Cavities around floating spheres in a complex plasma under microgravity conditions

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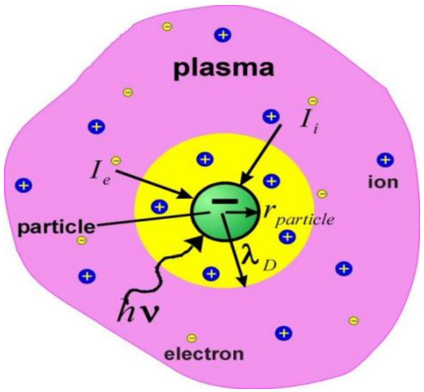
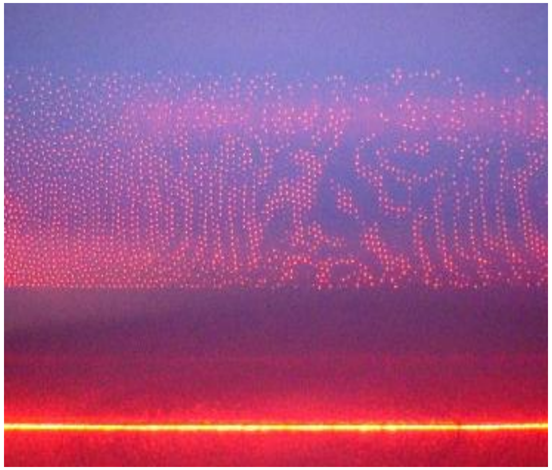
Complex Plasma: Interdisciplinary Research Field



- Solid particles in the plasma background
- Particles are charged (mainly by collecting electrons and ions)
- Interdisciplinary research area

Astrophysical topics:

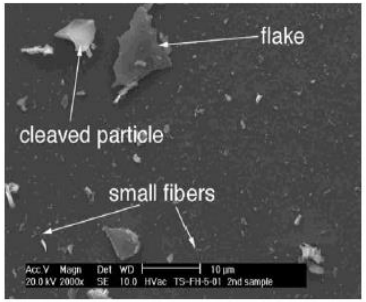
Laboratory:

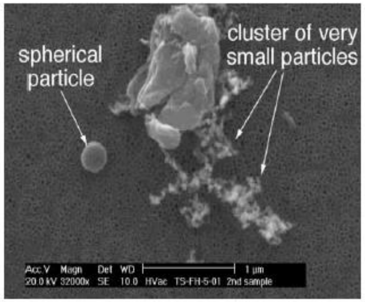


From Kretschmer, Selwyn, Sharpe, et al.

Industry:

Fusion:





Plasma Krystal (PK) Experimental Program on the ISS

- Russian – German cooperation
- Established by V.E. Fortov and G. E. Morfill
- PKE-Nefedov (2001-2005)
- PKE-3 Plus (2006-2013)
- PK-4 (2014- present)

Context:

- Plasma-particle interactions – important interdisciplinary topic
- In complex (dusty) plasmas: Particle charging, ion and electron drag forces, plasma screening of particle charge, interparticle interactions, etc.
- Here we will focus on interactions between a large massive body and complex plasmas
- One particular manifestation: creation of cavities (voids) free of particles in the vicinity of such objects
- What determines the cavity size?

Experiment:

- Last experiment of the PK-3 Plus laboratory performed by Pavel Vinogradov (2013)
- Dispensers shaken very strong -> 1 mm diameter metallic spheres broke through the sieve to bulk plasma (together with the particles)
- Shaking container -> accelerating spheres by collisions with plasma walls
- Interaction between flying spheres and complex plasma clouds
- Many interesting phenomena: Formation of bubbles, competition between attraction and repulsion, wave excitation (M. Schwabe et al. NJP 2017)

Experiment: Bubble formation

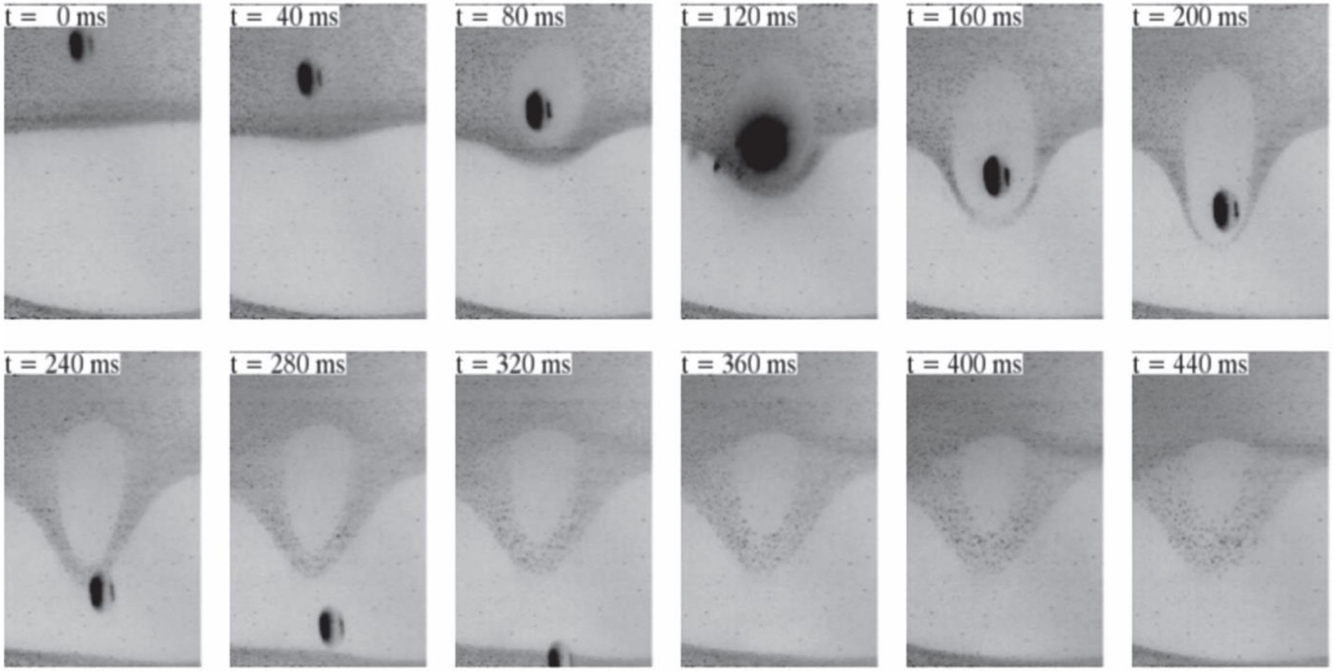


Figure 6. Negative of images with a field of view of 6.5 × 8.5 mm^2 showing a sphere moving from top to bottom through the void. A bubble around the sphere forms, and microparticles are displaced into the void. Once the sphere has left the vicinity of the void edge, the bubble loses cohesion, and the microparticles slowly move back towards the void edge.

M. Schwabe et al. NJP 2017

Experiment: Long-range attraction

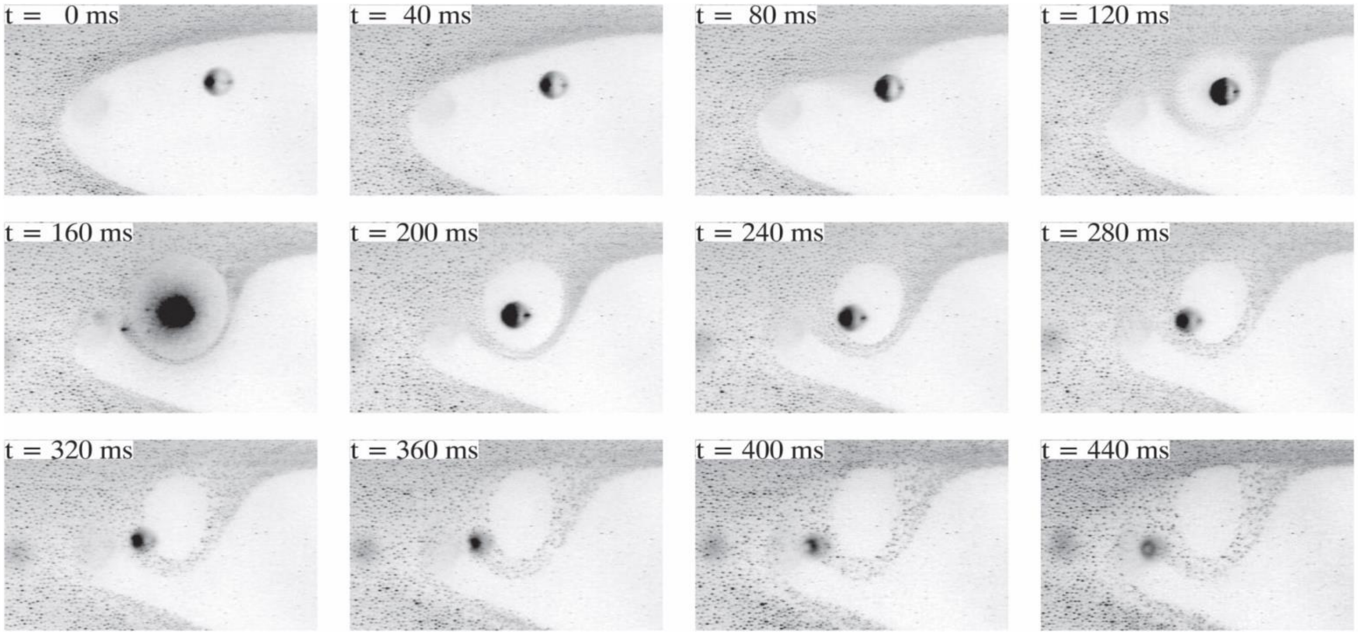


Figure 7. A metallic sphere is moving inside the void of a complex plasma cloud. The original images with a field of view of 11.9×7.2 mm^2 were inverted, and the contrast was adjusted. The sphere is moving simultaneously from right to left and perpendicular to the field of view. When it approaches the void boundary ($t = 80$ ms), the particles in the complex plasma cloud move towards the sphere, forming a bubble around it ($t = 120$ ms). The sphere crosses the laser plane at $t = 160$ ms (its image is overexposed). After the sphere has left the laser plane, the bubble loses cohesion, and the microparticles slowly fall back towards the main cloud. See the supplementary material for a movie.

M. Schwabe et al. NJP 2017

Experiment: Self-excited waves

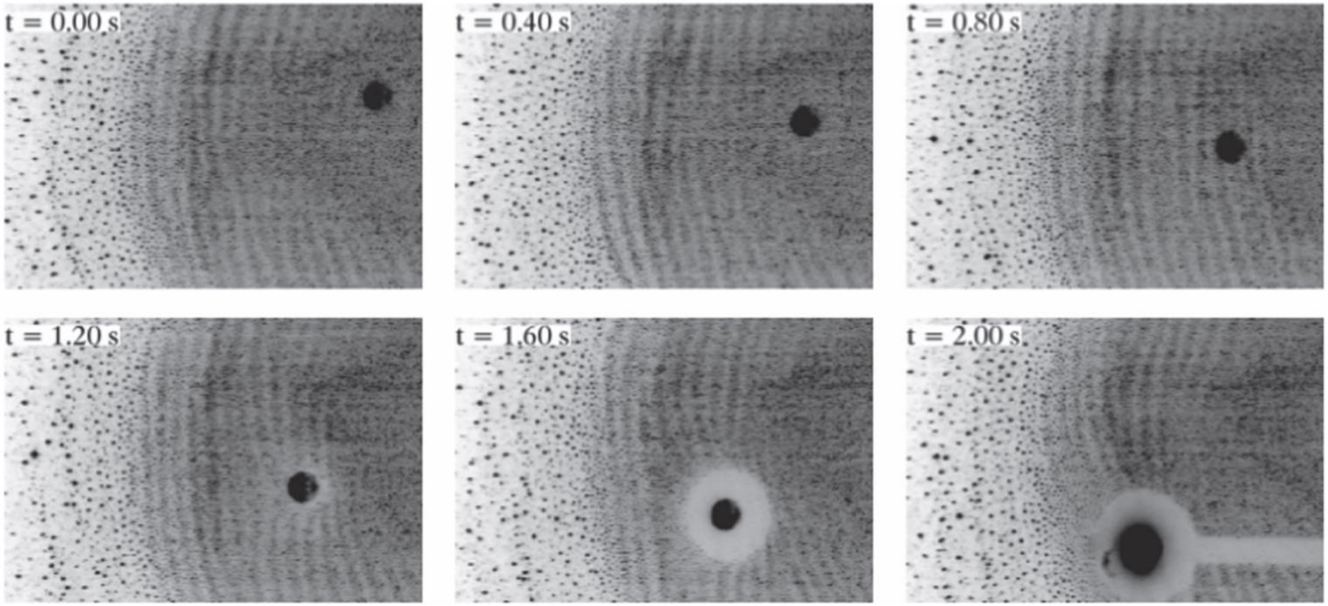


Figure 8. Experimental images showing a metallic sphere that moves through a complex plasma cloud with self-excited waves. The original images with a field of view of 16×9 mm^2 were inverted. First, the sphere is located outside the laser plane illuminating the microparticles. When it approaches the plane ($t = 0.8$ s), it induces waves in a region of the plasma cloud that was previously quiescent. As the sphere moves into the laser plane, it repels the microparticles, so that a cavity forms around the sphere. The wave ridges become visibly bent near the cavity surface. The sphere reaches the center of the laser plane at $t = 2$ s, where it casts an extended horizontal shadow. At that time, the wave ridges orient perpendicular to the cavity surface. See the supplementary material for a movie.

M. Schwabe et al. NJP 2017

Experiment: Cavity size

- The sizes of cavities measured for different neutral gas pressures (between ~ 15 and ~30 Pa) and different positions in the cloud (populated by particles of different size)
- Cavity size somewhat increases with pressure
- No dependence on the particle size
- Theory?

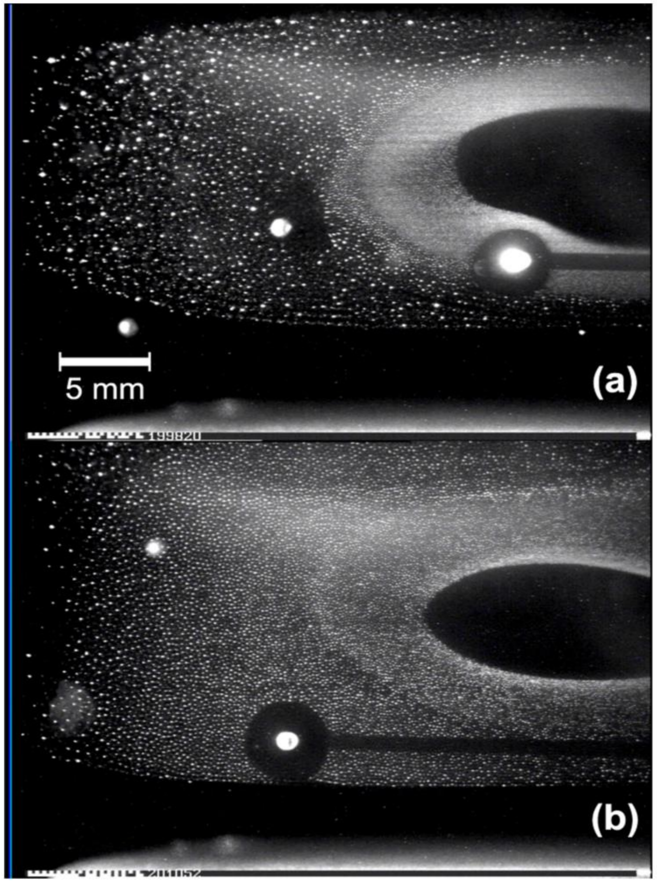


FIG. 2. Experimental video images showing a metallic sphere surrounded by complex plasma in an argon discharge. In (a) the pressure is 17.5 Pa, the particles interacting with the sphere have a diameter of 1.55 μm, the diameter of the cavity is $\simeq$4.2 mm; in (b) the pressure is 30.4 Pa, the complex plasma interacting with the sphere consists mostly of agglomerate particles, and the diameter of the cavity is $\simeq$4.8 mm.

Theory: Qualitative picture

- Large object is charged negatively, just as the dust particles are. The floating potential is of the order of electron temperature
- Particles experience strong electrostatic repulsion at short distances
- At long distances the ion drag force is responsible for particle attraction to the large object
- Pressure force towards the object exists, but is expected to be relatively small
- **Force balance for an individual particle** suffices as a first approximation

Theory: Qualitative picture continued

- It seems like we need to solve rather complex problem of plasma distribution in front of a large body absorbing plasma. This is, however, not necessary.
- The ratio of the ion drag force to the electric force is constant for sub-thermal ion drifts and decliners fast for super-thermal drifts
- The cavity boundary is roughly located at $M = u/v_{Ti} \sim 1$
- The cavity boundary is located in the weakly perturbed quasi-neutral plasma region
- We should focus on the long-range asymptote of the electric potential, which is governed by plasma absorption on the macrosphere

Theory: Long-range asymptotes

- Ion flux conservation determines the electric potential and electric field far from the plasma collecting sphere
- For a large sphere $R_s \gg \lambda$ and collision-dominated ion flux $R_s \gg \ell_i$

$$\phi(r) \simeq -(T_e/e)(R_s/r), \quad E(r) \simeq -(T_e/e)(R_s/r^2),$$

Theory: Ion drift and modified Frost's formula

- Modified Frost formula for the ion mobility

$$M = A\left[1 + \left(B\frac{E}{N}\right)^{C}\right]^{-1/2C}\frac{E}{N}$$

- C is an additional parameter, C=1 corresponds to conventional formula

- Improvements over conventional formula have been documented for He, Ar, and Ne

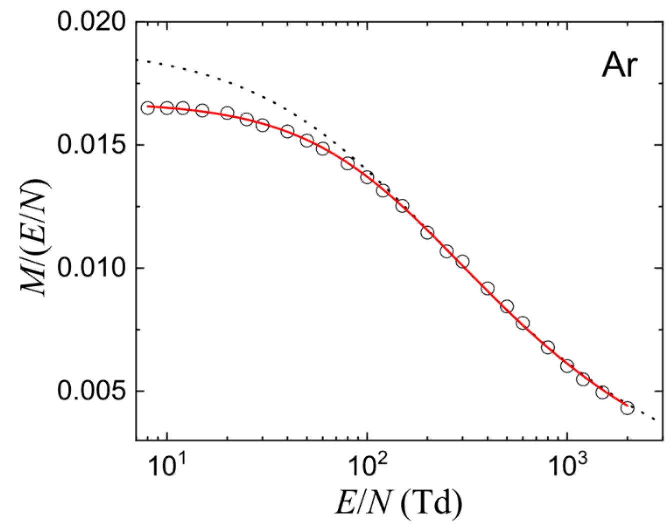


TABLE I. Fitting parameters in the modified Frost formula (4).

System	A (1/Td)	B (1/Td)	C	σ_{eff} (10^{-14} cm^2)
He^+ in He	0.0354	0.0118	1.355	1.09
Ne^+ in Ne	0.0321	0.0120	1.181	1.20
Ar^+ in Ar	0.0168	0.0070	1.238	2.30
Kr^+ in Kr	0.0136	0.0054	1.422	2.84

S. Khrapak & A. Khrapak AIP Adv. **9**, 095008 (2019)
A. Khrapak et al., High Temp. 58, 545 (2020)

Theory: Ion drag force

- Modified Coulomb scattering theory (Khrapak 2002), simplified for moderate degree of ion-particle coupling, and collisional correction factor included (Hutchinson&Haakonsen 2013)

$$F_i \simeq 6.0 a^2 n_i T_i M z \tau (\lambda / a) F(\tilde{\nu}),$$

$$F(\tilde{\nu}) = \frac{1 + A\tilde{\nu}}{1 + B\tilde{\nu} + C\tilde{\nu}^2}$$

- Reduced collisionality $\tilde{\nu} = \nu r_c / c_s$ and nonlinear screening radius $r_c \simeq 1.2 \lambda_{\mathrm{De}} \left(\frac{a}{\lambda_{\mathrm{De}}} \frac{T_i}{Te} \right)^{1/5}$

$$A = 7 + 3M, \quad B = 1.8M, \quad C = 0.5A$$

- The ratio of the ion drag and electric forces

$$|F_i / F_{\mathrm{el}}| \simeq 0.5(\omega_{pi} / \nu_{\mathrm{eff}}) F(\tilde{\nu})$$

Results

- Force balance condition is used to determine M_*
- From M_* and the long-range electric field asymptote the cavity size is calculated as

$$R_{\rm cav} \simeq R_s \left(\frac{T_e}{T_i} \frac{\ell_i}{R_s} \frac{1}{M_*} \right)^{1/2}$$

- Reasonable agreement with experimental results
- Weak dependence on the pressure and no dependence on the dust particle size are reproduced

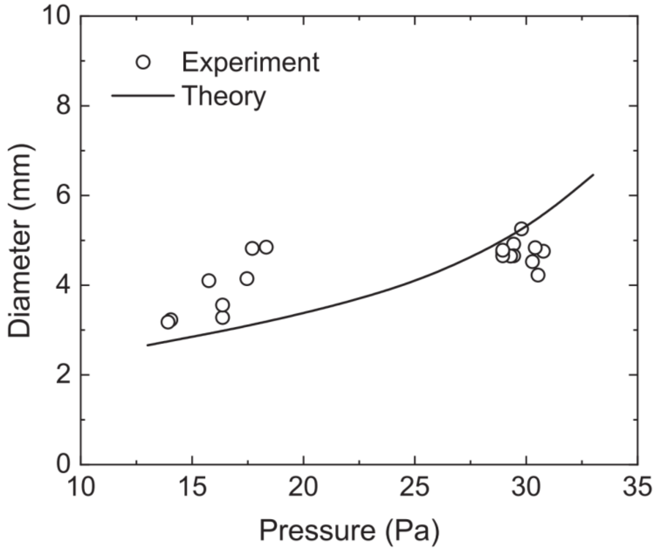


FIG. 3. Dependence of the cavity diameter on the neutral gas pressure. Circles are experimental measurements (symbol's size is comparable to experimental uncertainty), the solid curve corresponds to the theoretical calculation.

Conclusion

- Interactions between millimeter size floating spheres and complex plasmas have been studied in the PK-3 Plus laboratory onboard ISS
- Formation of cavities around the spheres was observed and cavity sizes determined
- A theoretical model, based on the balance of the ion drag and electrical force acting on an individual particle has been developed
- Theoretical results agree well with experimental ones
- Theoretical approach has also been generalized to collisionless plasma regime (very low pressure experiments, astrophysical context)

For more details see:

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Theory of a cavity around a large floating sphere in complex (dusty) plasma

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In the last experiment with the PK-3 Plus laboratory onboard the International Space Station, interactions of millimeter-size metallic spheres with a complex plasma were studied [M. Schwabe *et al.*, New J. Phys. **19**, 103019 (2017)]. Among the phenomena observed was the formation of cavities (regions free of microparticles forming a complex plasma) surrounding the spheres. The size of the cavity is governed by the balance of forces experienced by the microparticles at the cavity edge. In this article we develop a detailed theoretical model describing the cavity size and demonstrate that it agrees well with sizes measured experimentally. The model is based on a simple practical expression for the ion drag force, which is constructed to take into account simultaneously the effects of nonlinear ion-particle coupling and ion-neutral collisions. The developed model can be useful for describing interactions between a massive body and surrounding complex plasma in a rather wide parameter regime.

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Thank you for your attention!

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