric field strength decreased sharply in these regions (the *E/N* parameter decreased locally in the plasma), and therefore the average electron energy in the plasma decreased and the discharge glow disappeared in this region (Fig.1*d*). Since the *E/N* parameter decreased, the velocity V_a in these regions decreased sharply and the plasma changed its direction of motion due to the dominance of the gas pumping velocity *U* in these regions. The scheme of changing the regions of gas pumping dominance and ambipolar drift, according to (5) is shown in Fig.1***f***. In Fig.1*d*, in the center of the discharge tube, a window for the beam and a dark region of plasma column disturbance by a beam of fast electrons are visible. Based on the contrast of the glow and the places where it is observed (Fig.1*d*), one can judge the characteristic longitudinal and radial dimensions of the drift and diffusion caused by the violation of electroneutrality (Vysikaylo's shock waves of the electric field). In the work [8] more detailed comparisons of numerical 1D calculations, 3D analytical estimates with characteristic sizes of plasma structures in an inhomogeneous plasma with a current disturbed by an external ionizer are given.

5.1. Vysikaylo's Electric Field Shock Waves and Plasma Nozzles in Inhomogeneous Plasma

During Coulomb collisions of free electrons with each other, an energy flow arises in the tail of the electron energy distribution function. High-energy electrons leave the plasma structures and they are charged with a positive charge. This is how +CDS are formed. These structures return low-energy electrons back to the +CDS with their electric field. These flows of returning electrons form a dynamic surface tension at the +CDS. This tension is responsible for various types of symmetry of +CDS (Fig.2), arising due to the exit of some electrons from the visualized structure. These +CDS correspond to the schemes in Fig. 1*a, b, c.* If we assume that the charge density in the structure is uniform (droplet model), then the maximum value of the electric field strength and the *E/N* parameter is achieved at the boundary of the +CDS. Since the ambipolar drift in plasma is directed from small values of the parameter *E/N* to large *E/N*, then according to (5) and the principles of classical hydrodynamics, standing shock waves of the electric field should be formed around the luminous plasmoids in the regions of maximum values of the parameter *E/N* [2, 8]. The study of Vysikaylo's shock waves of the electric field is a rather complex task. The author, having experience in the theoretical description of plasma structures with violation of electroneutrality, proposed and calculated the conditions for the implementation of the formation of a shock wave in a discharge in a tube with longitudinal gas pumping. We studied in detail the structure of such Vysikaylo shock waves in a gas-discharge plasma of special purity nitrogen [2, 8] (Fig.1*d*).

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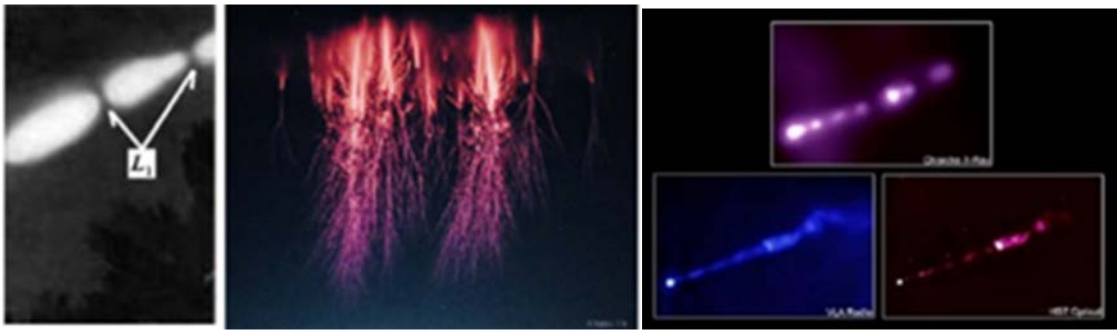

Figure 2: This is a demonstration of the similar dynamic surface Coulomb tension that accumulates energy in plasmoids with different characteristic dimensions:

a) Beaded lightning in the Earth's atmosphere, L_1 – Vysikaylo's cumulation points [9];
b) the sprite at altitudes of 50 - 90 km.
c) The central region of the M 87 galaxy with an active nucleus. Jet size ~ 1.5 kpc. We observe jet stratification and formation of cumulation regions. Hubble Telescope (NASA).

Fig.1*d* shows photographs of non-uniform plasma in a gas-discharge tube (with longitudinal pumping of ultra-pure nitrogen), locally perturbed by a beam of fast electrons. The photographs prove the existence of current self-cumulation processes under the action of an electric field in converging nozzles, as well as processes of dissipation (expansion) of the space charge region in the region of the Vysikaylo's shock wave, caused by the formation of a space charge layer [1, 2]. The obtained plasma parameter profiles are well described within the framework of Vysikaylo's perturbation theory, i.e. the modified Navier-Stokes equation (5), see Fig.1*f*.

In the photographs (Fig. 1*d*; Fig. 2) we see the cumulation points - L_1, discovered by Vysikaylo [9] between +CDS (MGMT was used by the author). These points are similar to the cumulation points (not librations points), discovered by Euler in 1767 in Russia. According to the classification [9], Euler discovered 3 cumulation points - $L_{1\text{-}3}$, and the triangular libration points $L_{4,5}$ were discovered by Lagrange in 1772 in France. The three cumulation points discovered by Euler's ($L_{1\text{-}3}$) should be called Euler points, not Lagrange's points. All five or more cumulation and libration points between +CDS for free electrons (analogs of Euler points $L_{1\text{-}3}$ and Lagrange's points $L_{4,5}$) will be called Vysikaylo points, as well as the lines and surfaces of cumulation of free electrons [2].

6. Conclusions

In our works, see references in [1-3, 5-14], we were the first to theoretically and experimentally study the processes of: 1) ambipolar transport due to violation of electrical neutrality 2) interference and diffraction of electric fields under external action on charged particles (using gas pumping as an example) in an inhomogeneous plasma with current. The author was the first to reduce the system of hydrodynamic equations (1), taking into account the Poisson equation for the electric field (2), to an equation of the Navier-Stokes type (5). Using the Vysikaylo's equation (5), we studied the three-dimensional co-organization (Fig.1*f*) of opposite flows of electrons and positive ions taking into account the internal electric fields as the third component of plasma with current [2,5-8]. Here we did not take into account the inertial and torsion fields acting on charged particles with mass. What processes of ambipolar transport this leads to, we indicated in [7]. The generation of a magnetic field in a current-carrying plasma confirms that the electric field is analogous to the third component in a simple current-carrying plasma.

Our experiments (Fig.1*d*), which confirmed our analytical and numerical calculations, clearly demonstrate that we do indeed observe 3D electric field shock waves (analogs of Mach's shock waves) and self-organizing 3D plasma nozzles (analogs of Laval's nozzles), which we predicted earlier [2, 5-8].

Experiments confirm that in [2, 5-8] we constructed the most complete 4D perturbation theory (5) for describing inhomogeneous and non-stationary +Vysikaylo's CDS in plasma with current taking into account the violation of electrical neutrality. This theory is devoid of all the shortcomings noted by A. A. Vlasov (1952) regarding incomplete theories for describing plasma, see references in [5-7]. Vysikaylo's perturbation theory and his equation (5) is the most complete modification of Schottky's perturbation theory, which for the first time (in 1924) described only ambipolar diffusion processes. Unlike Schottky's theory, we took into account all ambipolar drifts (in 1987 [1]) caused by the influence of electric field inhomogeneity due to electron diffusion processes on the processes of birth and death of charged and excited plasma particles [2, 5-8]. The main achievement of this theory – (5), is the establishment of a significant dependence of all effective coefficients of ambipolar transfers (drifts and diffusions), which we discovered, on the 3D-vectorized characteristic size of the violation of electrical neutrality – l_E (parameter E/n_e) [2, 5-8]. This parameter differs significantly from the parameter E/N introduced by Townsend (earlier the parameter E/P - the ratio of the density of electrical energy to the energy density of a neutral gas was introduced by Stoletov in 1889).

The parameter E/N is the main parameter in weakly ionized plasma (Fig.1*d*, Fig.2*a*, *b*), and the parameter E/n_e becomes significant in strongly ionized plasma (Fig.2*c*). If we take into account that the Sun and the heliosphere are positively charged, then for most of the electrons in the heliosphere a potential well is formed and only a small part of the electrons with energy greater than ($kQ_☼/R_☼$) ≈ 18,000 eV [3], capable of overcoming the potential barrier of the heliosphere, leave this well. The remaining electrons return to the center of the heliosphere and lose energy in electron-electron collisions. These collisions ensure the establishment of the electron temperature profile during the collisionless departure of positive ions from the heliosphere. In this model, the electron temperature profile in the heliosphere is determined by wave processes (multiple arrivals to the Sun and departures of high-energy electrons from the Sun). This complex problem was only posed in the author's works [2, 5-14]. The co-organization of electron flows leaving the Sun and returning to the potential well - the heliosphere leads to the formation of Vysikaylo's structural turbulence [1, 3].

The author was the first to study in detail self-forming shock waves of the electric field, arising due to the violation of the electrical neutrality of plasma with current, and plasma nozzles - analogues of Laval nozzles. Such self-focusing cumulative-dissipative structures discovered by the author are of great scientific and practical interest for astrophysics and gas-discharge plasma (from the Earth's atmosphere to intergalactic lightning). Theoretical results obtained in modeling shock waves of the electric field turned out to be useful for developing models describing cumulative-dissipative plasma phenomena during the destruction of meteoroids by beams of high-energy electrons formed in the plasma tail and catching up with the meteoroid [14]. +CDS phenomena are observed in the heliosphere, atmosphere and ionosphere of the Earth (Fig.2), since the Earth has a negative charge of about 500,000 C, and the Sun is charged positively at 1,400 C [3]. The author first estimated the charge of the Sun based on experimental observations of the types of iron ions in the solar wind at the L_2 point (Sun-Earth), see references in [3]. This charge is several times greater than the charge obtained by A.S. Eddington (1926) and with the help of the Parker's probe (2020 https://arxiv.org/abs/1912.02216v1).

The author claims and proves in his works that the violation of electroneutrality and the generation of global currents in the Universe occurs at all characteristic sizes of +CDS.

Fig.2*c* shows a linear inhomogeneous intergalactic lightning with cumulation points. This structure maintains a long-range dynamic order for more than 5 thousand years and has a functional significance for the positively charged black hole in the center of the galaxy M 87. Such an order can only be controlled by Coulomb forces as in plasma with current (Fig.2*a*). The author hopes that model (5) will be useful for the analytical description of cumulative formations in the intergalactic space of the galaxy M 87 (Fig.2*c*). And this will once again confirm the idea of Eratosthenes.

The idea, dating back to Eratosthenes, was used by us to study how the electric field affects matter, and matter (charged particles) affects 4D distribution and pulsations of the electric field in space [1-3,5-14]. This idea, already modified by us, is as follows. The analogy of the processes in CDS allows us to apply the method of generalized mathematical transfer (MGMT) of the most complete mathematical models to describe similar phenomena from well-studied areas of science in less thoroughly studied areas of natural sciences. With such a transfer of mathematical models, the specifics of the phenomena being described should be taken into account.

This method goes back to the idea of Eratosthenes, when he analytically calculated the diameter of the Earth within the framework of geometry. As a result of the development of this method into the Vysikaylo's method, we obtain the following general results from MGMT:

1) the survival condition for shock waves of all three types (Vysikaylo's electric field shock wave; ordinary Mach's shock wave and Sagdeev's magnetic field shock wave) is observed if the convective disturbances are directed into the shock wave. In the case of nonlinear Vysikaylo's electric field shock waves (VSW), these conditions are shown in Fig. 1*f* in the VSW region. Here, the disturbances to the left of VSW are carried away mainly by the ambipolar plasma drift *V*a (due to different dependences of the electron and positive ion mobility in an inhomogeneous plasma with current) [8], and to the right of VSW, the disturbances are carried away mainly by the gas pumping *U* in VSW, in the direction opposite to the shock wave ($\boldsymbol{V}_a$). Thus, we stopped theVysikaylo's shock wave by pumping gas in an inhomogeneous plasma with current [8];

2) in the V region (Fig.1*f*), where the disturbances are directed from the inflection point of the electron concentration (vector l_{Er}), a plasma nozzle is observed. Here, in Fig. 1*d*, we observe the formation of a Vysikaylo's plasma 3D nozzle (analogous to the Laval's nozzle in classical gas dynamics);

3) if Laval had not proposed his nozzle in 1890, then from the glow shape in Fig. 1*d* in region *V* we could have proposed for gas-dynamic phenomena its shape in the form of two combined truncated cones, conjugated by narrow ends. In this exchange of complete information about similar phenomena in CDS lies MGMT.

According to this idea, modified by us, in our models the description of shock waves (jumps) of all three types (Mach's shock waves, Sagdeev's magnetic field shock waves and Vysikaylo's electric field shock waves) is carried out by us using similar mathematical methods and equations (5) (the Navier-Stokes equation modified by us or the Burgers equation in the one-dimensional case) [2, 8]. This allowed us to apply the generalized mathematical transfer method (MGMT) modified by us of mathematical models from areas of natural sciences, where the descriptions of similar phenomena are the most complete, to areas of natural sciences, where a similar theoretical study is less complete [1, 2, 8]. When new results and laws for CDS are obtained in some areas of science, they can be transferred and verified in other areas of natural sciences, including economics, where Hegel's laws and the virial theorem have not yet been applied.

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Violation of electrical neutrality of plasma (system of charged particles) and processes of cumulation (due to ambipolar drifts) and dissipation (due to ambipolar diffusions) penetrate structures from femto-sizes (10^{-15} m) [9-11] to the sizes of intergalactic lightning (10^{26} m) [1]. Based on [1-14], we examined in detail quasi-stationary self-forming profiles in inhomogeneous plasma with current and classified them into drift profiles and diffusion jumps (the Vysikaylo's shock waves of electric field caused by violation of electrical neutrality).

Analysis of photographs of a 20 km long plasma trail and the features of the destruction of the Chelyabinsk's meteoroid [14], which exploded in the Earth's atmosphere with a Coulomb explosion, led the author to the discovery of a new mechanism of fractalization of celestial bodies in the electronegative atmosphere of the Earth and to propose a working scheme of an external combustion engine with an efficiency of 50% for moving bodies at speeds greater than 10 km/s.

The author considered quantum-Coulomb pulsars in nano- and femto-worlds [1, 10].

The fundamentals of the theory of Coulomb pulsars in quantum stars were discussed in the monograph [1]. Here, the violation of electroneutrality and the generation of reflective Coulomb potentials is due to the significant difference in the de Broglie wavelengths of electrons and positively charged particles (protons and atomic nuclei) [1]. The author hopes that, taking into account electric fields, it is possible to obtain Einstein's Λ-term.

The modified Navier-Stokes equation (5) that I obtained and the photographs of its solutions Fig. 1*d* will play a certain role in further research of plasma with current. Currents in plasma (gas discharge, in the heliosphere, in the arms of the Galaxy, in intergalactic lightning) arise due to high-energy electrons escaping from +CDS [8]. The positive charge of these structures heats free electrons (in their field), which are responsible for: generating surface tension, exciting gas atoms and molecules, which in turn are responsible for the glow of +CDS at all levels of their organization.

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