

Complex space charge structures in laboratory and natural plasmas*

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Experimental results are presented concerning the generation and dynamics of double layers and multiple double layers in laboratory plasmas. The nonlinear effects and the elementary processes related to their phenomenology are investigated. The transition to chaos of the dynamics of these structures is analyzed. The similarities with the phenomenology of natural phenomena such as aurora are emphasized. The potential role of such structures in cosmic particle acceleration is discussed.

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1. Introduction

Double layers (DLs) are well-known [1] localized deviations from the usual quasi-neutrality of plasma. They consist of two adjacent layers of opposite space charge, between which a potential jump exists, creating an electric field. The structure is maintained by driving an electron flux through it. This can be done, for example, by applying a positive potential on an electrode immersed in plasma in equilibrium. In this case, a complex space charge structure (CSCS) in form of a quasi-spherical luminous plasma body attached to the electrode is obtained [2]. This structure consists of a positive core (ion-enriched plasma) confined by a DL.

Under certain experimental conditions, more complex structures can appear, which were called multiple double layers (MDLs). There are two types of MDLs: concentric and non-concentric. The concentric MDLs appear as several bright and concentric plasma shells, attached to the anode of a glow discharge or to a positively biased electrode immersed in plasma [3-8]. The successive DLs are precisely located at the abrupt changes of luminosity between two adjacent plasma shells. Langmuir probes measurements show that the axial profile of the plasma potential has a stair steps shape with potential jumps close to the ionization potential of the applied gas [4,6]. The non-concentric MDLs appear as a network of plasma spots almost uniformly distributed on the surface of the electrode [9-12]. Each of the plasma spots is a CSCS as described above.

These complex space charge structures were intensively investigated during the last few years because of their possible applications in nano-technologies [13,14], as well as due to their implications in the phenomenology

of some complex phenomena in laboratory (hysteresis [15], chaos and turbulence [16], L-H transition in fusion plasma [17]) and natural plasmas [18,19]. Regarding the natural phenomena, such complex structures were observed or postulated in connection to auroras, ball lightnings, solar flares, X-ray pulsars, extragalactic jets, cosmic rays, accretion disks, etc.

Auroras are produced when highly energetic particles collide with and excite the atoms and molecules of the Earth's upper atmosphere. These particles, protons and electrons, are of solar origin and travel via the Earth's magnetic field to form two permanent rings of auroral light centred around the magnetic poles. By interpreting the visible motion of auroral forms, Carlqvist and Boström [20] postulated the existence of magnetospheric double layers with potentials of several kilovolts. The first experimental observations of double layers in the magnetosphere were made on the S3-3 polar orbiting satellite [21]. The double layers were detected in the electric field component parallel to the magnetic field. Later observations from the Viking satellite [22] at altitudes of around 10000 km have confirmed the existence of double layers, as well as solitary waves, in the magnetosphere.

Ball lightnings are spectacular natural phenomena in form of short-lived, glowing, floating object, sometimes associated with thunderstorms. Their shapes can be spherical, ovoid, teardrop, or rod-like with one dimension being much larger than the others. Sometimes the discharge appears to be attracted to a certain object and sometimes to move randomly. After several seconds the discharge leaves, disperses, is absorbed into something, or, rarely, vanishes in an explosion. The intriguing appearance and characteristics of ball lightnings give rise to a wide variety of physical models proposed for explaining the phenomenon. One of the models considers the ball lightning as a complex space charge structure confined by a double layer [23], similar to that obtained in some laboratory experiments.

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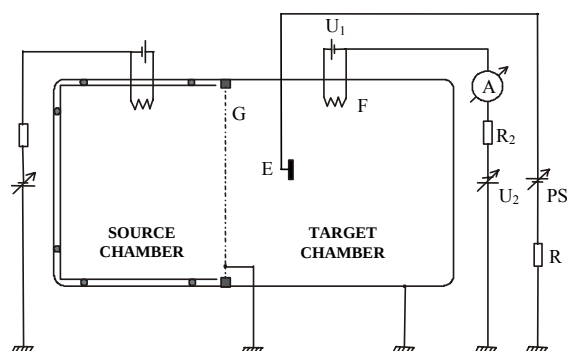


Fig. 1. Schematic of the DP machine (F – filament, G – grid, E – electrode, U_1 – power supply for heating the filament, U_2 – power supply for discharge, PS – power supply for electrode bias, R, R_2 – load resistors).

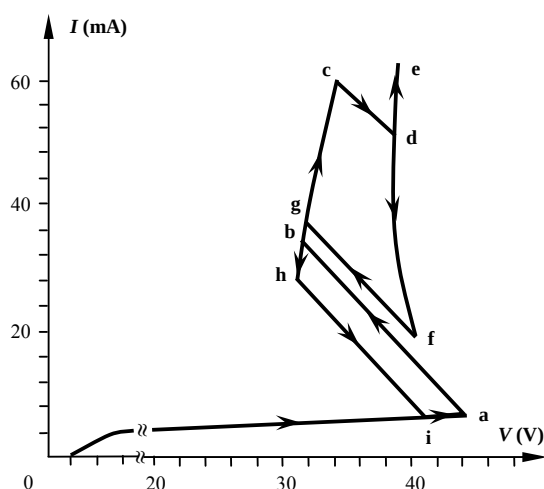


Fig. 2. Static current-voltage characteristic of the electrode.

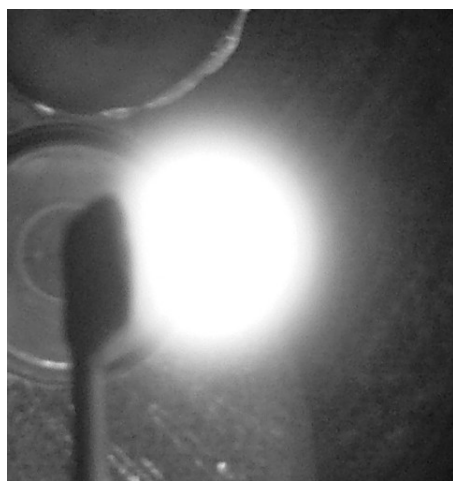


Fig. 3. Photo of a complex space charge structure (fireball) in plasma.

Solar flares are the result of a sudden release of energy in the corona and chromosphere of the Sun. They lead to particle acceleration and to a transient heating of the chromosphere and corona. Electromagnetic radiation is produced over an extremely broad range, from radio up to X and sometimes even gamma ray frequencies. A model for a flare has been proposed where the energy is stored in a current loop in the solar corona and released by the creation of a double layer [24,25].

Binary X-ray pulsars are considered to be powered by the kinetic energy of free falling matter accreting onto the magnetic poles of rotating neutron stars, this matter being supplied by a normal binary companion [26]. It has been suggested that the formation of a double layer may be responsible for the deceleration of the accreting matter. In the neutron star's atmosphere the electrons will be stopped more rapidly than the ions tending to set up a proton current and leading to a charge separation. The charge separation electric field decelerates the ions and in a steady state the resultant structure is a double layer.

Extragalactic jets are observed by radio techniques connecting the active nuclei of radio galaxies to pairs of extended lobes of emission. It is believed that they feed the energy required by the lobes from the nuclei. The radio emission from jets has been assumed to be produced by cold electron beams [27] and such beams are produced on the high potential sides of double layers.

Large scale current circuits in which double layers may exist have been proposed both for the heliosphere and for the galaxy [28]. A detailed analysis has been made on the possibility of accelerating high-energy cosmic ray particles using the energy stored in such a galactic circuit [29].

Here we present experimental data concerning the physical mechanism by which complex space charge structures in form of simple and multiple double layers are generated in laboratory plasmas. The nonlinear dynamics of such structures (including the transition into chaotic states) is investigated. The similarities with natural phenomena, like auroras, are discussed.

2. Experimental results

The experiments were performed in the double plasma (DP) machine of the University of Innsbruck, schematically presented in Fig. 1. The DP-machine consists of a large cylindrical non-magnetic stainless steel tube (about 1 m long and 0.6 m diameter), evacuated by a primary pump and a diffusion pump. A metallic grid (marked by G in Fig. 1) divides the tube into two chambers: the source chamber (left-hand side of the tube in Fig. 1) and the target chamber (right-hand side of the tube in Fig. 1). In each chamber the plasma is created by an electrical discharge between a hot filament (marked by F in Fig. 1) as cathode and the grounded tube as anode. Because of the small dimensions, the filaments will collect just a negligible part of the ions, most of them diffusing into the centre of the tube. The positive space charge will attract many electrons into this region. In this way, a high

ionization degree plasma is attained. To avoid plasma losses, on the walls there are small magnetic cups fields formed by rows of permanent magnets ($B \cong 1$ T at the surface) with alternate polarity.

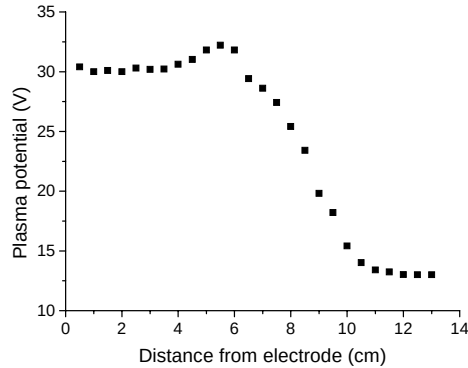


Fig. 4. Axial profile of the plasma potential in front of the electrode.

In our experiments we used only the target chamber of the DP-machine. Its plasma was pulled away from thermal equilibrium by gradually increasing the voltage applied on various tantalum disk electrodes (generally marked by E in Fig. 1), with different diameter (1 cm and 3 cm respectively), under the following experimental conditions: argon pressure $p = 5 \cdot 10^{-3}$ mbar, plasma density $n \cong 10^8 - 10^9$ cm $^{-3}$. The voltage is delivered by a power supply (PS in Fig. 1) through a load resistor $R = 500 \Omega$. The static current-voltage (I - V) characteristics of the electrode were recorded by a digital oscilloscope. The plasma potential was measured by an emissive probe. A cylindrical probe was used in order to derive the electron temperature.

Fig. 2 shows the static current-voltage characteristic of electrode E with a diameter of 1 cm, obtained by gradually increasing and decreasing the voltage of the power supply PS. When the increasing voltage reaches the critical value corresponding to point **a**, an intensely luminous quasi-spherical fireball appears in front of the electrode (photo in Fig. 3) simultaneously with a sudden current jump in the static I - V characteristic (**a** $\rightarrow$ **b** in Fig. 2). This structure is in a stationary state, no oscillations of the current being recorded. The emissive probe measurements prove that this structure consists of a positive nucleus (an ion-rich plasma) confined by an electrical DL (see the axial profile of the potential in front of E from Fig. 4). Fig. 4 shows that the voltage across the DL slightly exceeds the ionization potential of the used gas (argon). Cylindrical probe characteristics obtained outside and inside the fireball are shown in Figs. 5a and 5b, respectively. From the first characteristic (Fig. 5a) we obtain an electron temperature of $T_e = 1.48$ eV, a typical result for a DP machine [30]. On the other hand, the second characteristic (Fig. 5b) reveals the existence of two groups of electrons, with the temperatures $T_{e1} = 1.89$ eV and $T_{e2} = 9.51$ eV.

After the second jump of the current (**c** $\rightarrow$ **d** in Fig. 2), the structure passes into a dynamic state, in which the double layer periodically disrupts and re-aggregates [2].

Simultaneously, the current becomes time dependent, oscillations with a frequency of the order of kHz being recorded.

For decreasing voltage, two hysteresis loops appear, accompanying each of the current jumps. Their presence in the static I - V characteristic prove that the complex space charge structure can maintain its stationary or dynamic state in conditions weaker than those required for their emergence. This is a well-known characteristic of complex systems [31].

For higher values of the voltage applied to the electrode, a multiple double layers structure appears. Its type depends on the geometry and the dimensions of the electrode. When the small electrode with 1 cm diameter is used, a concentric multiple double layers structure is obtained (photo in Fig. 6a), while in the case of the large electrode (with 3 cm diameter), a non-concentric multiple double layers structure is obtained (photo in Fig. 6b). Both types of structures perform strong nonlinear dynamics, going to chaotic states through the same scenario of transition to chaos, namely by a cascade of period doubling bifurcations (the Feigenbaum scenario [32]) [33].

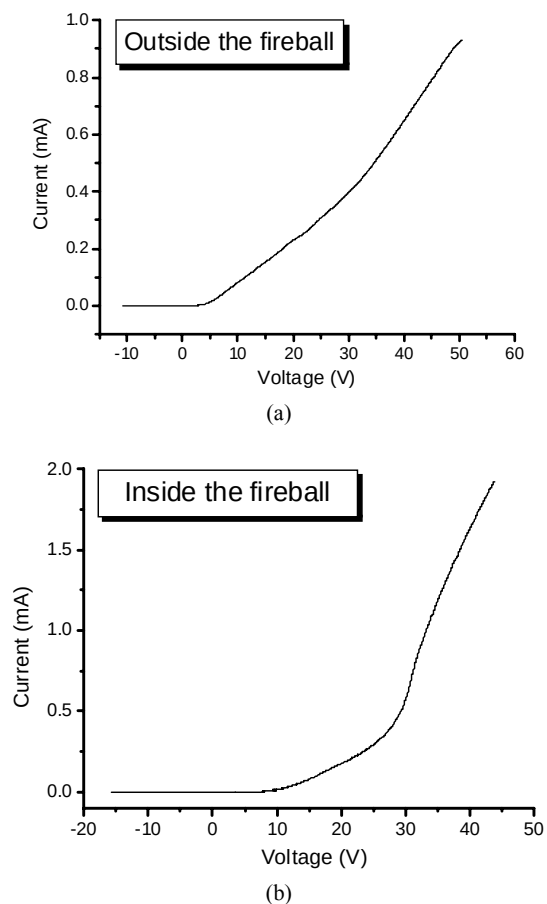
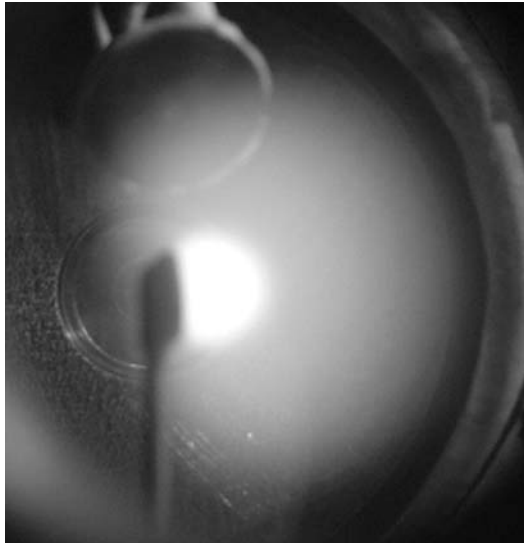
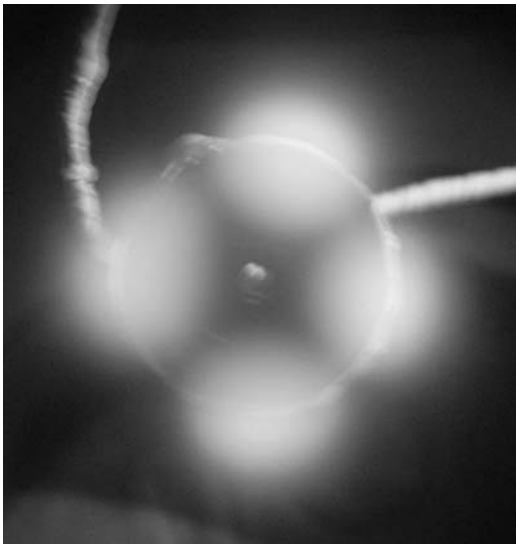


Fig. 5. Cylindrical probe characteristic obtained in plasma outside (a) and inside (b) the fireball, respectively.



(a)



(b)

Fig. 6. Concentric (a) and non-concentric (b) multiple double layers obtained in DP machine plasma on small (1 cm diameter) and large (3 cm diameter) electrodes, respectively.

3. Discussion

When a positive bias is applied to the electrode immersed in plasma, electrons from the neighbouring region are accelerated towards it. This region extends with the increase of the voltage on the electrode. The appearance of a planar luminous sheath near the electrode proves the occurrence of excitations processes of gas atoms there. Probe measurements complemented by spectral investigations show that a negative space charge is formed in the region where light is emitted [34]. This space charge is formed by accumulation of those electrons

that have lost their kinetic energy after neutral impact excitations, in the region where the average kinetic energy of the accelerated electrons reaches the necessary value so that for them the excitation cross-section of the gas atoms suddenly increases. Electrons that have not undergone excitation reactions gain more kinetic energy, eventually enough to perform impact ionization reactions with the gas atoms. The electrode quickly collects the electrons that have performed ionization reactions and those resulting from these impacts, so that a plasma enriched in positive ions (with net positive space charge) appears in front of the electrode. Simultaneously, electrostatic forces begin to act as long-range correlations between the two adjacent opposite net space charges. Consequently, the two space charge transform into a double layer configuration. The double layer supports a local potential drop, the value of which depends on the amount of electrons and positive ions located at its two sides. When the potential drop over the double layer reaches the ionization potential of the gas atoms, the charges production is suddenly amplified, which determines the first current jump in the static current-voltage characteristic (Fig. 2). Simultaneously, the electrostatic forces between the two opposite space charges suddenly increase and become dominant with respect to the external forces. Consequently, the space charge configuration performs a fast transition into a state characterized by a local minimum of the free energy, i.e., a state in which its shape becomes spherical. The electrons passing through the double layer are accelerated, which is proved by the cylindrical probe measurements (Fig. 5). A part of these electrons will produce excitation and ionization impact reactions with neutrals, contributing to the stability of the structure, while the other part of electrons will be collected by the electrode.

A similar physical mechanism was proposed for particle acceleration in auroras [35,36]. The aurora can be seen as a very large complex space charge structure, bordered by a double layer with the role to maintain their stability for a while. Optical observations reveal thin substructures, a few hundred meters wide, named “auroral arcs” (see Fig. 7a), which may be associated with a fine structure of the double layer or with concentric multiple double layers. Block [37] suggested that in the aurora case series of double layers along each magnetic field might exist, appearing and disappearing at random. Each of these double layers has a net potential drop only of the order of a few volts, but a large number of such double layers can build up much larger potentials. Other optical observations reveal a non-concentric structure of auroras (see photo in Fig. 7b), which lead to the supposition that under certain experimental conditions a non-concentric multiple double layers structure can be found at the origin of particle acceleration and the emergence of auroras.



(a)



(b)

Fig. 7. Photos of the auroras having a concentric (a, photo courtesy of Jan Curtis) and a non-concentric (b, photo courtesy of David Fritts) structure, respectively.

The stability of the double layer is ensured by a balance between the charges losses by diffusion and recombination and the charges created and accumulated in adjacent regions. The increase of the potential on the electrode will produce a shift of the double layer away from it. In this way, the electrons can again be accelerated between the double layer and the electrode to energies large enough to produce excitations of the neutrals and a second negative space charge develops near the electrode. This new negative space charge acts as a barrier for the current, reducing the flux of the electrons through the double layer. Thus, the balance needed for the double layer existence is perturbed and the structure disrupts. The electrons trapped in the double layer become free and move as a bunch towards the electrode, arriving in the region where a new double layer is in the growing phase. The excitations and ionizations rates will suddenly increase to the values for which the new double layer starts its dynamics. In this way, the phenomenon becomes a periodical one. Such a mechanism can be at the origin of the appearance of so-called “pulsating auroras” [38], which consist of repetitive intensity modulations of the auroral luminosity. The period of pulsation is typically of the order of 1-30 s. The intensity variations can be periodic, quasi-periodic or intermittent. This type of auroras is characterized by modulation of the fluxes of magnetospheric electrons.

4. Conclusion

Experimental results on the emergence and dynamics of complex space charge structures in laboratory plasmas are presented. These results present striking similarities with some natural phenomena, such as auroras. The mechanism of cosmic particle acceleration by such structures was discussed.

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