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Cumulative Point—L_1 Between Two Positively Charged Plasma Structures (3-D Strata)

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***Abstract*— Values of a cathode potential drop (CD) are estimated in nanosecond argon discharges with a hollow cathode over total number of strata in the discharge gap ($n \sim 10$). The CD dependence on the discharge parameters has been studied. The structurization of this discharge in experiments is analytically analyzed. It is proved that the strata in the nanosecond discharges are caused by the electron drift and the electron impact direct ionization forming the ionization—drift waves. The drift removal of electrons leads to formation of positively charged layers of a space charge, a significant increase of the peripheral ionization. At that the cumulation of the electron flow in to the plasma focuses takes place similar to cumulation of neural particle flows in to the Lagrange–Euler libration points L_1. The cumulative points L_1 arise between the attractors of any nature.**

***Index Terms*— 3-D strata, cathode potential drop (CD), cumulation of electrons, libration point, nanosecond discharge, peripheral ionization, strata, the L_1 cumulative point, violation of neutrality.**

I. Introduction

NEW applications of weakly ionized plasma requires investigation of discharge energy distribution over 3-D volume of a discharge device. Different plasma sources for excitation of gases require understanding of plasma formation creation, which leads to a variation of the energy input and their impact on gas discharges from a point of view of their applicability [1]. For example, a contribution of energy to the discharge is negligible [2] without formation of cathode spots or other plasma structures. The 3-D-formation processes and 3-D structure of the discharge current transport are still poorly understood. A system of charged plasma structures (plasmoids) with long-range coulomb potential possesses a number of specific features. In dissipative 3-D structures in the gas-discharge plasma occurs spherical, flat, and cylindrical mass-energy-momentum cumulation of charged particle flows. In particular, to interaction of positively charged 3-D plasmoids, such as of the cathode spots and a positive column, which redistribute energy put in the volume this paper is devoted.

Stratified discharges in the gas are the type of waves the most easily visualized in the plasma. It is believed that Faraday observed such strata (the planar cumulation of the charged particles flows). Nevertheless, this effect is not yet properly described even in review articles and books on wave phenomena. Now, the ionization mechanism of strata formation has been universally accepted. To ionize gas in the glowing region of a stratum, the electrons should accumulate the energy in the neighborhood of the ionization potential or about the energy of the metastable level excitation that is the main one in the process of the step ionization. When the values of the E/N parameter (where E is electric field strength in the discharge and N is density of neutral particles) are large; direct ionization is the main ionizing process.

In 1923, Holst and Osterui observed in pure Ne that, under certain conditions, there appeared some sequence of dark spaces near the cathode with glow regions behind them [see [3], p. 555]. Probe measurements showed that, in every case, the length of the dark spaces corresponded to a potential drop of just 21.5 V, in keeping with the Ne ionization energy I_{Ne} in volts [3]. Thus, the acceleration of electrons up to the ionization energies occurs in the region of the dark spaces; strong ionization and excitation of different electronic levels of atoms happen in the glowing regions. It is the glow of excited particles in the glowing region of the stratum. The direct ionization of gas atoms by the electron impact is the main mechanism under the conditions of these experiments. The voltage drop of $U_s = nI_{\mathrm{Ne}}$ falls within the whole stratified bulk of the discharge.

II. Problem Formulation

It is supposed that the observed layered positive column in any gas is an indication of the electrodynamic and kinetic processes that happen in the plasma's bulk. This supposition is analyzed as the basic. We consider the cathode potential drop (CD) in striated discharges with the typical times $\sim$10 ns and large values of $E/N \approx$ 100–170 Td. The experimental data for the our analytic examination are taken from [4] where the experiments were carried out in the hollow cathode discharge in argon plasma. Due to short t times of the discharge, the large values of the electric field strength, and the pressures of some dozens of torr. There is no effect on the stratum generation of the electrons and ions diffusion transfer processes, the electrons and ions convection transfer processes, and the density change of the gas particles (N) as it was heated. The role of step ionization is negligible under the conditions. A pulse-periodic mode of the discharge with a frequency up to 50 Hz was used in [4] for more accurate visual and photographic recording of the strata number within the discharge gap. Such a frequency of the discharge repetition, on the

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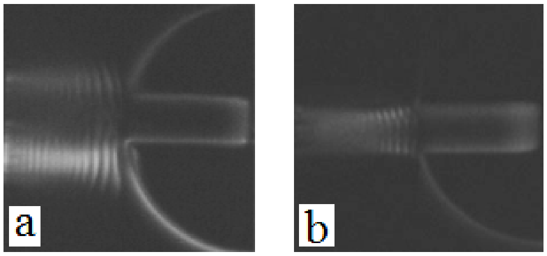

Fig. 1. (a) Open discharge [3]. (b) Limited discharge [4].

one hand, provides the enhancement of the stratum glow by dozen times and, on the other hand, ensures the full recombination of the plasma and the elimination of the metastable particles between the current pulses (during the time $\approx 2 \times 10^{-2}$ s). Such conditions allow determining the behavior of the CD depending on the pulse discharge parameters without any probes causing great disturbances. According to the mentioned suppositions, the CD near the cathode U_c is equal to the total drop in the whole discharge U_r less the voltage in the plasma bulk $U_s = nI_{\mathrm{Ar}}$. Here, I_{Ar} is the potential of ionization by the direct electron impact of argon atoms ($I_{\mathrm{Ar}} = 15.7$ V). Thus

$$U_c = U_r - nI_{\mathrm{Ar}}. \quad (1)$$

Using the values of the total voltage drop U_r, as measured experimentally in [4], and the determined total strata number in the discharge volume (it is desirable that n should be $\sim$10 or more), from (1) one can estimate the CD and establish the typical dependences of the CD on the main parameters of the discharge (for instance, on the total drop of the voltage U_r and the density of the gas particles N).

The discharge, as studied in [4], took place between two aluminum electrodes 40-cm-long mounted in the discharge chamber 0.6 cm apart. The cylindrical cathode 1 cm in diameter had a lengthwise slot 0.2-cm wide and 0.6-cm deep (Fig. 1). The anode was made of a flat plate 2-cm wide and 0.5-cm thick. The discharge current and the voltage in the discharge gap were measured with the help of an ohmic shunt and a gauged voltage divider. A dual channel analog to digital converter connected to a personal computer and a oscilloscope (Tektronix TD 3032B) were used as the recording devices. The space–time distributions of the optical discharge radiation were recorded with the aid of a charge coupled matrix device and a photoelectric multiplier connected with the computer. The electric characteristics and space dynamics of the optical discharge radiation depending on the amplitude of the voltage on the electrodes (U_r) and the pressure of the gas (N) in the chamber were studied experimentally in [4]. The measurements were carried out under the conditions of a continuous gas flow (argon) through the chamber. The gas was replaced during the period of $<10^{-2}$ s. The optical radiation in the open discharge gap is shown in Fig. 1(a) and in the gap limited by the dielectric inserts in Fig. 1(b).

III. To Analysis of the Experimental Data

It is seen from Tables I and II (based on the data of [4]) that the parameter $(E/N)_p$ averaged along the discharge gap

TABLE I
Parameters of the Open Discharge in Argon

U_p, V; N,10^{22} m^{-3}	n; τ,10^{-9} s	U_c=U_r-U_p,V; ζ=U_c/U_r	$(E/N)_p$,Td; n_e,10^{17} m^{-3}	l_A,10^{-4}m; r_1,10^{-3} m
380 33	10 100	223 0.58	79 7.7	6.0 4.3
680 33	13 60	475 0,7	103 21	4.6 3.0
490 49.5	15 100	254 0.51	79 45	4.0 2.8
660 49.5	19 70	362 0.54	100 20	3.2 2.0
680 66.0	22 35	335 0.49	87 16	2.7 1.8
700 75.9	24 40	323 0.46	83 19	2.5 1.8
770 82.5	30 50	299 0.38	95 19	2.0 1.2

TABLE II
Parameters of the Limited Discharge in Argon

U_p, V; N,10^{22} m^{-3}	n; τ,10^{-9} s	U_c=U_r-U_p,V; ζ=U_c/U_r	$(E/N)_p$,Td; n_e,10^{18} m^{-3}	l_A,10^{-4}m; r_1,10^{-3} m
720 33.0	16 20	469 0.65	127 3.3	3.7 1.5
1000 33.0	21 10	670 0.67	167 11.4	2.9 1.3
800 49.5	24 20	423 0.52	127 4.4	2.5 1.0
1200 49.5	30 7	729 0.6	159 15.8	2.0 0.9
700 66.0	26 50	292 0.4	103 4.3	2.3 1.5
1000 66.0	33 20	482 0.48	131 15.4	1.8 0.76

changes from 80 to 100 Td for the open discharge and, in the range from 103 to 167 Td, for the discharge limited by the special dielectric inserts. All the parameter dependences on t in the open and limited discharges are qualitatively repeated. The share of the CD in the open discharge is nearly halved with the pressure rising from $\zeta = U_c/U_r = 0.69$ to 0.38, and it slightly rises with the increase of the total voltage between the electrodes. Similarly for the limited discharge, the share of the CD ζ falls from $U_c/U_r = 0.67$ to 0.48 with the pressure of the neutral gas being halved. As is known [5], with an anomalous discharge, almost the whole voltage falls in the cathode region. According to the calculation results shown in Tables I and II, the nanosecond discharge in [4] and [6] is an intermediate one between the anomalous and normal discharges. Thus, the relations for the CD U_c were first derived for the nanosecond anomalous discharges (see Tables I and II)

$$U_c = \xi(N, E/N)U_r. \quad (2)$$

It should be noted that the proposed techniques to determine the CD according to the density of the strata number in nanosecond discharges with hollow cathodes within the framework of a 1-D model with symmetry of the surfaces limits the value of the CD at the top as the size of the voltage drop region in the glowing part of the stratum is assumed to be small. The consideration of the characteristic dimensions of the glowing region results in the reduction of the CD and a corresponding decrease of the parameter ξ.

IV. Analytical Calculation of the Ionization–Drift Structures (3-D Strata)

The structurization of a nanosecond discharge with a hollow cathode in argon, as found in [4], is analytically studied in this section. It is proved that the strata in nanosecond discharges are caused by the drift of electrons and the direct ionization via electron impact, thus they are the ionization–drift waves [Fig. 1(a) and (b)]. As mentioned previously, in [4], the discharge took place between a cylindrical cathode with a longitudinal slot 0.2-cm wide and 0.6-cm deep mounted at a distance of 0.6 cm from the anode (see Fig. 1). The measurements were carried out under the conditions of a continuous flow of argon through the chamber. The parameters of the strata in relation to the amplitude of the voltage on the electrodes (U_r), and the gas pressure (N) in the chamber are tabulated in Table I for the case of a free discharge [Fig. 1(a)] and Table II for the discharge limited by the dielectric inserts [Fig. 1(b)]. Here, n is the number of strata in the discharge gap space, and I_A is the spacing between the strata found experimentally in [4] [Fig. 1(a) and (b)]. When simulating, it has been assumed that, on one stratum, there occurs a voltage drop equal to (not less than) the ionization potential of an argon atom of 15.7 eV. It has been noted, the mean values $(E/N)_p$ within the discharge gap are computed on the assumption of the discharge's homogeneity, i.e., $(E/N)_p = (E_x/N)$. According to Tables I and II, the parameter $(E/N)_p$ averaged over the gap changes with the variation of the parameters (the gas pressure N and the voltage within the interelectrode gap U_r) in the case of a free discharge in the range from 80 to 100 Td and, in the case of a limited discharge, in the range from 103 to 167 Td. In the nanosecond discharge of argon at pressures of ∼20 Torr with such parameters $(E/N)_p$, the internal fields are determined only by direct electron impact ionization and the drift transfer of electrons in the electric field induced by the space charge of the ions, i.e., the strata observed in [4] are the ionization–drift waves [6] but not the diffusion–ionization ones as is believed in [7], and other works in the studies of the strata starting with the works of Langmuir and Clarfeld [3], [5], [7].

V. New Analytic Model of the 3-D Ionization–Drift Strata

Based on the experiments of [4], it is proved that the glowing areas of the strata in the argon nanosecond discharge are charged by the positive charge. In the positively charged layers, the parameter E/N by the Gauss theorem reaches its peak at the periphery of the charged structure (see Fig. 2, for the uniformly charged rectangle: $E_{x,y,z} = \rho l_{x,y,z}/2\varepsilon_0$).

Thus, the gas ionization frequency ν_i (exponentially depending on E/N) becomes the greatest at the periphery of the

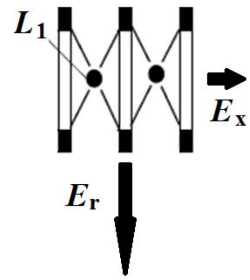

Fig. 2. Diagram of the electron flow cumulation in the region of positively charged 3-D structures–strata [6]. The peripheral areas of the increased ionization are marked by black rectangles. The focal points (L_1) are the analogs of the Lagrange libration points discovered by Euler (1767).

charged glowing structure (Fig. 2, the black rectangles). The presence of the longitudinal (E_x) and transverse (E_y, E_z, or E_r) electric fields in the area of the positively charged finite dimensional 3-D structures in the plasma with the current causes the cumulation of electron flows from the region with the increased ionization frequency to the formation of focuses (point L_1, Fig. 2) between the layers charged positively. Due to the cumulation of electrons, the concentration of plasma in point L_1 is determined by the peripheral ionization of the gas but not by the average value of the $(E_x/N)_p$ parameter. The points of the focuses behind the charged structures are the analogs of the libration (cumulative) points in the Euler–Lagrange problem [6]. In the charged glowing strata, the relation of the longitudinal dimensions l_x and the transverse ones l_r is equal to the ratio of the longitudinal and drift velocities of the electrons focusing to L_1, that is, $E_x/E_r \approx l_x/l_r$. Knowing l_x/l_r and E_x from the visual observations, let us estimate E_r and the frequency of the peripheral ionization determined by $|E_x + E_r|/N \approx E_r/N$ (Fig. 2), l_r/l_x for the open discharge [Fig. 1(a)] (∼ 9–10), and for the limited one (not >5–6) [Fig. 1(b)]. In the case of spherical or cylindrical symmetry, the divergence of the electron flow is

$$\mathrm{div} J = d(J)/dr + kJ/r \quad (3)$$

where $k = 2$ or 1, respectively. The term kJ/r, which is determined by the flow cumulation, can make a pronounced contribution to the balance of the sources and the runs off of the particles in the focusing flow J (Fig. 2) at the focus point [6]. By comparing the terms, determining the production of the particles in the flow ($Q = n_e\nu_i$), and with the term kJ/r responsible for the focusing (cumulative) process, it is possible to estimate the dimension of the focus of the self-focusing of the electron drift flow (Fig. 2) [6]: $rF \approx kJ/Q$. For the nanosecond discharge

$$r_F = kV_e/\nu_i = k/\alpha_i. \quad (4)$$

Here, V_e is the drift velocity of the electrons, ν_i is the frequency of the direct ionization by electron impact, α_i is the first Townsend coefficient, and Ne is the concentration of electrons. We take from [8] the relationship α_i/N for argon. If the dimensions of the glowing area are neglected in comparison with the cumulative region, the following relation should be fulfilled: $2r_F = I_A$. The calculated values for $r_F = r_1$

(at $k = 1$ and $\alpha_i(E_x/N)_p$), that is, without considering the peripheral ionization, are tabulated in Tables I and II. It is seen from Table I that, with the peripheral ionization not being considered, the calculated values of the focuses $2r_1$ are almost 10^{-16} times greater than the longitudinal dimensions of the real strata l_A observed in the open discharges in [4]. This discrepancy can be explained by only the 3-D effect connected with the peripheral ionization in the glowing 3-D layers with finite dimensions charged by the positive charge. The electrons produced at the periphery in the region of substantial transverse electric fields are focused by these fields to the center of a plasma lens or its focus (Fig. 2) and 10 times increase of the gas particles efficient ionization within the discharge region. If E_r/N with the value $E_r = (l_r/l_x)E_x$ tenfold greater than E_x is taken as the main parameter to estimate the focal distance of such a 3-D plasma lens r_F under the conditions of narrow (wide) strata, then, at the spherical symmetry $r_F = 2V_e/\nu_i = 2/\alpha_i$, according to [8], r_F decreases by 36 times. If the relative volumetric contribution to the ionization of the peripheral areas is considered, say by a factor 1/2, there can be obtained the characteristic dimension $2r_2$ coinciding with the measured values l_A for the nanosecond open discharge in argon. We act in similar way in the case of a discharge limited by a dielectric. Without regard for the peripheral ionization (Table II), the calculated values of the focuses $2r_1$ are nearly 8–12 times greater than the longitudinal dimensions of the real strata l_A observed in [4]. If E_r/N with the value $E_r = (l_r/l_x)E_x$ fivefold greater than E_x is taken as the main parameter to estimate the focal distance of such a 3-D plasma lens r_F under the conditions of narrow and wide strata, then, in this case too, $r_F \approx 1/\alpha_i$ according to [8] and r_F decreases by 10 times. If the relative volumetric contribution to the ionization of the peripheral areas is considered, say by a factor 1/2, there can be obtained the characteristic dimension $2r_2$ coinciding with the experimentally measured l_A for the case of a limited discharge in argon. Thus, both in open and limited discharges, the peripheral ionization, considering the parameter E_r/N, is tens of fold more than the ionization calculated within the framework of the 1-D model without considering the formation of finite-dimensional charged plasma structures with peripheral ionization and the cumulation of the flow of electrons at the focus L_1. It is evident from the 3-D calculation that two types of strata (and cathode spots) are possible. The structures with $l_r/l_x \approx 1$ (regular structures formed of elliptical structures—linear plasma polymer) can be referred to the first type and the structures with $l_r/l_x \sim 1$ [narrow strata (regular structures formed of plane sharply nonhomogeneous narrow charged layers—plane plasma polymer)] can be referred to the second one.

VI. Conclusion

The CD in nanosecond discharges is for the first time estimated according to the number of strata ($n \sim 10$) in the discharge's bulk. It has been found that the relative portion of the CD in nanosecond discharges in [4] ζ is a function of the pressure and voltage in the discharge. The value of

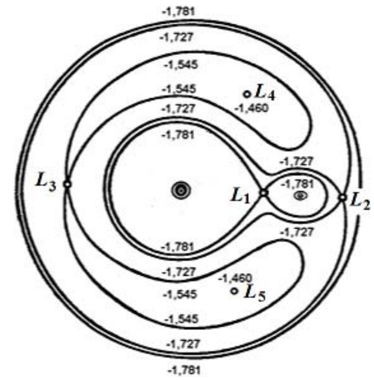

Fig. 3. Cross section of the equal potential surfaces (including the centrifugal potential) in the Roche model in the orbital plane of the binary system [9]. Roche surface scheme consists of two closed cavities surrounding the two material points (two stars or stars and planets, for example, the sun—a massive point to the left and Jupiter—a massive point to the right), and having a common point L_1. Lagrange's libration points (cumulative point $L_{2,3}$) L_{2-5} caused by considering the centrifugal and gravitating potentials of bodies.

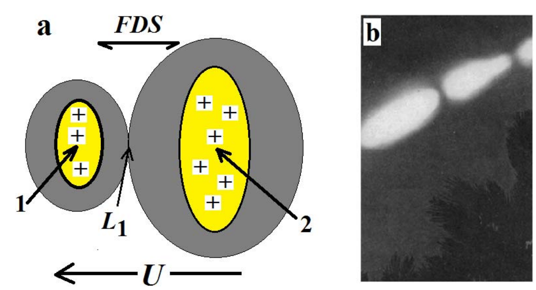

Fig. 4. (a) Cross section of equal potential in the model of Vysikaylo–Rocha [6] in the plane of the cross section of two positively charged plasma structures—the cathode spot and the positive column. The equipotential surface consists of two closed cavities 1 and 2, others are positively charged 3-D-finite plasma structures: the cathode spot—1, for example, to the left and the positive column—2, to the right (or two positively charged strata) and having common point L_1—point of the electrons cumulation flows (L_1—cumulative point or the focus for electrons). FDS—Faraday's dark space. U—the external potential drop, electrons move from the point 1 to 2. (b). Bead lightning with the cumulative points of MEMF of electrons and with FDS.

$\zeta(N, (E/N)_p)$ falls in inverse proportion to the gas pressure from 0.69 to 0.38 and slightly grows with the rise of the total voltage over the interelectrode gap, which correlates with the classic investigations of anomalous discharges [5]. The efficient mean values of the parameter E/N in the plasma's bulk in the experiments [4] are determined in accordance with the realized estimations. These values change for the open discharge from 80 to 100 Td and, for the limited discharge, from 100 to 170 Td (Tables I and II). The increase of the voltage of the discharge and the decrease of the gas pressure results in the growth of the nanosecond discharge's abnormality. The author tries to dispel the myth concerning of plasma structures neutrality. The 3-D phenomena caused by even slight violation of neutrality are discussed in this paper. It is proved that the strata in nanosecond discharges are determined by the process of the direct ionization by the electron impact of argon atoms and the drift removal of electrons and the formation of nonuniform positively charged 3-D glowing plasma structures focusing the electrons produced at the periphery of the positively charged structures into focuses (point L_1). Due to the localization at the periphery of the greatest electric field strength (transverse to the total current), the peripheral ionization is by 10 times greater than the frequency of the ionization in the center of the charged structures. It is proved that the strata in the nanosecond discharges are ionization–drift waves, whose characteristic longitudinal dimensions are well described by the first Townsend coefficient [see (4)]. According to (4), the characteristic stratum dimension is inversely proportional to the gas pressure and the parameter E/N, which correlates with the experiments [4] (see Tables I and II). In 1-D (x) models not limited with respect to y and z with plane symmetry dating back to the works of Langmuir and Clarfeld [3], [5], [7], some mistakes are made because the real dimensions of the charged strata and the formation of focuses (point L_1) were not considered. These mistakes are repeated in all the works (including [7]) devoted to the description of the gas discharge strata of both neutral ionization–diffusion waves and the strata in the Gann effect in semiconductors. In 1-D models dating back to the Langmuir 1-D model, the focal distance of the plasma lens becomes equal to the infinity and the cumulative phenomena (point L_1) disappear; that is why there appear errors in the calculation of the oscillation periods in the gas discharge plasma strata and in the Gann effect in the semiconductors.

Cumulative points L_1 [9] arise between the two attractors of any nature (Figs. 3 and 4). In Fig. 3, for example, one can see the profile of the gravitation field from [9, Fig. 14.1] and in Fig. 4 the similar profiles of the electric field between two positively charged plasmoids with crossing of potentials in the point L_1.

The definition of cumulation was given by Zel'dovich in the preface to [10]—the cumulation, i.e., the concentration in a small volume of force, energy, or other physical quantity is the most important phenomenon of nature. This definition is the most successful and comprehensive definition as a forced accumulation and self-focusing mass-energy-momentum flows (MEMFs) in extreme natural phenomena in any continuous media. The cumulative processes are the main feature of the any nature attractor (power center) formation. Cumulative structures are: lightning, tornadoes, gutters, cyclones, stars, planets, galaxies, intergalactic lightning, any plasmoids, molecular ions, city, state, and so on.

Long-range potentials between the attractors of any nature form the points of cumulation (L_{1-3}) and libration ($L_{4,5}$). Presence of these cumulative points—L_1 between the positively charged plasmoids causes the formation of the Faraday dark spaces (FDSs). In the point of the cumulation, streams of electrons are focused and hence the electric field (or the E/N) decreases, so the glow of the gas disappears in this area.

In the case of the Kepler's problem, the motion description of a small body in the gravitational and Coulomb attractors is carried out identical. In this paper, we have proved that the flow of electrons between positively charged structures 1 and 2 [Fig. 4(a)] takes place similar to the case of binary star system with mass transfer [9]. Investigation of analogs (see Figs. 3 and 4) allows verifying the general laws and generalizing the description of analogs, regardless of the type of long-range potential. Opening cumulative points between attractors of any nature and spent my analysis of the impact of long-range potentials of MEMF cumulation may be useful in the analysis of many other cumulative phenomena in nature (in biophysics, chemistry, quantum mechanics, sociology, and so on).

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