Shock Waves of the Electric Field—Part 2: Experimental Studies of Vysikayl's Jumps and Plasma Nozzles in Plasma With Current

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Abstract—In our works, we prove that the cumulation (self-focusing) of charged particles in a plasma (with current) is a universal property of cumulative-dissipative structures (CDSs) with characteristic sizes from 10^{-15} to 10^{27} m. The basis of such cumulation is the self-formation of electric field shock waves. Earlier (in Part 1) we proved that the electric field (in a gas-discharge plasma with current) behaves as an additional (to the concentrations of charged particles) component of the plasma. Therefore, both drift profiles and diffusion jumps (sharper discontinuities) should be observed in the plasma, analogs of ordinary Mach shock waves or magnetic field shock waves described by Sagdeev. In electric field shock waves, the pressure is created by the electric field (E) pressure—$P_E \sim E^2/8\pi$. Electric field shock waves were first predicted by the author in 1985. The author claims that these standing shock waves focus structures (in a plasma with current) by ambipolar drifts caused by the nonlinearity of the processes of transport of charged particles of the plasma. In this article, we will dwell in detail on the experimental studies of 3-D self-forming plasma cumulative-dissipative Vysikaylo's structures in gas-discharge plasma. By comparison with experiments, we prove that it is necessary to take into account the violation of electrical neutrality (Poisson's equation for the electric field) in gas-discharge plasma with current. In this part 2, we will use photographs and double probes to study the self-formation of inhomogeneous 3-D structures (plasmoids) due to the interference of ambipolar drift and gas pumping in inhomogeneous plasma using a local ionizer. For this purpose, we preliminarily locally disturbed the homogeneous plasma in the gas-discharge tube with a beam of fast electrons. This leads to self-formation of local: 1) shock waves of the electric field (a monolayer of positive space charge with jumps of the electric field), stopped by pumping gas (on one side of the fast electron beam); 2) transient 3-D profiles; and 3) Vysikaylo's plasma nozzles in quasi-neutral homogeneous plasma (on the other side of the beam disturbing the plasma). Based on laboratory experiments and theoretical studies of gas-discharge plasma, we prove that the ambipolar drift caused by different dependences of the electron and positive ion mobility in a simple plasma (with one type of ions) determines the dynamic processes of cumulation (self-focusing) and the formation of 3-D shock waves of the electric field due to the violation of electrical neutrality in electropositive gases.

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Index Terms—Ambipolar diffusion, ambipolar drift, electric field shock waves, inhomogeneity of the electric field ambipolar transport, perturbation theory, violation of electrical neutrality.

I. INTRODUCTION

THREE types of shock waves are currently known [1], [2].

1) Shock waves (or sharp jumps in parameters—P = kTn—gas pressure, n—particle number density, and T—particle temperature) in gas dynamics. Their study began with the work of Mach (1881)—Austrian physicist, born in Czechoslovakia.
2) Magnetic field shock waves (here sharp jumps is in $P_H \sim H^2/8\pi$) were described by R. Z. Sagdeev in 1961–1962 in the USSR. When describing the shock waves of a magnetic field, Sagdeev used Maxwell's equations and the Boltzmann–Vlasov's equation.
3) Shock waves of the electric field (sharp jumps in—$P_E \sim E^2/8\pi$), described theoretically and experimentally in detail in the works of P. I. Vysikaylo in the USSR, see in [1], [2], [3], [4], [5], [6]. When describing the shock waves of an electric field, Vysikaylo used Poisson's equation and assumed that the density of gas particles was constant (P, T = const). Although Vysikaylo's shock waves were observed by Faraday, then by Klyarfel'd (1952) in the form of standing and traveling layers in gas-discharge plasma in tubes, and by Gunn (1963) in the form of current oscillations in semiconductors (probably, Gann was the first to call these waves shock waves of the electric field, although he did not provide worthy evidence or study of their parameters). The cumulation of shock electromagnetic waves was of theoretical interest to E. I. Zababakhin (1957, 1965, 1988). E. P. Velikhov, A. S. Kovalev, and A. T. Rakhimov took into account the weak violation of electrical neutrality when describing the formation and propagation of high-field domains in a nonself-sustaining discharge in an electronegative gas (with electron attachment) (1987). Even earlier, in 1979, Shapiro G. I. and Soroka A. M. analytically studied the occurrence of forced ambipolar diffusion under the influence of a high-frequency electric field. They showed that

ambipolar Schottky's diffusion is not the only ambipolar diffusion.

However, the main results on experimental and theoretical research and proof of the existence of electric field shock waves were obtained in the works of P. I. Vysikaylo and his co-authors for almost 40 years, see [1], [2], [3], [4], [5], [6]. The main achievement in his work was taking into account (according to the 3-D Vysikaylo's perturbation theory) the violation of electrical neutrality of charged plasma particles. This account led to the description of a number of completely new 3-D transport processes: 1) analogs [1], [2], [4] of classical ambipolar Schottky's diffusion and 2) various analogs [1], [2], [3] of ambipolar drifts. The main processes of ambipolar transfer, which appeared due to taking into account the 3-D Poisson's equation for the electric field [div $E = 4\pi(n_+ - n_e)$], are given in (1). This nonstationary 3-D modification of the hydrodynamic model of Schottky's ambipolar diffusion for describing ambipolar flows taking into account the violation of electroneutrality (3-D Poisson equations) was proposed by Vysikaylo [1] and [2]. Furthermore, for simplicity, we will assume that the particle number density of the neutral gas $N =$ const.

The remaining types of shock waves (plasma parameter jumps—pressure of ions, electrons, etc.) can be reduced to these three main types [3] or the Fisher–Kolmogorov–Turing–Prigogine's problem, where diffusion and production (birth, ionization, etc.) or two diffusions with different characteristic diffusion sizes are used, for example, in the case of the Prigogine's Brusselator [7]. From the point of view of mathematics, shock waves arise when it is impossible to describe the concentration profile in the ambipolar drift approximation terms with the first derivative in coordinates ($V\nabla n$). It becomes multivalued (theoretically). In order to obtain physically significant solutions, it is necessary to theoretically take into account smoothing diffusion flows [1], [2], [3], [4], [5], [6]. This leads to the need to describe a shock wave or a jump in plasma parameters using terms with a second derivative in coordinates ($\nabla D\nabla n$).

In 1985, P. I. Vysikaylo theoretically predicted the existence of shock waves in collisional plasma with violation of electroneutrality and the dependence of the width of such a Vysikaylo's shock wave on the discharge current, see [1]. In [1], [2], [3], [4], we constructed the most complete 3-D nonstationary Vysikaylo's perturbation theory to describe the profiles of nonstationary inhomogeneous 3-D structures in gas-discharge plasma with current (hereinafter referred to as 4-D theory). The small parameters of this 4-D theory are: 1) the smallness of the positive ion current relative to the electron current ($\mu_+ l_E/\mu_e L \ll 1$) and the smallness of the electron energy relaxation length relative to the characteristic dimensions of the inhomogeneity—l_u/L. Here, $l_E = E/(4\pi e n_e)$ is the vectorized characteristic size of the violation of electroneutrality of plasma with current, determined by the vector parameter E/n_e [1], [2], [3], [4], [5]. All coefficients of drift, diffusion, and reaction rates are the functions of the parameter E/N (N is the density of the number of neutral gas particles), in accordance with the works of Stoletov and Townsend, see [2]. The smallness of the ratio of the ion current to the electron current (smallness of the parameter—$\mu_+ l_E/\mu_e L \ll 1$) allows solving problems with a significant violation of electrical neutrality due to the smallness of the ratio of ion mobility—μ_+ to electron mobility—μ_e, see [1], [2], [3], and [4], in the zero approximation according to the specified parameters using the positive ion balance equation modified by me in the form [1], [2], [5]

$$\begin{aligned}
&\partial n_e/\partial t - \partial\,(l_{E0}/\mu_{e0})\nabla(\mu_{e0}n_e)/\partial t + (j/e)\nabla(\mu_{+0}/\mu_{e0})\\
&\quad + U\nabla n_e - \nabla(U(l_{E0}/\mu_{e0})\nabla(\mu_{e0}n_e))\\
&\quad - \nabla\{l_{E0}(\mu_{+0}E_0/\mu_{e0}\nabla)(\mu_{e0}n_e)\}\\
&\quad - \beta n_e(l_{E0}/\mu_{e0})\nabla(\mu_{e0}n_e) = q + I_i - R_{i0}. \qquad (1)
\end{aligned}$$

Here, the terms with the *vector*—l_{E0} appeared from the Poisson equation for the electric field strength (E) $n_+ = \nabla E/4\pi e + n_e$ and the conditions for the current density $\nabla j = \nabla(e\mu_e E n_e) = 0$; $(j/e)\nabla(\mu_{+0}/\mu_{e0}) = V_a\nabla n_e$. V_a arises due to different dependences of the electron and ion mobilities on E/N [1], [2], [3]; R_{i0}—recombination of electrons and positive ions in zero approximation; $\beta n_e l_{E0}$ is the speed of the ambipolar recombination flow caused by the violation of electrical neutrality in the plasma with current [1], U is the gas pumping speed, β is the effective coefficient of ion–electron recombination, I_i is the ionization of gas molecules by electron impact, and $q(x)$ is the external ionizer of gas molecules (in our experiments, this is a beam of fast electrons with an energy of 100 keV). According to (1), in Vysikaylo's 4-D theory, which takes into account the violation of electrical neutrality, it is possible to describe the parameter profiles of 3-D nonstationary inhomogeneous structures in plasma with current.

Moreover, according to (1), all coefficients with vector l_E are vectors. This means that all characteristic 3-D sizes of transition layers between plasma 3-D structures and their characteristic 3-D sizes are significantly determined by the vectorized characteristic size of the violation of electroneutrality of plasma with current—$l_E = E/(4\pi e n_e)$ and, therefore, are determined by the vectorized parameter E_0/n_e.

In Part 1 [5], this perturbation theory (1) was applied to describe stationary 1-D parameter profiles in Vysikaylo's shock waves with violation of electroneutrality in a current-carrying plasma perturbed locally by an external ionizer. It is also shown there that the characteristic size of the Vysikaylo's shock wave in the longitudinal current direction is determined by the parameter—l_{Ex}. Based on the 4-D [5, eq. (1)], considerations are given about the possible dependence of the width (effective radius in the case of cylindrical symmetry) of the discharge on the radial component of this parameter—$l_{Er} \sim E_{0r}/n_e$. Thus, we predicted in [5] an inversely proportional decrease in the discharge cross section with increasing electron concentration. In this Part 2, we present experiments in a gas-discharge tube in a high-purity nitrogen plasma, proving the theoretical conclusions presented in [5].

II. Experimental Studies of Vysikaylo's Shock Waves Exist in an Electropositive Gas

Under the conditions of these experiments in plasma in nitrogen, the main processes of ambipolar transfer were gas pumping from the anode to the cathode at a speed U and ambipolar drift—V_a [the third term in (1)]. The velocity V_a in nitrogen depends on the E/N parameter, reaches, according to analytical calculations and experiments [1], [3], 70 m/s, and is directed from the region of small values to the region of large values of the E/N parameter. Since V_a is directed from Faraday's dark space to the positive column, then to form regions with shock waves and Vysikaylo's plasma nozzles, where the complete ambipolar drift $U + V_a(E) \rightarrow 0$ and the role of ambipolar diffusion processes increases, the gas pumping speed should be selected from the anode to the cathode.

Since the works of Stoletov and Townsend, it is known that in weakly ionized gas-discharge plasma, the parameter E/N should be used, and the concept of the temperature of electrons and positive ions for gas-discharge plasma is a harmful concept, since the electron energy distribution function is essentially not Maxwellian. The plasma in our experiments is essentially nonequilibrium. The energy drain from all plasma components was carried out into neutral nitrogen molecules and removed by pumping the gas. This allows us to abandon the concept of temperatures for ions and electrons in the theoretical description and use the parameters E/N and E/n_e. The parameter E/n_e was introduced by Vysikaylo to take into account the importance of the violation of plasma electroneutrality [1], [2], (1). Under our conditions, the relaxation of the energies of charged particles occurs on unexcited molecules of the neutral gas—nitrogen, and not during interactions of electrons and positive ions with each other ($n_e/N < 10^{-7}$). The gas pumping rate was such that the gas in the tube did not heat up and its density did not change significantly as it passed through the tube. Therefore, there were no energy redistributions between all the components of the plasma. This allowed us to visualize the quasi-stationary interaction of the electric field described by the modified Vysikaylo nonlinear Navier–Stokes (1) (or the Burers equation in the 1-D quasi-stationary case). Under such conditions, the electron energy distribution function and all electron transfer coefficients and their birth and death frequencies are determined only by the parameter E/N.

A. Experimental Setup and Method of Local Plasma Disturbance in a Gas-Discharge Tube

For an experimental study of electric field shock waves, P. I. Vysikaylo an installation was designed with longitudinal (discharge current) pumping of gas in a tube [Fig. 1(a)]. Such tubes have been used to study discharge in various gases since the time of Faraday [Fig. 1(b)]. For experimental and theoretical studies of nonlinear interaction of external electric field with charged particles in nonuniform plasma with current in this work, we chose gas discharge plasma in molecular nitrogen with constant gas pumping. The pumping rate ensured the absence of significant excitation of neutral gas molecules,

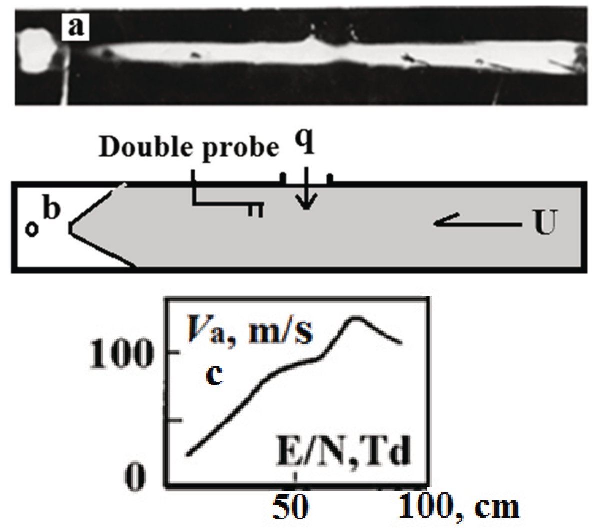

Fig. 1. Discharge in a tube with a window for a beam of fast electrons in the middle: (a) Photograph in nitrogen (P = 15 torr, U = 40 m/s, and I = 4 mA). On the left is the cathode spot and Faraday dark space. J_q = 0. (b) Scheme of the experimental setup. (c) Velocity of ambipolar plasma drift due to the different dependence of the electron and ion mobilities on the parameter E/N [3].

and small currents ensured the absence of influence of the energy of charged particles on each other. In this case, the plasma and its energy are a weak perturbation of the flow of molecular electropositive gas, but this energy is sufficient for visualization of 3-D discharge behavior. The setup was a glass tube with a cross section of 3 cm^2 and a length of 45 cm. We have long used such tubes in experiments to directly prove the existence of ambipolar plasma drift—V_a, caused by nonlinearity—the difference in the dependences of the mobilities of electrons and ions on the field—E, or rather on the parameter E/N, see [1], [3]. The pumping speed U, at a gas pressure—nitrogen in the tube P = 15 torr, could vary within 1–100 m/s. The distribution of electric potential along the entire length of the tube was measured with probes soldered through ~3 cm (they are visible in all photographs in the form of black stripes). Typically, the gas pumping speed was chosen, so that the gas did not heat up significantly ($N \approx$ const—the density of the number of gas particles in the tube).

The ignition of a stationary longitudinal (gas flow) discharge occurred when a small cathode spot was formed on the cathode and behind it, due to the ambipolar drift—V_a, a dark Faraday space was established at the cathode (Fig. 1, left). The dependence of V_a on the parameter E/N [3] is shown in Fig. 1(c). In high-purity nitrogen plasma, according to numerous experiments, see [1], and numerical calculations, the electron drift velocity is well described by a simple approximation $V_e = 1.83 \cdot 10^6 \cdot \gamma^{0.75}$ [m/s], here γ = E/N [V/cm^2]10^{16} in the range of E/N parameter values from 1 to 240 Td. According to experiments, see [1], 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^+), and 2.33 (N_4^+) in the range of parameters of our experiments ($1 < E/N$[Td] < 60) and remains virtually

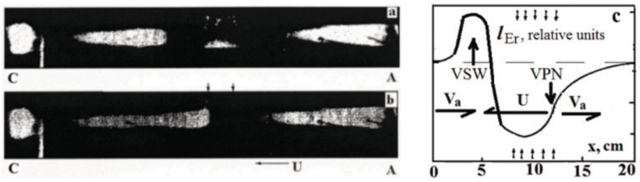

Fig. 2. Discharge glow. (a) (U = 40 m/s, P = 15 torr, and I = 4 mA) perturbed by a beam of fast electrons: *a*-case of a strong ionizer (J_q = 3 μA/cm^2) or a strong shock. The shock is outside the ionization zone. (b) Case of a weak ionizer. The jump is located in the region of the external ionizer. The ionizer area is indicated by arrows in the tube center. (c) Diagram of the main processes of ambipolar transport during interference of ambipolar drift and gas pumping—U in plasma with current in case—(a), according to [5]. VSW—self-forming standing shock wave of electric field stopped by gas pumping—U; VPN—self-forming 3-D Vysikaylo's plasma nozzle (with conical geometry).

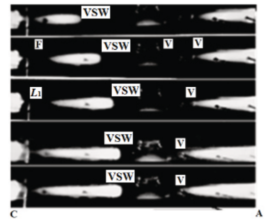

Fig. 3. This is photographic evidence of the formation of Vysikaylo's shock waves—VSW and Vysikaylo's plasma nozzles—V (in plasma with current). U = 40 m/s (from A to C), J_q = 3 μA/cm^2, density I varies from 0.33 mA/cm^2 to 1.52 mA/cm^2. F—Faraday dark space. L_1 is Vysikaylo's cumulation point between positively charged luminous plasma structures (cathode spot and positive column).

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.

The question of boundary conditions in a gas-discharge plasma with a cathode spot and Faraday dark space is quite complex, see [1], [6]. Therefore, in experiments to study shock waves of the electric field (Figs. 2 and 3), P. I. Vysikaylo proposed a method for local disturbance of the plasma concentration of a previously homogeneous extended [more than 30 cm long, Fig. 1(a)] plasma column with current in a gas-discharge tube far from the electrodes, see [1]. To do this, a 2 × 2 cm^2 window was located on the side surface of the tube in its center, through which a quasi-stationary beam of fast electrons with an energy of 100 keV and a current density of up to $J_q \sim 10$ μA/cm^2 was introduced into the discharge through a Mylar film. The beam carried out additional ionization of the gas and thereby created a quasi-stationary, controlled local inhomogeneity of the plasma concentration in the center of the tube in the previously homogeneous positive discharge column. After the beam was introduced, in this region and the region of perturbation relaxation, the electron concentration sharply increased and, accordingly, the electric field strength decreased (the parameter E/N decreased locally in the plasma); therefore, the average energy of electrons in the plasma decreased and the discharge glow disappeared in this region (Figs. 2 and 3) and, accordingly, the velocity V_a sharply decreased and the plasma could change the direction of its movement. In Figs. 1–3, in the center of the discharge tube, one can see a window for the beam and a dark region of disturbance of the plasma column by a beam of fast electrons (Figs. 2 and 3). Based on the contrast of the glow and the places where it is observed, one can judge the characteristic longitudinal and radial dimensions of the drift and diffusion (jumps) 3-D profiles of the plasma parameters.

In our experiments and numerical models, we perturbed the homogeneous positive plasma column locally (by introducing a high-energy electron beam). The small concentration of the beam electrons did not significantly affect the perturbation of the electric field, but the high energy of the electrons led to a local increase in the frequency of electron and positive ion production [$q \neq 0$ in (1)]. We used the introduction of a fast electron beam to create a stationary locally high concentration of charged particles (electrons and positive ions) and nothing more. In this case, nonlinearities appear in this setup without any other interaction between the electron beam and ambipolar drifts, the velocities of which are determined only by the parameters E/N and E/n_e. We did not conduct plasma re-equilibration experiments. This was not necessary, since gas pumping completely eliminated excited particles from the gas-discharge tube. The goal of our work was to prove the formation of stationary inhomogeneous plasma structures by internal ambipolar drift using the example of gas pumping and internal ambipolar drift. We stopped these cumulative-dissipative structure (CDS) by pumping gas and photographed them to illustrate the solution of the Navier–Stokes equation modified by me to describe the shock waves of the electric field and plasma nozzles.

At this installation, experimental studies were carried out to study the self-focusing of plasma in the regions of plasma nozzles predicted by P. I. Vysikaylo, see [1], [5]. These regions (with plasma nozzles) are located asymmetrically with respect to Vysikaylo's shock waves in inhomogeneous plasma structures (plasmoids), see [1], [5]. *We photographically recorded the 3-D heterogeneity of the discharge*. Let us consider the results obtained experimentally when studying the complex phenomena of *interference of internal flows of inhomogeneous plasma—V_a with longitudinal flow of gas—U.*

B. Types of Experimentally Studied Standing Vysikaylo's Shock Waves

Here, we photographically demonstrate the two types predicted by P. I. Vysikaylo, shock waves of the electric field (drift jumps) with a violation of the electrical neutrality of the plasma with current and longitudinal pumping of gas, see [1], [5] (Fig. 2). In the first case, in Fig. 2(a), there is a jump outside the region of the external ionizer. This corresponds to the case of a strong disturbance—a strong ionizer. In the second case, in Fig. 2(b), the Vysikaylo's shock wave is observed inside the ionizer region. This corresponds to the case of a weak ionizer [1], [5]. Experiments (Fig. 2) fully confirm Vysikaylo's predictions, see [1] and [5], weak and strong shock waves of Vysikaylo's electric field. Thus, in experiments, we confirmed the classification of Vysikaylo's shock waves in an inhomogeneous plasma with current and gas pumping, see [1], [5]. Fig. 2(c) shows a diagram of the dominance of ambipolar flows along the length of a nonuniform discharge, disturbed in the center by a beam of fast electrons (which carry out additional local ionization in the area of its action).

C. Photographic Evidence of the Discovery of Vysikaylo's Shock Waves and Plasma Nozzles

In experiments in 1986 and 1987, see [1], according to theory (1), [1], [5], we chose: 1) the gas pumping speed—U (detailed experimental studies were carried out in high-purity nitrogen); 2) the density of the beam of fast electrons, locally increasing the plasma concentration; and 3) the magnitude of the discharge current—I, conditions were created under which, according to the model [1], [2], [3], [4], [5], the total velocity of the inhomogeneous plasma $U + V_a$ in the positive column and in the area of influence of the external ionizer had opposite directions and thus an ambipolar drift—$V_a + U$ cumulated (collapsed) plasma energy-mass-impulse flows (EMIFs). This can be achieved according to the model [1], [5] by pumping gas from the anode.

As we established in theory [1], [5], disturbance of the plasma column by a local additional ionizer (a beam of fast electrons) should lead to the formation of asymmetric profiles of plasma parameters. According to the 1-D theory [1], [5], on one side of the disturbance, a Vysikaylo's shock wave is formed, and on the other side of the external disturbance, a Vysikaylo's plasma nozzle should be formed. In the experiments, we created conditions under which, in regions perturbed by an external ionizer, standing Vysikaylo's shock waves of the electric field arose and, on the opposite side of the Vysikaylo's shock wave and external disturbance (windows for the beam), plasma 3-D structures self-formed in region V—Vysikaylo's plasma nozzles (Fig. 3). These Vysikaylo's plasma nozzles are similar to Laval's nozzles in conventional gas dynamics [1], [5]. These [1], [5] asymmetric luminescence profiles are observed in experiments (Figs. 2 and 3). The Vysikaylo's 3-D plasma nozzle is formed behind a window for a beam of high-energy electrons (Figs. 2 and 3)—this area is marked with letter V.

Fig. 3 shows the five photographs of the discharge depending on the discharge current, varying five times, from 0.33 to 1.52 mA/cm^2. From a comparison of photographs (Fig. 3), it is clear that with increasing discharge current: 1) the dimensions of the luminous plasmoids longitudinal to the current increase, while; 2) the left glowing plasmoid (toward the anode—A) ends with the Vysikaylo's shock wave. The Vysikaylo's shock wave has an elliptical shape; 3) the shape of the Vysikaylo's shock wave and its width depend on the discharge current, in accordance with the theory, see [1], [5]. At the maximum discharge current, the width of the Vysikaylo's shock wave in these experiments reaches $l_{Ex} \approx 1.5$ cm and its shape becomes elliptical (Fig. 3, photographs 4 and 5). This indicates the generation of dynamic surface tension in 3-D plasma luminous structures with a space charge; 4) the intensity of the glow of the Vysikaylo's shock wave increases significantly with increasing discharge current, which indicates an increase in the E/N parameter in the shock wave (Fig. 3, region—VSW), as predicted in theory, see [1], [5]. An increase in the E/N parameter leads to an increase in the space charge and the ejection of plasma particles onto the walls of the tube, which leads to an increase in the effective cross section of the discharge in the region of the Vysikaylo's shock wave; 5) behind the window area for introducing a beam of high-energy electrons, the formation of a 3-D Vysikaylo's plasma nozzle is observed, approaching the window with increasing discharge current—I; 6) the radial cross section of the discharge in region V of the Vysikaylo's plasma nozzle is many times smaller than the radial cross section in the shock wave of the electric field (Fig. 3, VSW); and 7) with increasing discharge current, the areas of formation of shock waves of the electric field and the areas of Vysikaylo's plasma nozzles approach the area of action of the high-energy electron beam (Fig. 3). This indicates that the role of ambipolar: recombination flux and ambipolar diffusion terms 5 and 7 in (1), caused by the violation of electrical neutrality in plasma with current, decreases with increasing current. The role of these members requires further research.

Experiments (Figs. 2 and 3) clearly prove the presence of the processes of radial cumulation and dissipation predicted by us, determined by the parameter E/n_e or the vector l_E. These self-cumulation processes determine the radial sizes of plasmoids according to (1) due to changes in the E/N parameter in an inhomogeneous plasma with current. These 3-D phenomena of a sharp change in the discharge cross section occur without the influence of a magnetic field.

According to our experiments, the glow profiles (reflecting the E/N parameter profiles) are established at times of the order of 10^{-2} s. This corresponds to the velocity of ambipolar plasma drift in the positive column. At large times, the glow structure observed in our experiments is stable and clearly defined. At shorter times, a cathode spot and a Faraday dark space with a Vysikaylo's cumulation point between the positively charged cathode spot and the positive plasma column are formed. At these times, the interelectrode gap is penetrated by substantially nonstationary ionization and recombination waves (1), and the glow structure is pulsating. In the region of the cumulation point L_1 (for electrons) [8], over time, a stationary Vysikaylo's plasma nozzle is formed between the positive cathode spot and the positive column.

D. Probe Studies of E/N Profiles in Standing Vysikaylo's Shock Waves

To obtain the statistical profile of the field—$E(x)$ in the Vysikaylo's shock wave region, we used a double probe. We moved the probe from one experiment to another at established discharge parameters, gas pumping speed and high-energy electron beam current. This is how $E(x)$ measurements took place, see [1]. The E/N parameter profiles obtained as a result of (about 30) experiments are presented in Fig. 4 in the form of three curves. From Fig. 4, it is clear that the parameter E/N in the shock is significantly ~20% higher than its value in a homogeneous unperturbed positive plasma column ($E/N \sim 40$ Td). This is a 3-D

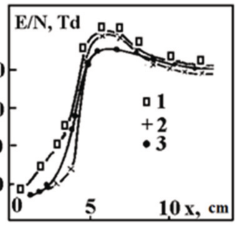

Fig. 4. Distribution of reduced electric field strength measured by a double probe [$E/N(x)$ in Td] in the shock (standing Vysikaylo's shock wave) P = 15 torr, 1—I = 4 mA and U = 80 m/s (A→C); 2—I = 1.5 mA and U = 40 m/s (A→C); 3—I = 1.0 mA and U = 40 m/s (A→C).

effect. It is associated with a significant difference between 3-D phenomena in electric field shock waves and phenomena in Mach shock waves. This is due to the generation of electric fields transverse to the current in the Vysikaylo's shock wave and the release of positive ions onto the walls of the tube. The more intense removal of plasma in the direction transverse to the current and its destruction on the walls of the tube lead to an increase in the E/N parameter in the zone of the Vysikaylo's shock wave, stopped by gas pumping, see [1].

III. Studies of Vysikaylo's Cumulative Dissipative Structures

Until 1985, certain differences between finite-dimensional 3-D electric field shock waves and Mach shock waves were obvious to the author. These differences (with the interference of internal ambipolar drift with the pumping of neutral gas in an inhomogeneous plasma) are associated with the generation of electric fields transverse to the current and with the local cumulation of the space charge in 3-D jumps in plasma parameters with the current. In Vysikaylo's shocks, monolayers of positive charge are formed, rather than double layers, as is usually assumed in the literature. (The second negative layer is carried far beyond the boundaries of the problem by electrons.) In 3-D monolayers of space charge, profiles of the E/N parameter are formed, in which inhomogeneous heating of charged plasma particles occurs. The cumulation of space charge can be carried out by ambipolar drift of one nature or another, both in the longitudinal direction to the current and in directions orthogonal (transverse) to the current, leading to contraction of positive discharge columns. The most complete list of ambipolar drifts is presented by us in [1], [2], [3], [5], and [8]. Space charge cumulation can be of three types: 1) spherical; 2) cylindrical and conical; and 3) planar in the form of strata, shells [1], [6], [8]. In accordance with the types of cumulation, corresponding types of 3-D shock waves of the electric field (E/N parameter) arise.

The perturbation theory, which takes into account the violation of electrical neutrality, was initially formulated by us for 1-D nonstationary problems (with spherical, cylindrical, and planar geometry), see [1]. Already at this stage, this theory made it possible to explain the experimentally observed Pekarik's effect: the opposite directions of the group and phase velocities of strata (electric field shock waves) in a current-carrying plasma. This phenomenon is associated with the significant role of the second term in (1), [1]. The bicumulation of positive ion fluxes on a cumulative electron jet (toward the anode) in the region of the cathode spot was discovered and explained. On the basis of this model, the reverse motion of the cathode spot (a positively charged structure that cumulates free electrons), discovered by Stark in 1903, was explained. We also explained other cumulation phenomena in CDSs discovered by Vysikaylo, see [1], [9].

Four-dimensional theory (1) for the first time allows us to explain all the 3-D phenomena we observed in experiments, presented in Figs. 2–4. In these experiments, a standing Vysikaylo's shock wave in an inhomogeneous plasma with current is formed by ambipolar drift—V_a (due to different dependences of the drift velocities of electrons and positive ions on the E/N parameter [3]) propagating from the Faraday dark space to the anode and gas pumping (positive ions frozen in gas flow) from the anode to the cathode. In this case, the ambipolar flows collapse. From opposite sides, they accumulate flows of ambipolar inhomogeneous plasma to the space charge layer and thereby form a standing shock wave with a space charge in the plasma with current [1], [5] (Fig. 3). We applied 4-D perturbation theory (1) to describe the behavior of lightning, stationary (Faraday et al.), and traveling (Pekarik's effect and Gann's effect) strata, plasma tails behind meteoroids, and the electric field shock waves and Vysikaylo's plasma nozzles previously predicted by the author (Fig. 3). Our experiments confirm the discovery of 3-D electric field shock waves, which, due to the space charge, tend to dissipate (expand, form shells, or strata that are more extensive in the transverse direction) and self-focusing (cumulating their sizes into narrow ones in the transverse direction) Vysikaylo's plasma nozzles in inhomogeneous plasma with current. The phenomena of increase and decrease in the characteristic dimensions of the violation of electrical neutrality in the discharge are described by the vectorized parameter E/n_e (1).

Unlike Kolmogorov–Turing–Prigogine's dissipative structures, where the main transfer processes are diffusion processes, in Vysikaylo's plasma CDS, the main transfer processes are convective processes—V_a, U, and so on [3], leading to cumulation (self-focusing, collapse) of EMIF in inhomogeneous plasma with current. We have proven theoretically and experimentally (Figs. 2–4) that the cumulation of EMIF can lead to local self-focusing of a space charge in a current-carrying plasma, the formation of surface dynamic tension of plasmoids (Fig. 3), the formation of electric field shock waves in them, and Vysikaylo's plasma nozzles—analogs of Laval's nozzles and cumulative jets of both electrons and positive ions. In full agreement with theory (1), see, [1], [5], as experiments have shown (Figs. 2 and 3), on one side of the local ionizer in a current-carrying plasma, a Vysikaylo's shock wave profile is formed, and on the opposite side from the disturbance, a Vysikaylo's plasma nozzle is formed, where the derivative of the electron concentration tends to ∞. An external local ionizer in a current-carrying plasma plays the role of a piston, simultaneously forming inhomogeneous profiles of plasma parameters that are asymmetric with respect to the local disturbance. This asymmetry of shock waves and Vysikaylo's

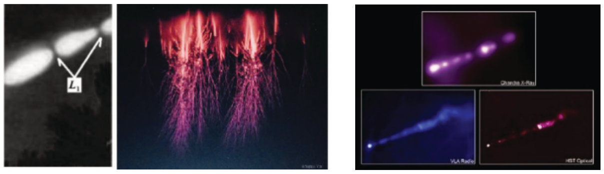

Fig. 5. This is a demonstration of the similar dynamic surface Coulomb tension that cumulates energy in plasmoids with different characteristic dimensions.

plasma nozzles (relative to each other) allows one to visually determine in current-carrying plasma: 1) the directions of flows of charged particles; 2) the direction of growth of E/N; and 3) determine the Vysikaylo's cumulation points, lines, and planes (analogs of Lagrange's libration points—L_{1-3}, discovered by Euler in 1767 between Jupiter and the Sun), see [8].

In the general case, if the cumulation of a space charge occurs in the longitudinal direction of the current, then the dissipation of its EMIF (or spraying) occurs in orthogonal directions. This leads to the formation of shells with characteristic dimensions $\sim l_E$ or self-forming Vysikaylo's plasma nozzles. And vice versa, if cumulation occurs in the radial direction to the current, as in the plasma tail behind meteoroids, in linear lightning or in the jet from the M 87 galaxy, then EMIF spraying (or dissipation, including in the form of a beam of charged particles) occurs in the longitudinal current direction [10].

We observed Vysikaylo's shock waves in experiments (Figs. 2–4). This proves their existence, but they are observed not only in laboratory studies but also in the heliosphere [11], the Earth's ionosphere [Fig. 5(a) and (b)] and even in intergalactic lightning, for example, in the region of the M 87 galaxy [Fig. 5(c)]. The jet in the region of the M 87 galaxy practically does not change its transverse size [Fig. 5(c)], which indicates the presence in this structure of forces focusing EMIF from the center of the galaxy. Such forces can only be Coulomb forces with electric fields. It can be argued that a cumulative jet of protons shoots out from the center of the galaxy, self-focusing by the electrons surrounding it [as in linear lightning in the atmosphere, Fig. 5(a)]. The characteristic distances and length of such a jet are about 4.9 thousand light years. At such characteristic sizes, the plasma becomes collisional and the main parameters for it are probably E/N and l_E (E/n_{e-} Vysikaylo's parameter).

Figs. 3 and 4 show quasi-stationary inhomogeneous discharges (perturbed locally by a beam of fast electrons) with gas pumping. In this case, from the profiles and shape of the inhomogeneous profiles, we can determine the direction of the global current. Fig. 5(a) and (b) shows the glow profiles of inhomogeneous nonstationary (pulsed) plasma CDS in electronegative gas (air). In air plasma, the role of negative ions should be taken into account: the rate of electron attachment to oxygen molecules, the rate of destruction of negative ions, and so on. However, we see that in these structures in the air, dynamic surface tension is formed. The dynamic surface tension of such heterogeneous CDS is also determined by the breakdown of electrical neutrality, the generation of electric fields, and the formation of electric field shock waves. We have just begun to study these processes in our works, and here, we have to figure out where the current flows. For such structures, oscillatory processes or pulsating current are possible. A. Vlasov discussed such pulsations.

For determining the direction of the global current in the stationary CDS presented in Fig. 5(c) (according to their visualized glow, their lifetime is more than 4.9 thousand years), then here we should use the knowledge we have acquired about CDS.

The author claims that all 3-D plasma structures are formed with the participation of shock waves of the electric field (E/N parameter). These waves perform the function of skin, fur coat, or cover for plasma structures of various geometries. The shock waves of the electric field cumulate (focus) electrons into positively charged structures form cumulative jets from them and more slowly spray positive ions generated in the CDS.

1) Beaded lightning in the Earth's atmosphere, L_1—Vysikaylo's cumulation points [6].
2) The sprite at altitudes of 50–90 km.
3) 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).

Systems with current have long-range dynamic order and hyperproperties in cumulative jets of high-energy electrons that close the current in dark regions (Fig. 5). For cosmic hydrogen-proton plasma with free electrons, it is not yet possible to carry out such calculations taking into account the violation of electrical neutrality in an inhomogeneous plasma with current. There are no reliable experimental data on the dependence of drift velocities and effective diffusions on the E/N parameter. However, we are gradually solving these problems for the heliosphere [11]. In [11], the main features of inhomogeneous plasma in the heliosphere and the causes of the emergence of the solar wind were identified. The solar charge of 1400 C determines the temperature of the helisphere at altitudes greater than 1000 km above the Sun [11]. In this work, we demonstrate the photographs of M 87 jets, photographically proving that electrical phenomena clearly similar to phenomena in laboratory plasma take place in 3-D CDS with dimensions up to 10^{27} m. In the jet from a black hole (from M 87), protons and alpha particles are ejected. In this jet, electrons cumulate and accelerate to energies at which they are able to penetrate into the black hole and thereby stop its Coulomb explosion due to the space charge. Links to my publications and the mechanism of quantum charge separation during the interference of electric and gravitational fields in quantum stars are given by me in [9].

IV. Discussion of the Results

In positively charged plasma structures, the ambipolar drift is directed toward the boundary of the positively charged structure. This clearly follows from the drop model of a positively charged structure, in which the maximum value of the electric field strength, and hence the parameter E/N, is achieved at its boundary. This gives grounds to assume that similar stratification phenomena presented in Fig. 5 are described by the Navier–Stokes equation modified by the author in various plasmaswith current with collapsing ambipolar drifts toward the boundary of the positively chargedstructure. At this boundary, a Vysikaylo's shock wave is formed, separating differently activated plasmas. In this case, the shock wave plays the role of a sheath focusing the plasmoid. Electrons external to the positively charged plasmoid focus the plasmoid and compensatefor its charge, acting as a coat of the positively charged structure.

In electronegative gases, such as air, it is necessary to take into account the balance of negative ions, but for positive ions, (1) doesnot changesignificantly, although new ambipolar flows appear, including plasma-chemical ambipolar drift [1], [3]. For this reason, the results we obtained in our experiments are generalized to other gases, including those in the heliosphere and ionosphere, where the current flows between the negatively charged Earth (its charge is 500 000 C) and the positively charged Sun (its charge is 1400 C [11]). The ionosphere and heliosphere are a heterogeneous gas discharge of enormous size. The study of this discharge has only just begun. We determined the charge of the Sun by the types of positive ions in the solar wind. Unfortunately, this method of ours was not used on the Parker's probe. More details on the comparison of the charge of the Sun obtained in the works of Eddington, Vysikaylo, and Halekas can be found in [11].

As an extension of the theoretical basis, the author formulates the method of generalized mathematical transposition (MGMT). MGMT consists in transferring mathematical models from the areas of natural sciences, where the phenomena have been studied well enough, to areas where they have been studied worse. Cumulation (self-focusing) of charged particles in inhomogeneous media with electric fields is a universal property of a number of CDSs [1], [2], [3], [4], [5], [6], [8], [9], [10], [11], [12], [13]. CDS includes such structures as atoms, molecules, lightning, tornadoes, stars, galaxies, and so on. The analogy of processes in CDS allows us to apply the MGMT of the most complete mathematical models to describe similar phenomenafrom well-studied areas of science to the areas of natural sciences studied in less detail. When transferring mathematical models in this way, we must take into account the specifics of the phenomena being described. This method was used by: 1) Newton to study and generalize the description of gravitational forces on Earth and in space; 2) de Broglie to describe quantum phenomena using his hypothesis (particles behave like waves); 3) Einstein to describe the photoelectric effect (waves behave like particles); and 4) Vysikaylo to discover libration and cumulation points, lines, and surfaces for free electrons between charged plasma structures (Coulomb (electric) potentials in 4-D space-time function similar to gravitational potentials [2]). This method goes back to the idea of Eratosthenes, which he applied when calculating the length of the Earth's meridian (geometric structures are similar, the Pythagorean theorem can be applied to them, etc.). Here, we used this general method to extend (transfer) the achievements obtained in solving the Navier–Stokes equation (or, in the 1-D case, the Burgers equation) to describe phenomena in an inhomogeneous plasma with current.

The study of electroneutrality violation in stars led the author to the discovery of a new mechanism of thermonuclear reactions in quantum stars (white dwarfs, neutron stars, and black holes) [9], [14]. The basis of this mechanism is the synergetic electric field of a positively charged star core surrounded by a standing or pulsating shock wave of the electric field. In this wave, electrons are focused to the center of the star and gain energy sufficient for their e-capture into protons of atomic nuclei.

The analysis of photographs of a 20-km-long plasma trail and the features of the destruction of the Chelyabinsk meteoroid [10], 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. In the next work, the author will dwell in more detail on this phenomenonof the formation of the Vysikaylo's cannon (gun), which stands in defense of the Earth from meteoroids [10].

V. Conclusion

Our experiments clearly prove that we are indeed observing 3-D shock waves of the electric field (analogs of Mach shock waves) and self-organizing 3-D plasma nozzles (analogs of Laval nozzles), predicted by P. I. Vysikaylo. Experiments confirm that in [2], [3], and [4], we constructed the most thorough 4-D perturbation theory (1) to describe inhomogeneous and nonstationary Vysikaylo's CDSs (3-D CDS) in plasma with current, taking into account the violation of electrical neutrality. The main achievement of this theory (1), which takes into account the violation of electrical neutrality, is the establishment of a significant dependenceof all the effective coefficients of ambipolar transfers (drifts and diffusions) that we have discovered on the vectorized characteristic size of the violation of electrical neutrality—l_E (parameter E/n_e) [1], [2], [3], [4], [5], [6].

In [1], [2], [3], [4], [5], [6], [7], [8], and [9], we proposed the most complete perturbation theory to describe the processes of ambipolar transport in inhomogeneous structures in plasma with current. This theory is devoid of all the shortcomings noted by A. A. Vlasov about inferior theories, see [1], [2], [3], [4].

Theoretical results obtained by modeling shock waves of the electric field (E/N), discovered by the author in experiments with laboratory plasma, see [1], [2], [3], [4], turned out to be useful for the development of models describing cumulative-dissipative phenomena during the destruction of meteoroids by a high-energy electrons beam [10], to explain the cumulative formations in the intergalactic space of the M 87 galaxy, the heliosphere, atmosphere, and ionosphere of the Earth, since the Earth has a negative charge of about 500 000 C, and the Sun is positively charged at a level of 1400 C [11].

REFERENCES

[1] P. I. Vysikaylo, *Processes of Ambipolar Transfer in Cumulative-dissipative Structures in Gas-Discharge Plasma*. Moscow, Russia, 2022, p. 226. [Online]. Available: https://www.litres.ru/author/f-i-vysikaylo/ AQ:3

[2] P. I. Vysikaylo, "Model of ambipolar processes in cumulative-dissipative self-focusing structures in plasma—Part 1: Perturbation theory for Vysikaylo's structures in plasma with current," *IEEE Trans. Plasma Sci.*, vol. 51, no. 8, pp. 2160–2164, Aug. 2023. [Online]. Available: https://ieeexplore.ieee.org/document/10199161?source=authoralert, doi: 10.1109/TPS.2023.3296771.

[3] P. I. Vysikaylo, "Model of ambipolar processes in cumulative-dissipative self-focusing structures in plasma—Part 2: Classification of ambipolar drifts with current in the zeroth approximation according to the Vysikaylo's perturbation theory," *IEEE Trans. Plasma Sci.*, vol. 52, no. 1, pp. 30–35, Jan. 2024. [Online]. Available: https://ieeexplore.ieee.org/document/10365721, doi: 10.1109/TPS.2023.3342269.

[4] P. I. Vysikaylo, "Model of ambipolar processes in cumulative-dissipative self-focusing structures in plasma—Part 3: Classification of ambipolar diffusions in plasma with current in the first approximation according to the Vysikaylo's perturbation theory," *IEEE Trans. Plasma Sci.*, vol. 52, no. 6, pp. 1983–1988, Jun. 2024. [Online]. Available: https://ieeexplore.ieee.org/document/10615225,doi: 10.1109/TPS.2024.3350370.

[5] P. I. Vysikaylo, "Vysikaylo' shock waves of electric field—Part 1: Theoretical studies of jumps and Vysikaylo's nozzles in plasma with current," *IEEE Trans. Plasma Sci.*, vol. 53, no. 12, pp. 1–6, 2024.

[6] V. N. Babichev, P. I. Vysikaylo, and S. A. Golubev, "Experimental confirmation of the existence of jumps in gas-discharge plasma parameters," *RF Lett. ZhTF*, vol. 12, no. 16, pp. 992–995, 1986. [Online]. Available: https://www.mathnet.ru/links/73508114db2060af246f7b5e043b9cc7/pjtf234.pdf

[7] B. S. Kerner and V. V. Osipov, *Autosolitons: A New Approach to Problems of Self-Organization and Turbulence*. Dordrecht, The Netherlands: Springer, 1994, p. 672. [Online]. Available: https://link.springer.com/book/10.1007/978-94-017-0825-8

[8] P. I. Vysikaylo, "Cumulative point—L_1 between two positively charged plasma structures (3-D strata)," *IEEE Trans. Plasma Sci.*, vol. 42, no. 12, pp. 3931–3935, Dec. 2014. [Online]. Available: https://ieeexplore.ieee.org/document/6951517, doi: 10.1109/TPS.2014.2365438.

[9] P. I. Vysikaylo, *Cumulative-Dissipative Phenomena and Structures*. Moscow, Russia, 2021, p. 319. [Online]. Available: https://www.litres.ru/author/f-i-vysikaylo/

[10] P. I. Vysikaylo. *Vysikaylo's Cumulative Plasma Cannon on the Protection of the Earth From Meteorites*. [Online]. Available: https://www.techrxiv.org/doi/full/10.36227/techrxiv.23635200.v1 AQ:4

[11] P. I. Vysikaylo, "Quantitative investigation nonequilibrium inhomogeneous plasma of the heliosphere with runaway electrons," *IEEE Trans. Plasma Sci.*, vol. 50, no. 4, pp. 810–816, Apr. 2022. [Online]. Available: https://ieeexplore.ieee.org/document/9745462,doi: 10.1109/TPS.2022.3160189.

[12] P. I. Vysikaylo, "Cumulative quantum mechanics—Quantum-sizeeffects for: Nano-, angstrom- and femto-technologies," *Nano Carbons*, vol. 2, no. 1, p. 1297, Jun. 2024, doi: 10.59400/n-c.v2i1.1297.

[13] P. I. Vysikaylo. (2024). *Cumulative Quantum Mechanics: RF Textbook*. Accessed: Jan. 27, 2024. [Online]. Available: https://elibrary.ru/item.asp?id=49515864

[14] P. I. Vysikaylo, "Detailed elaboration and general model of the electron treatment of surfaces of charged plasmoids: From atomic nuclei to white dwarves, neutron stars, and galactic cores. Part III: Behavior, variation, and synergetism of positively charged cumulative-dissipative plasma structures (+CDS) under external actions," *Surf. Eng. Appl. Electrochem.*, vol. 49, no. 3, pp. 222–234, May 2013, doi: 10.3103/s1068375513030125.

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