Observation of metallic sphere – complex plasma interactions in microgravity

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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

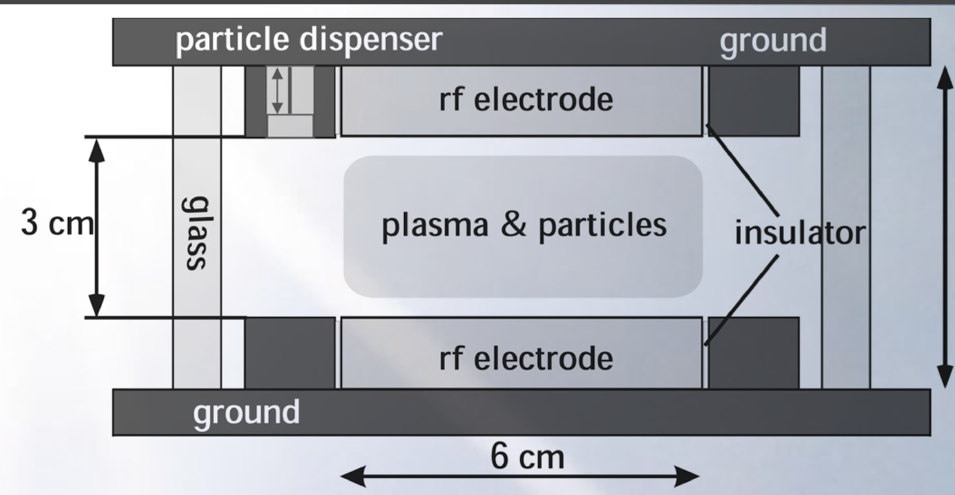
Microgravity is essential for this project.

- under influence of gravity, microparticles fall to sheath where they are suspended by electric field
- metallic spheres would not be trapped in plasma at all

→ microgravity essential for study of interaction

We use the PK-3 Plus Laboratory on board the International Space Station.

- PK-3 Plus Laboratory on board the International Space Station
- capacitively coupled plasma chamber, filled with argon
- microparticles injected with dispensers, illuminated with laser sheet, motion recorded with cameras (frame rate: 50 fps)



Forces Acting on the Spheres

The sphere motion is dominated by inertia.

- sphere mass: $m_s = 4.1 \times 10^{-6}$ kg
- sphere radius $R = 0.5$ mm
- typical velocity: $v_s = 30$ mm/s
- stopping sphere from v_s during $\Delta t = 1$ s would require force $F_s = m_s v_s / \Delta t = 120$ nN
- Reynolds number: $Re = 2R\rho v_s/\mu$ (ρ: gas mass density) low → laminar flow of gas around sphere
- see Table for experiment parameters

The drag forces are negligible.

- Knudsen number $Kn = \lambda_{mfp}/R$ (mean free path of gas atoms / sphere radius)
- transitional regime between free-molecular ($Kn \gg 1$), continuum ($Kn \ll 1$) regimes
- Stokes drag: $F_d \propto v_s$, correction for slip
- $\mathcal{O}(F_d) = \mathrm{nN} \ll F_s$
- drag due to viscosity and friction of microparticle fluid [1]: $F_{add} \sim 0.3$ nN $\ll F_s$

Sphere charge estimated with rule of thumb: $Q_s \approx 1400\, T_e|_{eV}\, a|_{\mu m}\, e \approx 1.8 \times 10^6$ e [2]

Experiment parameters

Exp.	p (Pa)	v_s (mm/s)	Kn	Re (10^{-4})	F_d (nN)	n_e (10^{14} m^{-3})	d_d (µm)	n_d (10^{10} m^{-3})	q_d [a] (e)	H	c_d (mm/s)
(1)	30.0	26.2 ± 1.2	0.5	5.5	3.5 ± 0.3	5	6.8	1 [b]	11000	0.2	5.8
(2)	29.0	34.3 ± 1.1	0.5	6.9	4.6 ± 0.3	5	3.4	6 [b]	5200	0.6	16.0
(3)	29.3	50.8 ± 12.5	0.5	10.4	7 ± 2	5	3.4	4 [b]	5400	0.4	14.0
(4)	15.5	6.0 ± 1.3	0.9	0.65	0.6 ± 0.2	3	3.4	30 [c]	3600	2.6	19.0
							6.8	20 [c]	6600	4.4	9.3

Table: Experiments (1) Simple interaction, (2) Bubbles, (3) Repulsive attraction, and (4) Exciting waves, spheres interaction with microparticles of diameter d_d. [a]estimated with drift motion limited theory (DML) [3]; [b]calculated from the position of the first peak of the radial pair correlation function; [c]estimated by counting particles

(1) Simple Interactions between the Microparticles and Spheres

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

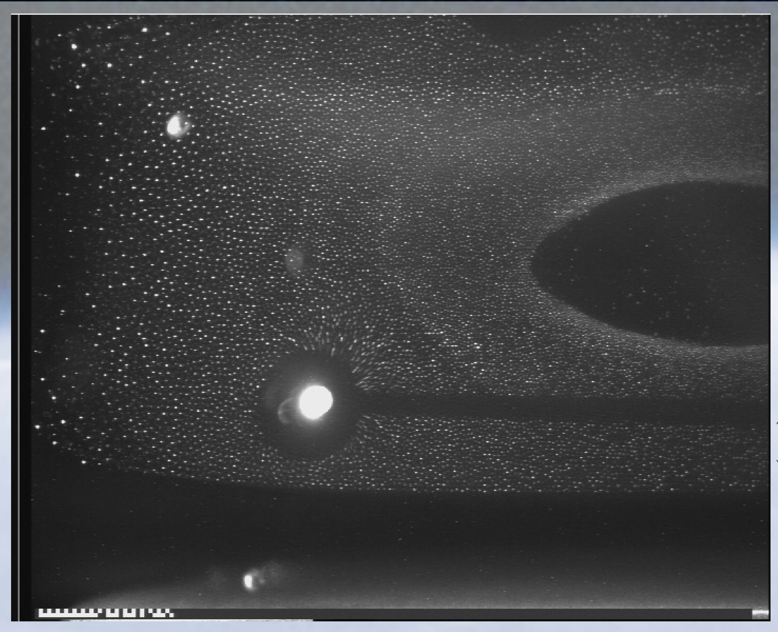


Figure: Side view of microparticle cloud with several spheres. One sphere is moving through the laser plane, casting a shadow on the microparticle cloud. FoV: 35.7 × 26.0 mm².

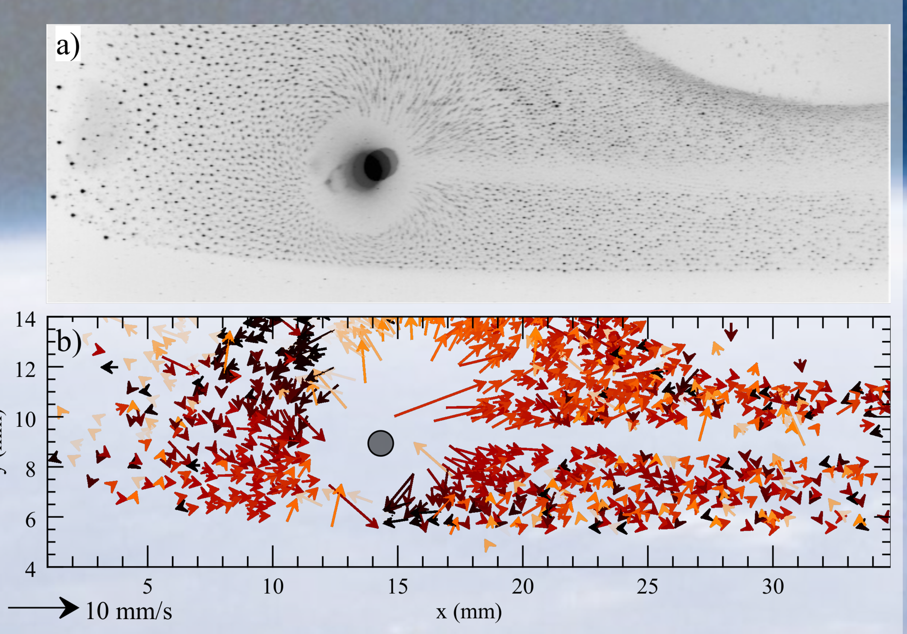
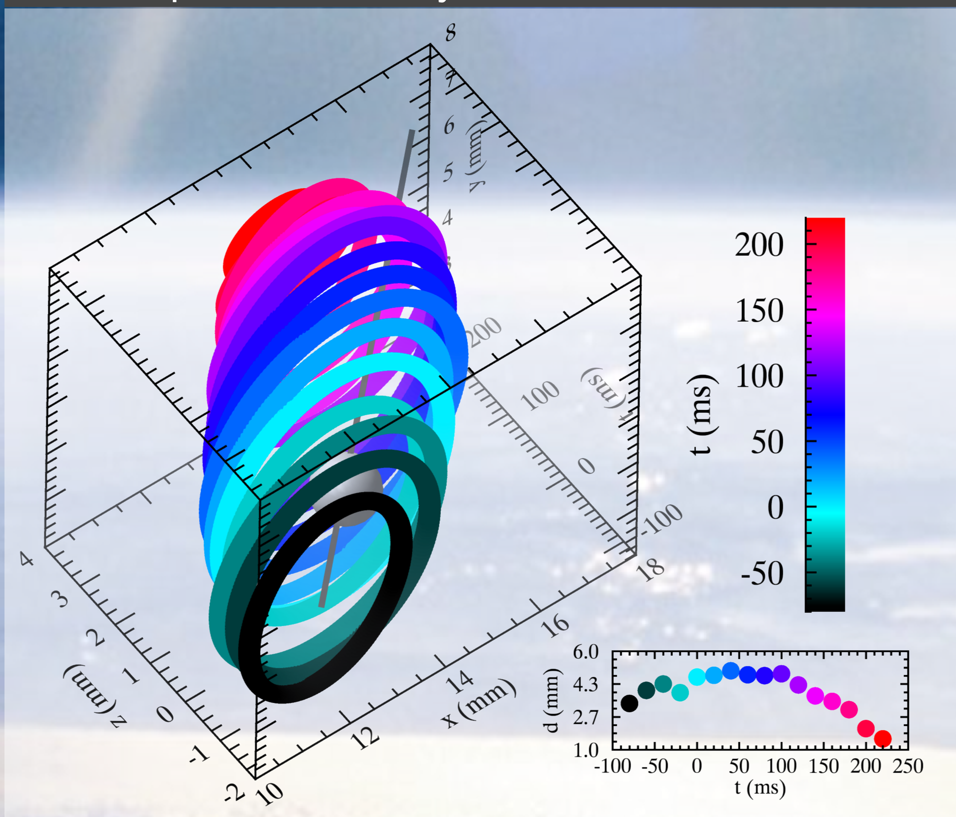


Figure: a) Inverse of superposition of three frames, spanning time interval $\Delta t = 40$ ms, fov: 35 × 10 mm². b) Velocity vectors of microparticles; color codes direction.

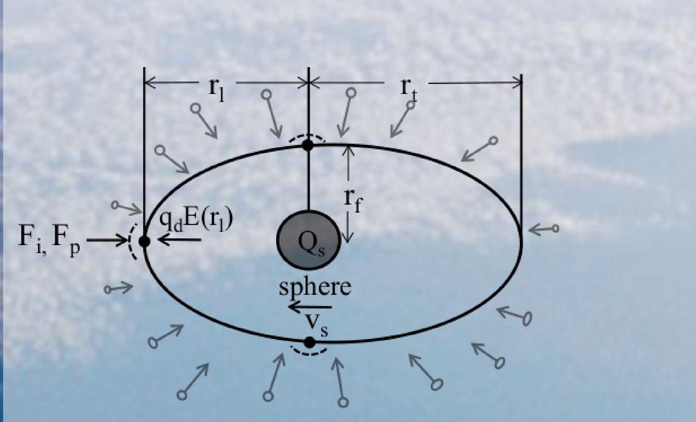
The shape of the cavity can be measured in three dimensions.



- 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 v_z 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 8.4 mm/s (comp. to speed of sound $c_d = 5.8$ mm/s)

Circles: Edge of cavity in laser plane as function of time / z-position. Gray ball and line: sphere position when transversing laser plane ($t = 0$ s) resp. sphere trajectory. Inset: Diameter of cavity projected on laser plane as function of time

The forces approximately balance at the cavity edge.



At the cavity flank: $r_f = 1.8$ mm

$$m_d \frac{d\boldsymbol{v}_d}{dt} = \boldsymbol{F}_p + q_d \boldsymbol{E}(r_f) + \boldsymbol{F}_i = 0$$

directed towards the sphere:

- pressure force
  $F_p \simeq 4\, k_e \frac{q_d^2}{\Delta^2}\left(1 + \frac{\Delta}{\lambda_{Di}}\right) e^{-\Delta/\lambda_{Di}} \simeq 62$ fN
- ion drag force [4]
  $F_i = f(r_d, q_d, n_i, m_i, v_{Ti}, v_i, T_i, T_e, \lambda_{eff})$
  $F_i(r_f) \simeq 110$ fN

directed away from the sphere:

- electric field
  $E(r) = k_e \frac{Q_s}{r^2} e^{-r/\lambda_{De}}\left(1 + \frac{r}{\lambda_{De}}\right)$
  $E(r_f) \simeq 120$ V/m
  $q_d E(r_f) \simeq 210$ fN

(λ_{De} used as screening length inside cavity because of high ion velocity)

At the leading cavity edge: $r_l = 3.0$ mm

$$m_d \frac{d\boldsymbol{v}}{dt} = \boldsymbol{F}_{Ep} + \boldsymbol{F}_p + \boldsymbol{F}_i + q_d \boldsymbol{E}(r_l),$$

assuming that microparticles move with sphere velocity v_s

$$F_{Ep} = m_d \gamma_{Ep} v_s \simeq 360 \text{ fN}$$

$E(r_l) = 6.7$ V/m → $q_d E(r_l) = 12$ fN
$F_i = 5.9$ fN

calculate the distance d over which the microparticle decelerates:

$$F_{Ep} + F_i + F_p - q_d E = m_d \frac{d\vec{v}}{dt} = \frac{m_d v_s < v >}{d} \sim m_d v_s^2/(2d)$$

→ $d = 210$ µm
compare: interparticle distance $\Delta = 270$ µm

(2) Sphere generated bubbles

The spheres cause bubbles in the void.

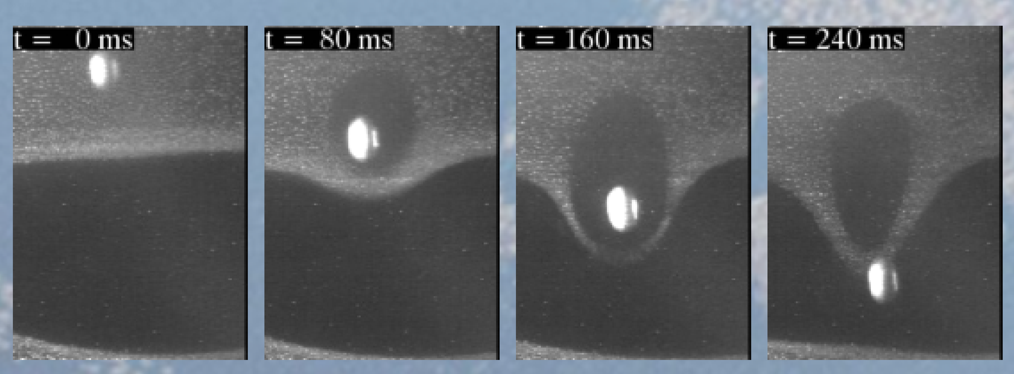


Figure: A bubble forms around a sphere at the void edge. Fov: 6.5 × 8.5 mm².

- bubbles similar as under influence of thermophoresis [5]
- effective surface tension = mass M moved during bubble breakup in time τ, $\alpha \simeq M/\tau^2 \sim 4 \times 10^{-11}$ kg/s² (about 1/2–1/3 of value in [5])
- bubble lid loses cohesion after sphere left

(4) Exciting waves

Spheres excite waves in the vicinity of self-excited waves.

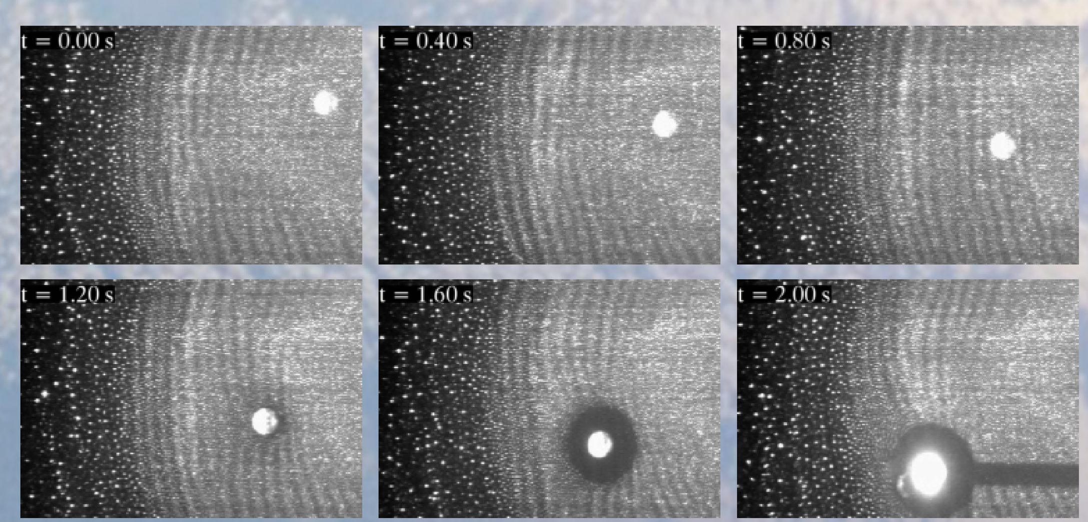


Figure: An approaching sphere excites waves in its vicinity. Fov: 16 × 9 mm².

- dust density waves are excited at low pressure and high dust density
- here, waves appear once a sphere gets close

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 stronger than critical field E_{cr} [6]

$$E_{cr} = \frac{\gamma_{Ep} k_B T_i}{c_d\, |e|} \simeq 80 \text{ V/m}$$

- for experiments (1) – (3) with higher gas pressure, $E_{cr} = 180$ V/m to 250 V/m → 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], which is due to the attraction of the ions to the sphere

(3) Repulsive attraction

Inside the void, spheres effectively attract microparticles.

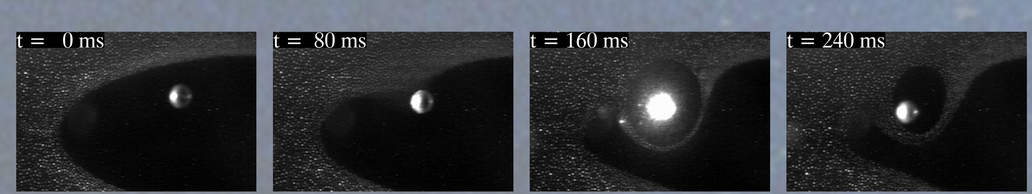


Figure: Negatives of images with fov of 11.9 × 7.2 mm²

- sphere moving inside the void first attracts microparticles, then repels them
- probably due to ion flux towards the sphere

Conclusions

Summary

- interaction between metal spheres and microparticles in plasma
- cavities in the microparticle cloud surround 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 ion drag force) at intermediate distances, forming bubbles with effective surface tension
- the spheres extend the region where microparticles waves are excited, and bend the wave ridges

Outlook

- study excitation of waves and effective attraction in more detail
- compare with previous experiments

References

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