Bubbles, blobs, and cusps in complex plasmas

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Complex plasmas are low temperature plasmas containing microparticles in addition to the ions, electrons and neutral particles. Under most laboratory conditions, the microparticles are charged negatively by collecting electrons from the plasma. They then interact with each other via a screened Coulomb potential, forming, for instance, a crystalline phase [1].

When the microparticles are illuminated with a laser sheet, their positions can be recorded with a conventional camera. This allows tracing the motion of individual microparticles, therefore making possible an investigation on the atomistic level.

In this paper, we present complex plasma experiments on bubbles and blobs such as those shown in Figure 1. *Bubbles* are small, particle free regions (with a “lid”, see Figure 1) that appear in the microparticle fluid below the void. The lid typically consists of up to a few layers of microparticles, which are ejected upwards, and the microparticles are pushed towards the upper part of the cloud. *Blobs* are microparticle droplets which are compressed into nearly

Figure 1: Bubble (lower left) and blob (right) in a complex plasma composed of 6.8 µm MF particles (Argon at a pressure of 18 Pa, temperature difference between upper and lower part of the chamber 64.5 K). Field of view: $23 \times 19\,\mathrm{mm}^2$.

spherical shape when a group of microparticles is pushed into the void. Sometimes, the cloud beneath the void forms tips–*cusps*–pointing upwards.

The experiments were performed in the PK-3 Plus chamber. This radio-frequency (RF) plasma reactor consists of two parallel electrodes of 6 cm diameter with a distance of 3 cm [2]. As buffer gas, usually Argon or Neon at pressures in the range of (10 to 100) Pa is used. Monodisperse melamine-formaldehyde particles of various sizes in the range of (3 to 7) µm are inserted into the plasma and illuminated with laser light spread into a plane. Their motion is recorded with a camera at a frame rate of up to 1000 fps.

As is typical for RF discharges, the microparticles in PK-3 Plus are normally levitated by the strong electric fields in the plasma sheath near the lower electrode. However, it is desirable to perform experiments in the bulk of the discharge, away from the anisotropies and strong fields imposed by the sheaths. The best method to achieve this is to perform experiments in microgravity, for instance on the International Space Station [2]. Under those conditions, a central, particle free region is formed–the void. It is caused by the drag force of the ions streaming from the center of the discharge to the sides of the plasma vessel.

Another way to eliminate the influence of gravity is to compensate it by an equally strong force. This can, for instance, be done by applying a strong temperature gradient between the upper and lower base plate of the vacuum chamber. This induces a thermophoretic force on the microparticles, lifting them into the plasma bulk.

This way, it is possible to adjust the temperature gradient such that particles are levitated in the center of the discharge. Under those conditions, phenomena typical for microgravity can be observed; specifically a central void is formed.

Usually, when the temperature difference is large enough to compensate for gravity, the void boundary is smooth and well defined. In contrast, under certain conditions, an instability and the subsequent formation of bubbles and blobs can be triggered. The first sign of

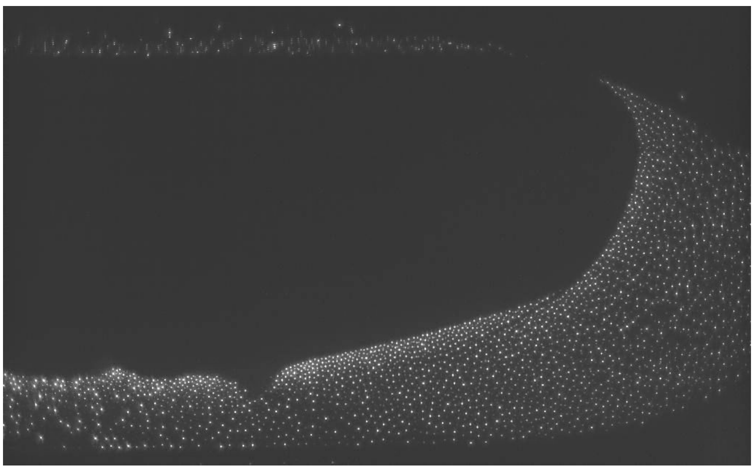

Figure 2: The beginning stage of the instability, recorded with 6.81 µm size MF particles in Argon gas at a pressure of 18 Pa and a temperature difference between the top and bottom of the chamber of 64 K. The field of view is $29\times18\,\mathrm{mm}^2$.

the instability is that the void boundary begins to show indentations, as is shown in Figure 2. Then, microparticles start to move through the void, and bubbles and droplets appear [3, 4]. The instability can be triggered by either increasing the temperature gradient, the pressure or the particle number density, or by lowering the discharge voltage. It can be stopped by the inverse actions.

The velocity of the microparticles moving through the void upwards decreases with rising pressure [3]. This result excludes normal Rayleigh-Bénard convection as the cause of the particle movement, as this convection becomes stronger with pressure.

A mechanism that occurs in refined gases is *thermal creep*. It is present if a temperature gradient is maintained along a surface that is immersed in the gas. This effect induces a gas flow along the surface in the direction of the temperature gradient [5]. In our system, it can cause a convection of the whole gas; upwards in the center and downwards along the vertical glass walls. In order to visualize this gas flow, the plasma was turned off while a temperature difference of 50 K was maintained between the upper and lower part of the chamber. We observed a flow of microparticles to the sides of the chamber and even a reverse of direction close to the side walls, indicating the gas convection.

The influence of this upwards movement of neutral gas in the central part of the plasma vessel is also visible in the paths traced by the microparticles in the void. As mentioned above, they are accelerated upwards inside the void. Also, the streamlines of microparticles inside blobs show distinct vortices. An example is shown in Figure 3, where the streamlines are visualized using the method of line integral convolution [6]. The particles move upwards on the edges of the blob and downwards in the center.

Figure 3: Streamlines traced by particles inside a blob [4].

This movement reminds of that of water molecules inside small drops in an air stream–drops with diameters as small as nanometers, as the number of particles in our blobs is only 10^3 to 10^4. The dimensionless number relevant for the scaling of multiphase flows is the *Weber number*

$$\mathscr{W} = \frac{\rho v^2 l}{\sigma}, \quad (1)$$

where ρ is the fluid density, v its velocity, l the characteristic length, and σ the surface tension. The Weber number gives the ratio of inertia forces to surface tension forces. Estimating it in our case results in $\mathscr{W} \sim 100$, which is well within the typical range of the break-up of water drops.

The origin of the instability can be described theoretically by considering that the void boundary is normally stabilized by the drag force of the ions streaming from the discharge center to the walls. When the discharge power is lowered, the ion flux becomes very weak. The acceleration of the microparticles upwards into the void may then lead to the development of a Rayleigh-Taylor instability. In our case, this occurs in comparatively thin membranes in the particle fluid beneath the void. Therefore, the dispersion relation applicable to the "deep-water regime" can be used to describe the instability [3]

$$\omega^2 + i\gamma_{\mathrm{Ep}}\omega = -\tilde{g}k + (\sigma/\rho)\,k^3, \tag{2}$$

where ω denotes the frequency, γ_{Ep} the coefficient of the drag force exerted on the microparticles when they move through the gas, $\tilde{g}$ the acceleration caused by the destabilizing forces, k the wave number, σ the surface tension, and ρ the mass density of the microparticle cloud. By measuring the growth rate of the instability, the surface tension can be estimated as $\sigma \sim 10^{-10}\,\mathrm{N\,m^{-1}}$. In comparison, we estimated the surface tension by considering the break-up of a bubble and measuring the mass transported during the time needed for the break-up. The result agrees with that obtained from the dispersion relation by order of magnitude, demonstrating that the Rayleigh-Taylor model is feasible.

In conclusion, we present an investigation of microparticle bubbles and blobs in complex plasmas under the influence of gas convection induced by a temperature gradient. The bubbles and blobs can be considered as models for nanometer-sized water drops, and the instability mechanism can be described in terms of the Rayleigh-Taylor instability, demonstrating that this hydrodynamic mechanism is still applicable even in systems with few particles.

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