Complex-plasma boundaries

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This study deals with the boundary between a normal plasma of ions and electrons, and an adjacent complex plasma of ions, electrons, and microparticles, as found in innumerable examples in nature. Here we show that the matching between the two plasmas involve electrostatic double layers. These double layers explain the sharp boundaries observed in the laboratory and in astrophysics. A modified theory is derived for the double layers that form at the discontinuity between two different complex plasmas and at the point of contact of three complex plasmas. The theory is applied to the first measurements from the Plasma Kristall Experiment (PKE) Nefedov Laboratory in the International Space Station.

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Self-organization and self-structuring of complex plasmas are phenomena, that have only recently been discovered in microgravity experiments [1,2]. The system forms sharp stable boundaries with a characteristic length of the surface roughness comparable to the inter-particle distances. The surfaces are, nevertheless, quite porous, the solid (microparticle) fraction being of the order $(a/\lambda_D)^2$, with a being the particle radius and λ_D the Debye length. This fraction can be as low as 10^{-4} in the experiments performed so far. In this paper we investigate the microscopic and collective processes that give rise to this self-structuring and the surprisingly sharp surfaces observed. In the absence of gravity (normally the dominant force on the microparticles, and hence a decisive factor determining any surface structure of complex plasmas), either electrostatic forces, ion drag, or thermophoresis are responsible for the phenomena observed [1]. Microgravity thus allows us to study new collective effects that are not otherwise accessible.

When the plasma sheaths surrounding the particles interact, unexpected effects arise [3–6]. Among those is the counterintuitive effect that the negative particles are pushed away from the center of the discharge, which is generally the most positive part of the plasma. Figure 1 represents a typical steady state central meridional view for two complex plasmas under microgravity. It is easy to identify four regions that, although not completely uniform, show internal coherence. The first region is the central void. Its extension is much larger than any screening length so that we can assume quasineutrality inside. Ionization does actually occur in the void but, because of symmetry, no net current crosses the void–complex-plasma boundary. The second region surrounding the void is a three-component plasma where the negative charge is distributed between the electrons and the particles to equal the ion density. Since the free-electron density is lower than in the void, the electron screening length is longer. Here the ionization rate is reduced with respect to the void. The third region shows larger intergrain distances, hence larger screening lengths. This means fewer free electrons, and we can assume the particles' size to be larger, although the charge on a particle is not strictly proportional to the particle's surface area. The fourth region is dominated by the electrode/wall radiofrequency sheath.

Our approach in analyzing the boundaries between the above regions assumes quasineutrality in the first three. Large discontinuities in the electrostatic potential, charge double layers (DL), will match the flow of ions and electrons from any of the above plasmas. These DL are similar to the double layers found at the edge of a metal [7] or at the discontinuity between different work-function metals or semiconductors. The difference with respect to the above examples is that in complex plasmas all three components, electrons, ions, and charged microparticles, can participate in

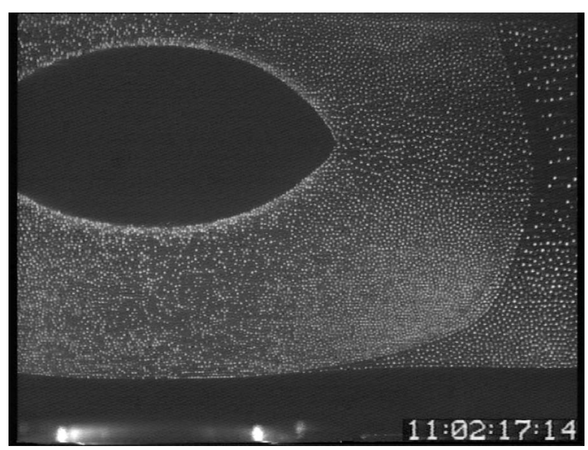

FIG. 1. Measurements from the PKE-Nefedov Laboratory, showing the distribution of two complex plasmas in the central meridional plane of the cylindrical plasma chamber (for an experimental description, see Ref. [2]). The experimental parameters are $V_{rf}=35.75$ V (effective), $P=74$ Pa of argon, $\phi=6.8$ μm, for larger particles (located outside), and $\phi=3.4$ μm for smaller particles (located inside).

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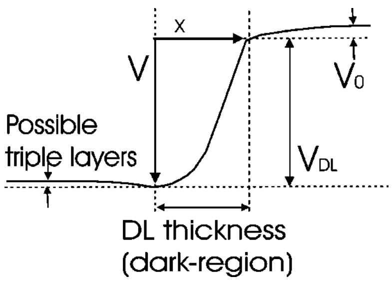

FIG. 2. Schematics of the potential profile across a triple layer with the reference system.

the conduction; and, in general, their densities are not in equilibrium.

Using the same notation as Ref. [8], where the DL forming at a hot cathode has been analyzed, potentials will be measured from a plane at the void DL boundary. Figure 2 shows a schematic of the potential profile at the interface between complex-plasma and void. The reference system is also shown. On the void side, ions are accelerated in the DL after having acquired a velocity of the order of the Bohm speed in the void. Some of the electrons entering the DL will reach the complex plasma, and others will be turned back. From the lower-potential three component plasma, only some electrons will be accelerated towards the void, whereas the ions are turned back by the potential. The charged microparticles are assumed to be at rest, consistent with the observations. In this figure a possible confining mechanism for the particles, the triple layer, is outlined. In the following, the charge densities for the individual species are derived.

The beam of electrons, j_b, leaving the complex plasma is accelerated by the DL field to reach a velocity v_b. Their initial potential energy is eV_{DL}, where V_{DL} is the edge potential on the lower potential side of the DL. Assuming flux and energy conservation, we have

$$n_b=\frac{j_b}{e}\left(\frac{m}{2e}\right)^{1/2}(V_{DL}-V)^{-1/2}. \tag{1}$$

Here m and e are the mass and charge of the electron, respectively.

The ions arrive at the void-DL boundary with an averaged velocity acquired in a presheath potential V_0. Here we assume monoenergetic ions. In the absence of collisions in the DL, the flux of ions is continuous across the sheath and energy is conserved. The velocity and the density of the ions are given below:

$$v_i=\left(\frac{2e}{M}\right)^{1/2}(V_0+V)^{1/2}, \tag{2}$$

$$n_i=n_{i0}\left(1+\frac{V}{V_0}\right)^{-1/2}. \tag{3}$$

Here n_{i0} is the ion density at the void edge and M is the mass of the ion.

The void electrons enter the sheath with random velocity. For their density in the DL we can assume, in most cases, the Boltzmann distribution law. Some correction for small DL potentials leading to non-Maxwellian distributions can be made, but are not given in this paper. In the case of electronegative gases or in the presence of impurities, some *negative ions* should be taken into account as indicated in the hot cathode equations in Ref. [9].

We have used the following *normalization*, where T_e is the electron temperature, k is the Boltzmann constant and ϵ_0 is the electric permittivity. The subscripts i, e, b, and 0 refer to ions, void electrons, beam electrons, and the zero reference point. The normalized potential is $\eta=eV/kT_e$ and particle densities are $\nu=n/n_{e0}$. The normalized current density is

$$J=\frac{j}{n_{e0}e\left(\frac{kT_e}{m}\right)^{1/2}(2\eta_{DL})^{3/2}}. \tag{4}$$

The distance from the complex-plasma edge is normalized to the electron Debye length $\xi=x/\lambda_{De}$.

The normalized *Poisson's equation* is

$$\frac{\partial^2\eta}{\partial\xi^2}=\frac{\nu_i}{\sqrt{1+\frac{\eta}{\eta_0}}}-\frac{2J_b(\eta_{DL})^{3/2}}{\sqrt{(\eta_{DL}-\eta)}}-\exp(-\eta). \tag{5}$$

The *boundary conditions* are derived strictly from geometrical considerations. The scales of the two adjacent plasmas are much larger than the Debye length and the double-layer thickness. Hence we assume quasineutrality at the DL edges. The quasineutrality condition at the void edge, $\eta=0$, implies $\nu_i=1+2\eta_{DL}J_b$. At $\eta=0$ we also assume no charge gradient. From these conditions, following Ref. [10], we can calculate the presheath potential that accelerates the ions into the DL:

$$\eta_0=\frac{1+2\eta_{DL}J_b}{2(1-J_b)}, \tag{6}$$

where the usual Bohm criterion is obtained in the limiting case $J_b=0$. The condition of quasineutrality at the complex-plasma side implies a negligible or constant electric field in the complex plasma. These conditions can be implemented by the integration of the Poisson equation (5) to obtain the Maxwell stress.

$$\frac{1}{2}\varepsilon^2=2\nu_i\eta_0\left[\left(1+\frac{\eta}{\eta_0}\right)^{1/2}-1\right]-J_b(2\eta_{DL})^{3/2}[(2\eta_{DL})^{1/2}-(2\eta_{DL}-2\eta)^{1/2}]+\exp(-\eta)-1. \tag{7}$$

We can then impose zero electric field at the complex-plasma edge:

$$2\nu_i\eta_0\left[\left(1+\frac{\eta_{DL}}{\eta_0}\right)^{1/2}-1\right]-J_b(2\eta_{DL})^2+e^{-\eta_{DL}}-1=0. \tag{8}$$

TABLE I. Parameters for a void–complex-plasma boundary.

$1/2E_{DL}^2$(Stress)	I(Current)	η_{DL}	η_0	J_b
0	0	1.007	0.577	0.049
0.2	0	1.67	0.514	0.011
0.4	0	2.24	0.504	3.92×10^{-3}
0.6	0	2.79	0.503	1.45×10^{-3}
1.0	0	3.96	0.500	1.08×10^{-4}
0	−0.1	0.732	0.562	0.048
0	0.1	1.317	0.589	0.047
0	0.3	2.114	0.606	0.039
0	0.5	3.42	0.613	0.028

Alternatively, we might assume a uniform field in the complex plasma. In the specific case of Fig. 1 the momentum acquired by the ions in the DL is probably thermalized by the scattering with the particles. The last condition for the void–complex-plasma boundary is ‘‘zero current’’ deduced from the ‘‘closed’’ geometry in Fig. 1. The ‘‘open void’’ case, which allows some circulation of current, is discussed later. In a low-temperature rf plasma ionization occurs mostly where the electron density is highest, i.e., in the void, as remarked earlier. Recombination in the void is forbidden by the conservation rules so that always a couple electron-ion will leave the void, giving zero net particle current across the DL. Some of the electrons generated at the rf electrode sheath edge, or secondary electrons from the electrode, will enter and exit the void without giving an extra contribution to the current. The total current density across the double layer is

$$J=\frac{m^{1/2}(1+2\eta_{DL}J_b)^{3/2}}{M^{1/2}(2\eta_{DL})^{3/2}(1-J_b)^{1/2}}+J_b-\frac{\exp(-\eta_{DL})}{(2\pi)^{1/2}(2\eta_{DL})^{3/2}}. \tag{9}$$

The boundary conditions of neutrality and zero-charge derivative at the void boundary, together with the condition of zero current and fixed Maxwell stress at the complex-plasma side, can only be consistently satisfied by a unique choice of the three parameters; the presheath V_0, the DL voltage V_{DL} and the electron beam current J_b, as given in Table I. Here a normalized Maxwell stress of 1 corresponds to a stress equal to the pressure of the electrons from the void. This should be compared to the usual floating sheath in which the electron and the ion pressure act on the wall, giving a floating potential of $4.64kT_e/e$ in argon and the Bohm presheath. For the above cases, the profiles of the electrical potential are shown in Fig. 3. At zero Maxwell stress, a voltage of about 1 kT_e/e will reduce to 20% of its value in about 5 λ_D. From $V_0=0.577$, we know that a presheath, slightly modified with respect to the Bohm case, develops in the void.

When *two different complex plasmas are in contact*, a localized difference of potential arises. Figure 1 shows a narrow ‘‘empty’’ space between the complex plasma with smaller microparticles (near to the void) and the plasma with larger particles (outside). In a complex plasma, the ratio of the ions to the free electrons is given by $\alpha=1+P$, where P is the ‘‘Havnes parameter,’’ $P=z_pn_p/n_e$, see Ref. [6], with z_p and n_p the particles' absolute charge and the density, respectively. As some of the negative charge is bound to the microparticles, the free-electron density is reduced, and a lower number of electrons will traverse the DL when compared with the void–complex-plasma case. The condition of quasineutrality at the DL edge can then be written as $\nu_i=\alpha+2\eta_{DL}J_b$. Because of the normalization of the particles' density to n_{e0}, Poisson's equation (5) and the total current equation (9) are not modified with respect to the void–complex-plasma case. The presheath equation (6) is then modified as:

$$\eta_0=\frac{\alpha+2\eta_{DL}J_b}{2(1-J_b)}, \tag{10}$$

and the Maxwell stress boundary condition remains as in Eq. (8), with the modified values for ν_i and η_0. In Table II, V_0, V_{DL}, and J_b are given for four values of the parameter α for zero Maxwell stress at both sides of the DL. For the above cases, the profiles of the electrical potential are shown in Fig. 4. For the DL between two complex plasmas, a direct comparison of our theory with the experiments allows us to derive the Havnes parameter as shown below. To our knowledge, this is the only direct determination available so far. It can be used to estimate the coupling parameter too. For the

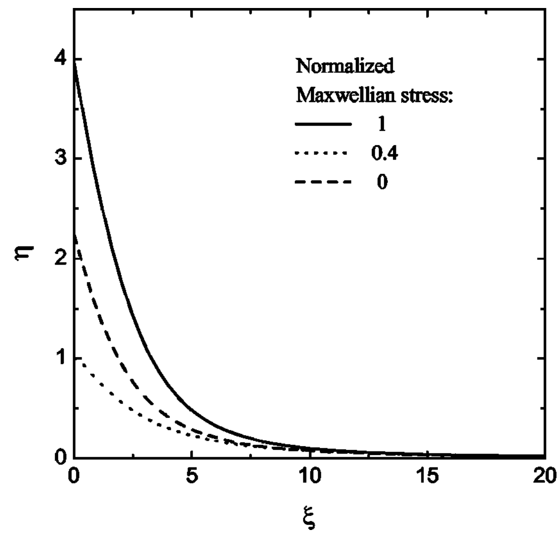

FIG. 3. Potential profiles for three values of the Maxwell stress at the ‘‘low-potential’’ side (hypothesis of zero current across the double layer).

TABLE II. Parameters for the boundary between two complex plasmas at zero current and zero Maxwell stress.

$\alpha(n_e/n_i)$	η_{DL}	η_0	J_b
1.0	1.007	0.577	0.049
1.1	0.683	0.664	0.122
1.2	0.443	0.896	0.296
1.3	0.276	2.31	0.701
1.31	0.261	3.01	0.767

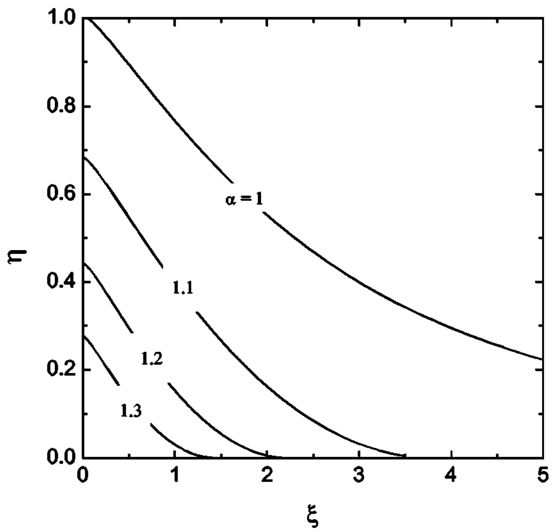

FIG. 4. Potential profiles for several values of the ratio between the density of the ions and the density of the electrons at the higher-potential plasma (hypothesis of zero current across the double layer).

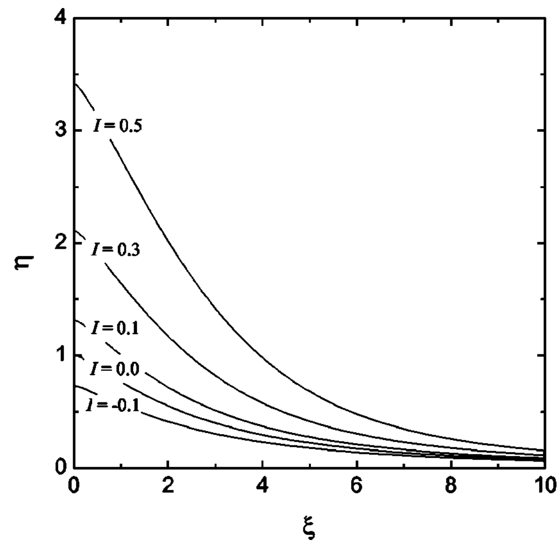

FIG. 5. Potential profiles for several values of the current across the double layer (hypothesis of zero Maxwell stress on the low-potential plasma edge of the double layer).

measurements of Fig. 1 the empty region between the two complex plasmas of different particle sizes is roughly twice the intergrain distance of the ''upper voltage'' plasma, i.e., approximately twice the Debye length. This is shown by the curve $\alpha = 1.2$ in Fig. 4, from which we deduce a Havnes parameter of 0.2 in the upper plasma. Note that for DL less than kT_e/e, some correction to the value of Table II and Fig. 4 to take in account the non-Maxwellian electrons might be needed. Instead in presence of a residual Maxwell stress in the ''lower'' plasma, the derived Havnes parameter would be correct because the stress would increase the DL voltage but not the thickness (see also Fig. 3).

In a closed void, as in Fig. 1, *the particle current across the DL* is zero. This condition may not hold for open voids or for *triple points*, i.e., the point of contact between three different plasmas or two plasmas and the sheath. In this latter case, the circulation of some current would help the matching of the electrostatic potential in the three regions. The profiles of the potential for five electron currents, zero stress, and $\alpha = 1$ are given in Fig. 5, and the relevant data in Table I. Here the net particle current across the DL is normalized as in Eq. (4). To give a better idea of these quantities, the normalized Bohm flux is 6.5×10^{-4}. A positive current represents a net flow of ions from the upper plasma, this will increase the dc voltage difference. The double-layer theory provides information on the potential structure of the observed sharp interface between the void plasma and the complex plasma. The complex-plasma surface, although extremely porous, behaves almost like a wall with zero net current passing through. Without the dominant effect of gravity, i.e., in a microgravity environment, the microparticles arrange themselves around a void, where the ionization mainly occurs. Different complex plasmas will then self-organize and arrange themselves in order of decreasing free-electron density. A modified equation for the DL between complex plasmas was derived taking into account the variations in the electron density. This allows a determination of the Havnes parameter and the coupling strength.

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