32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.29C, O-2.010 (2005)

Theory of dust and dust-void structures

S. V. Vladimirov[1], V. N. Tsytovich[2], and G. E. Morfill[1,3]

[1]*School of Physics, The University of Sydney, New South Wales 2006, Australia*

[2] *General Physics Institute, Vavilova 38, 117942 Moscow, Russia*

[3] *Max-Planck-Institut für extraterrrestrische Physik, D-85740 Garching, Germany*

A dust void appears as a dust-free region where the plasma ionization rate supports an outward ion flow exerting an outward ion drag force on the dust particles. The dust-void boundary presents a new type of discontinuities in a dusty plasma where the dust density can change rapidly while the ion and electron densities as well as the dust charge are continuous. In [1,2], the theory of dust void was proposed; it was demonstrated that the presence of the plasma ionization is crucially important for the theory of voids since the ionization source produces the ion flow to the boundary thus supporting the void. Here, we investigate the dust void structures in the case when the ion diffusion on the neutral gas atoms plays an important role.

The results are found by investigation of the stationary force balance equations for the void structure. We show that if the ion diffusion on neutral gas atoms is taken into account, the dust density has no discontinuity (according to the boundary conditions used) at the surface of the dust boundary; nevertheless, the ion diffusion process still creates sharp dust boundaries with complete absence of dust in the void region and the derivatives of various plasma parameters having discontinuities at the boundary.

With the continuous dust density at the boundary, some solutions reveal negative dust density in the region occupied by dust and should be excluded. Thus at the center of the void, in addition to the ion density, we fix the ratio of the electron to ion density. By varying and adjusting the latter, we determine the critical value when the dust density starts to increase from the void's boundary. This is the necessary condition for the boundary to exist and the structure of the dust region can then be calculated. We also point out possible singularities in the dust region. In the one-dimensional model considered here, they indicate the points where the ion flow velocity tends to zero or the electron density tends to zero. In these cases the size of the obtained dust cloud can be of the order of the ion-neutral mean free path, i.e. corresponding to a rather thin cloud. Note that sets of thin dust layers found theoretically in the present paper were also observed in the laboratory experiments [3] as well as in the lower ionosphere [4].

We consider the one-dimensional model; the overall approach assumes a planar geometry that is symmetric about the center of the void which is located at $x = 0$. The ion drift velocity is zero at the center. When the void appears, its center is at $x = 0$.

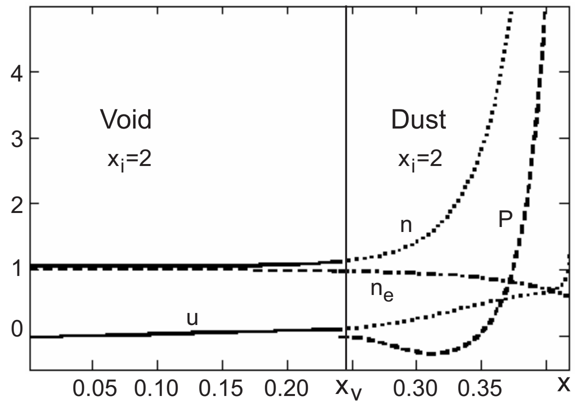

Figure 1: Distribution of the main dimensionless parameters in the void and the dust regions in the case when the ion diffusion taken into account. Here, the normalized ionization length is the same $x_i = 2$ in the void as well as in the dust regions. Note the non-physical domain of the negative values of $P = n_d Z_d / n_{00}$.

The void's surface corresponds to x_v. The dust region corresponds to $x > x_v$ where the dust number density n_d is finite (and positive). We use the dimensionless variables given by [2,5]. The total system of balance equations is given by: (1), the electron balance equation including the electron pressure force balanced by the electric field force; (2), the ion balance equation including the ion pressure force balanced by the electric field force, the friction on the dust force and the friction on the neutral atoms force; (3), the dust balance equation (balancing the dust pressure force by the electric field force and the ion drag force); (4), the ion continuity equation determining the ion drift velocity and containing the ionization source x_i and dissipation on the dust component; (5), the ion flux relation including the convective flux and the diffusion flux; (6), the dust charging equation obtained from the balance of charging currents on the dust grains; (7), the Poisson's equation.

When we take into account both the ion pressure effects and the ion diffusion effects, the total ion flux vanishes when the ion flow velocity $u \to 0$. The asymptotics of the equations in the center of the void where $u \to 0$ and the electric field $E \to 0$ allows us to determine the values of the second derivatives of the electron and ion densities in the center of the void. The total ion flux close to the center is a sum of the convective flux $\Phi_0^{\rm conv}$ and the diffusive flux $\Phi_0^{\rm diff}$, with the special parameter s regulating the ratio of the diffusive to the convective flux at the void's center. When comparing to the case when the ion diffusion was ignored, the ion density at the void's center decreases, the dust void size increases and the ion drift velocity at the boundary of the void substantially increases (although still being much lower that the ion thermal velocity). With further decrease of the ion density in the void's center, solutions of the boundary equations exist

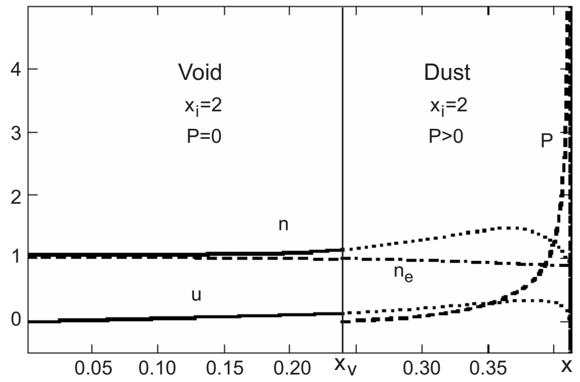

Figure 2: Distributions of the dimensionless parameters in the void and dust regions with the continuous change of the direction of ion flow. The normalized ionization rate is $x_i = 2$ both in the dust and in the void regions.

showing a decrease of the void size with a decrease of the ion density in the center. The condition that the diffusion flux at the center is zero appears as the optimal for a *diffusive void* to be created.

Figure 1 shows the result obtained for the case of equal ionization rates in the dust and void regions. We find that there exist a non-physical domain of negative values of P, and the sharp increase of P is related with dust convection while for the case when the ionization rate in the dust region is larger than that in the void region the parameter P is everywhere positive, but the singularity appears at $u \to 0$. The parameters at $u = 0$ can be properly adjusted but then the void is not a symmetric void (with its center in the center of the computation region) and should satisfy different boundary condition (for example the wall boundary conditions). The results shown in Fig. 1 with the negative values of P suggest that although $dP/dx = 0$ at the boundary, the second derivative of P is negative there. The only way to avoid this effect is to decrease the ion density in the center of the void (to the value 5×10^{-3}) to reach P positive in the dust region.

Figure 2 shows distributions of the parameters in the void and dust regions with the continuous change of the direction of ion flow. The dust layer appears to be not symmetric relative to the point where we start the calculations at $u = 0$. We can notice the discontinuities of derivatives of P, n_e, and E at the void boundary supporting our statement that the ion diffusion is not removing them although discontinuity of the dust density is disappearing because of the ion diffusion. Note that the singularity still appears in the region $u \to 0$. Thus we should allow such discontinuities of dP/dx; note that its value at the void boundary is very sensitive to the ion density at the void's center. Thus although the diffusion relates the parameters of the system stronger, it cannot eliminate all discontinuities of the parameters at the dust boundary.

New types of dust-charge diffusive shocks can be created in the void-dust structures

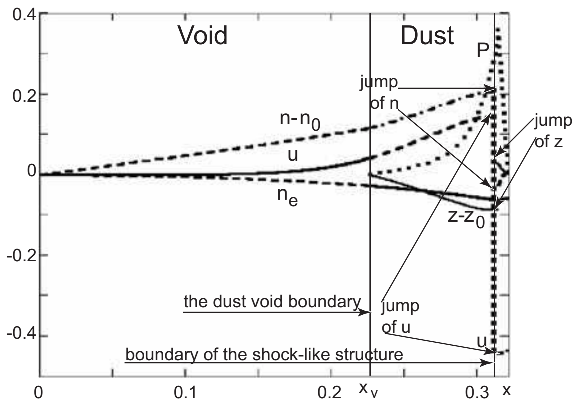

Figure 3: Distributions of the dimensionless parameters in the void and dust regions with the continuous change of the direction of ion flow. The normalized ionization rate is $x_i = 2$ both in the dust and in the void regions.

in the presence of the ion diffusion on neutral atoms, Fig. 3. We see that the jumps of the dust and plasma parameters exist in the dust region around the point where $u = 0$. The results are: (1) the jump of the ion flow velocity is from 0.2 to -0.44, (2) the jump of the ion density is from 1.384 to 0.97593, (3) the jump of the dust charge is from 2.91 to 2.84, (4) the jump of the parameter P is from 0.3595 to 0.3449, and (5) the electron density is continuous (as it should be) but the derivative of the electron density also has a discontinuity. Together with the jumps of the values at the dust-charge diffusive shock front, the derivatives of the corresponding parameters also change. After we obtain all the parameters on the other side of the shock, we further integrate the balance equation in the dust region until we reach the point where $P = 0$.

Thus, the ion diffusion does not prevent the void formation. It is shown that the latter with the absence of any dust grain in the void region exists, and can create a new type of void boundaries and new type of diffusive dissipative structures in dusty plasmas.

Acknowledgments. This work was supported by the Australian Research Council and the Max Planck Society (Germany).

References

[1] J. Goree, G.E. Morfill, V.N. Tsytovich, and S.V. Vladimirov, Phys. Rev. E **59**, 7055 (1999).

[2] V.N. Tsytovich, S.V. Vladimirov, G.E. Morfill, and J. Goree, Phys. Rev. E **63**, 056609 (2001).

[3] D. Samsonov and J. Goree, Phys. Rev. E **59**, 1047 (1999).

[4] O. Havnes, T. Aslaksen, and A. Brattu, Phys. Scripta **T89**, 133 (2001).

[5] V.N. Tsytovich, S.V. Vladimirov, and G.E. Morfill, Phys. Rev. E **70**, 066408 (2004).