We study the interaction between a complex plasma and metal spheres.

- last experiment with the PK-3 Plus Laboratory on board the International Space Station
- argon plasma + microparticles + metallic spheres of 1 mm diameter
- spheres set into motion by manual shaking of the experiment container, are reflected off the chamber walls, decelerated slowly compared to time scale of microparticle dynamics

Microgravity is essential for this project:

- under influence of gravity, microparticles fall to earth where they are suspended by electric field
- metallic spheres would not be trapped in plasma all
- microgravity essential for study of interaction

**Forces Acting on the Spheres**

### The sphere motion is dominated by inertia.

- sphere mass: \( m = 4.1 \times 10^{-6} \) kg
- sphere radius \( R = 0.5 \) mm
- typical velocity: \( v = 30 \) mm/s
- stopping spheres from \( v \) during \( \Delta t = 1 \) s would require force \( F_T = m \Delta v/\Delta t = 120 \) N
- Reynolds number: \( Re = 2 \pi R v/\mu \) (gas mass density) \( \rightarrow \) laminar flow of gas around sphere
- see Table for experiment parameters

### Sphere charge estimated with rule of thumb:

\( Q_0 = 1.8 \times 10^8 \) [\( \mu \)C]

**The drag forces are negligible.**

- Knudsen number \( K_x = h/2\pi \rho \) (mean free path of gas atoms / sphere radius)
- transitional regime between free-molecular \((K_x \geq 1)\), continuum \((K_x < 1)\) regimes
- Stokes drag: \( F_D \propto \rho \) correction for slip
- \( C_F \) \( \propto \) \( v \) \( \propto \) friction of microparticle fluid \( F_D \rightarrow 0.3 \text{ N} \ll F_T \)

**The forces approximately balance at the cavity edge.**

\[ F_T = F_D = F_{\text{ion}} = F_{\text{electric}} = 0 \]

- directed towards the sphere:
  - pressure force \( F_P = \frac{4}{3} \pi R^3 \rho \Delta P \approx 62 \) N
  - ion drag force \( F_{\text{ion}} = \frac{1}{2} c_F \rho v^2 \approx 110 \) N

**At the cavity edge:** \( r_1 = 1.8 \) mm

- \( m \Delta v/\Delta t \rightarrow F_D = F_{\text{ion}} = F_{\text{electric}} = 0 \)

- \( \Delta P \rightarrow \Delta v \rightarrow \rho \rightarrow \text{cavitation} \)

**Experiment parameters**

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*Table: (1) Simple interaction, (2) Bubbles, (3) Repulsive attraction, and (4) Exciting waves.*

**Spheres cause cavities in the microparticle cloud and cast shadows when in the laser plane.**

**The shape of the cavity can be measured in three dimensions.**

- use sphere traveling through the laser plane as probe to get 3D structure of cavity
- assume constant sphere speed in \( z \)-direction (perpendicular to laser plane), measure \( r_1 \) from time needed to transverse laser plane
- the cavity forms very fast with a shock in the microparticle fluid
- after the sphere is gone, the cavity closes slowly with a microparticle velocity of approximately 8 mm/s (\( \approx \) speed of sound \( c_s = 5.8 \) mm/s)

**The wave excitation is controlled by the electric field.**

- spheres attract ions and bend ion stream lines
- dust density waves are excited when electric field strength is less than critical field \( E_{\text{cr}} \) [4]

\[ E_{\text{cr}} = \frac{300 \text{ V/m}}{\left( \frac{c_s}{v} \right)} \]

- for experiments (1) - (3) with higher gas pressure, \( E_{\text{cr}} \rightarrow 100 \) V/m to 250 V/m \( \rightarrow \) no excitation of waves
- here, the sphere's electric field is strong enough to bring total electric field over the threshold in vicinity of self-excited waves (also, there is a density increase due to compression by sphere)
- the wave fronts bent towards cavity, similar as towards a rod [7]

**Conclusions**

- interaction between metal spheres and microparticles in plasma
- cavities in the microparticle cloud around the spheres, caused by ion drag, pressure force by the other microparticles, and electric force
- when moving in the void, spheres attract microparticles (due to the ion drag force) at intermediate distances, forming bubbles with effective surface tension
- the spheres extend the region where microparticle waves are excited, and bend the wave ridges

**References**