Convective Dust Clouds Driven by Thermal Creep in a Complex Plasma

S. Mitic, R. Sütterlin, A. V. Ivlev H. Höfner, M. H. Thoma, S. Zhdanov, and G. E. Morfill
Max-Planck-Institut für extraterrestrische Physik, D-85741 Garching, Germany
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Steady-state clouds of microparticles were observed, levitating in a low-frequency glow discharge generated in an elongated vertical glass tube. A heated ring was attached to the tube wall outside, so that the particles, exhibiting a global convective motion, were confined vertically in the region above the location of the heater. It is shown that the particle vortices were induced by the convection of neutral gas, and the mechanism responsible for the gas convection was the thermal creep along the inhomogeneously heated tube walls. The phenomenon of thermal creep, which commonly occurs in rarefied gases under the presence of thermal gradients, should generally play a substantial role in experiments with complex plasmas.

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Convective motion of dust particles in complex (dusty) plasmas is a phenomenon that is often observed in very different experimental conditions. In particular, vortices in complex plasmas can be produced both in ground-based laboratories and under microgravity conditions, in dc and rf discharges of fairly different configuration, upon inhomogeneous heating, and in rather isothermal environments [1].

There are many publications, both theoretical and experimental, in which the origin of the vortex motion in complex plasmas has been investigated [2–11]. Basically, there are several mechanisms that can produce vortices: This can be due to the presence of nonpotential force(s) exerted on charged dust particles in the discharge (caused by inhomogeneous charges [7] or ion drag [9]), because of the convective motion of the background neutral gas or microparticles themselves [12], or due to a dissipative instability [10,11], affecting dust rotations with angular velocities decreasing with pressure [10,11]. This clearly indicates that the nature of such vortices—despite a quite similar appearance—might be very different.

In this Letter, we report on a recent series of experiments performed in a low-frequency glow discharge under gravity. We investigate the convective motion of dust particles in the presence of an external controllable heating and unambiguously show that under such conditions vortices in complex plasmas occur due to the neutral gas convection, with clouds of microparticles resembling convective clouds in the atmosphere (produced from, e.g., warm air pockets rising upwards and composed of water droplets, ice crystals, ice pellets, etc.). An important conclusion of our research is that the neutral gas convection is triggered by the *thermal creep*. This phenomenon occurring in rarefied gases under inhomogeneous heating is very different from conventional (Rayleigh) mechanisms for convection. We suggest that the thermal creep can be an essential factor in determining steady-state configurations of complex plasmas.

The experiments were conducted in a complex plasma produced by a low-frequency discharge in neon gas (with constant pressure between 30 and 100 Pa) of the PK-4 facility [13,14]. The plasma chamber consists of an elongated glass tube as shown in Fig. 1.

A gas discharge was maintained between the electrodes by a regulated discharge current of 1 mA. The discharge voltage polarity was changed with a frequency of 1 kHz (50% duty cycle). This frequency is more than an order of magnitude higher than the dust-plasma (response) frequency [1], so that the effective longitudinal force on microparticles (electric plus ion drag) vanishes.

In the course of the experiments, dust particles (spherical melamine-formaldehyde particles with a mass density of $1.51\ \mathrm{g/cm^3}$) of two different radii $r_p = 1.64$ or

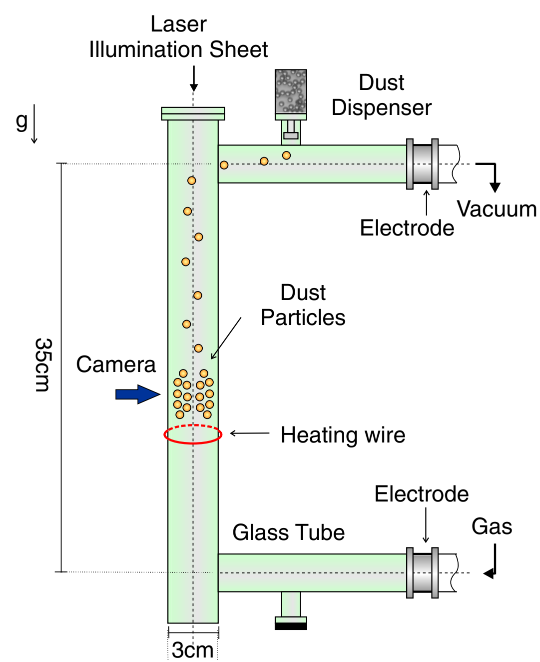

FIG. 1 (color online). Experimental setup.

3.05 μm were injected by a dispenser from above into the plasma and confined inside the vertical glass tube. The dust particles were illuminated along the tube axis by a laser sheet (wavelength 686 nm, power 20 mW, thickness 100 $\pm$ 30 μm, and width 15 mm), and the images were recorded by a PCO 1600 camera.

A metal wire (alloy of 70% Ni, 11% Fe, and 14% Cu and 0.5 mm in diameter) was put around the lower part of the tube to produce a temperature gradient. A dc current between 0.5 and 1.8 A was applied to this wire using a 10 V power supply. For avoiding unwanted electromagnetic effects on the plasma, only one loop of the wire (one-turn coil) was attached. The wire was insulated electrically (but not thermally) against direct contact to the tube walls.

Because of the gas temperature gradient, a thermophoretic force acts on the dust particles [15]:

$$\mathbf{F}_{\rm th} = -\gamma_{\rm th}\nabla T_n, \qquad (1)$$

where $\gamma_{\rm th}[{\rm N\,cm/K}] \simeq 2.17 \times 10^{-6}(r_p[\mu{\rm m}])^2$ [16]. The thermophoretic force required to levitate particles is $F_{\rm th} = m_p g \simeq 2.74 \times 10^{-13}$ N for the smaller ones and $\simeq 1.76 \times 10^{-12}$ N for the larger ones (m_p is the particle mass). According to (1), temperature gradients of $|dT/dz| \simeq 4.65$ K/cm for the smaller particles and $\simeq 8.64$ K/cm for the larger ones are required to compensate gravity.

The measured temperatures along the tube and the temperature gradients are shown in Fig. 2, where $z = 0$ is the position of the heating wire. It turns out that the maximum values of the temperature gradients are smaller than those necessary for thermophoretic levitation. Nevertheless, we observe that the particle cloud is confined in the area above the heating wire. Figure 3 shows vertical cross sections through the center of the clouds obtained for different pressures. As pointed out above, plasma forces cannot be responsible for this effect: Because of the fast polarity switching, neither an electric force nor an ion drag force [17] could support the levitation.

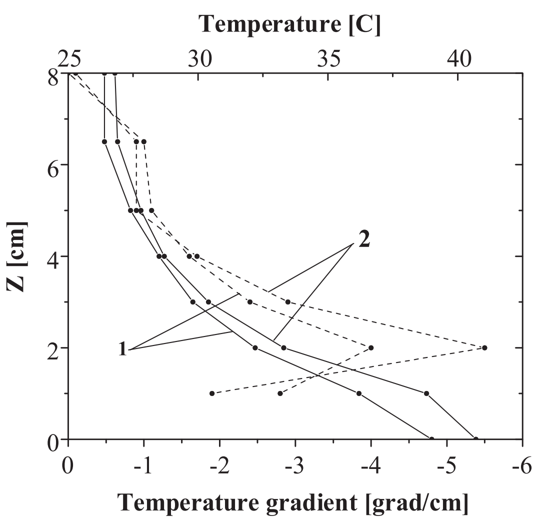

FIG. 2. Measured temperatures (solid lines) and calculated temperature gradients (dashed lines) for particles of (1) $r_p = 1.64$ μm and (2) $r_p = 3.05$ μm.

The dust particles are frictionally coupled to the neutral gas. Therefore, it is natural to assume that the intense convective motion of the particles seen in Fig. 3 is induced by the gas motion, which, in turn, is triggered by the local tube heating. Favorably directed, the gas convection could result in a global dust rotation and also contribute to the levitation of the particles, in addition to the thermophoresis. (Note that $\mathbf{F}_{\rm th}$ alone cannot cause the convection, because it is a potential force: $\nabla \times \mathbf{F}_{\rm th} \equiv 0$.)

The neutral drag force acting on a spherical particle is [18]

$$\mathbf{F}_n = \gamma_n(\mathbf{v}_f - \mathbf{v}_p), \qquad (2)$$

where $\mathbf{v}_f$ is the velocity of gas flow, $\mathbf{v}_p$ is the particle velocity, and the Epstein friction coefficient for neon at room temperature reads $\gamma_n[{\rm N\,s/cm}] \simeq 2.7 \times 10^{-16}(r_p[\mu{\rm m}])^2 p[{\rm Pa}]$.

Note that the radial electric field of discharge exerts an additional force F_r [19] which confines the particle cloud in radial direction. We observed that the dust particles after switching off the discharge expand across the tube, and particles keep rotating one or two cycles before eventually falling down.

In order to verify the hypothesis of the neutral gas convection as the principal mechanism responsible for the observed particle dynamics, we will analyze in detail one of our experiments performed with 3.05 μm particles at a pressure of 50 Pa.

As the first step, we determine the velocity field $\mathbf{v}_f$ of the convective gas flow and the radial electric force F_r. The particle motion is recorded at a frame rate of 500 frames/s in the course of the experiment comprising two separate cases: with and without plasma. The particles are detected in each frame, and then, based on the position of each particle in a few consecutive frames, their velocities and accelerations are extracted. Based on these data, the particle velocity profiles are reconstructed in the entire cloud. Particle velocities and accelerations are derived by fitting cubic splines to the complete particle trajectories.

The dynamics of individual particles (assuming weak interparticle interaction) is determined by the balance of forces:

$$m_p\ddot{\mathbf{r}} = \mathbf{F}_{\rm th} + \mathbf{F}_n + \mathbf{F}_r + m_p\mathbf{g}. \qquad (3)$$

To separate the remaining unknown forces—the radial electric force and the neutral drag force—appearing in Eq. (3), we analyze first the data when no plasma was in the tube, and, hence, no radial electric force ($F_r = 0$) acts on the particles. This allows us to get the velocity field of the conveying gas molecules. With this information and assuming that switching on and off the plasma does not alter the gas convection, we calculate the radial electric force of the plasma in the region where particle trajectories recorded with and without plasma overlap, as shown in

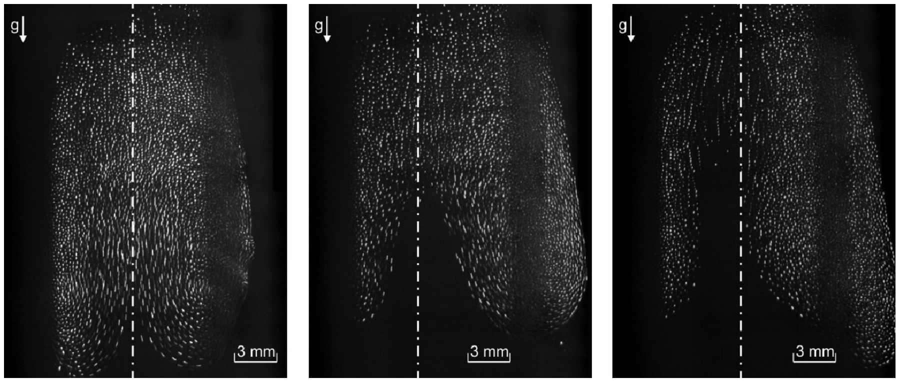

FIG. 3. Dust clouds of $r_p = 1.64$ μm particles at pressures of 30, 50, and 100 Pa (from left to right). The vertical dashed-dotted lines indicate the center of the tube. The field of view is 21×26 mm.

Fig. 4. In Fig. 4(a), the particle cloud in the presence of the plasma is a bit higher and further away from the tube wall. After switching off the plasma [Fig. 4(b)], particles come closer to the wall and the cloud expands further down. For the overlapping region, any differences in the particle motion between the cases with and without plasma must be due to electrical forces, since neither the temperature distribution nor the gas velocity field are affected by the discharge.

Figure 5 shows the velocity field of the gas convection as calculated for the case without plasma. The particle trajectories are overplotted. The distribution of flow velocities has a clear rotational tendency. Since the neutral drag force on the particles depends on the relative velocities of the particles and gas, the particles do not follow the gas flow but rotate eccentrically from the center of gas convection in the area of upward gas draft.

The radial force on the particles when plasma is on can now be fitted using the gas flow velocities in the overlapping region. Figure 6 shows that the radial force is zero at the tube axis and rapidly increases towards the tube walls.

The results obtained above clearly demonstrate the presence of gas convection. This is not free convection, though, merely because the onset of free convection is too high in terms of the critical Rayleigh number to cause gas flow under the conditions of our experiments. It is well known, however, that if one puts a nonuniformly heated body in a rarefied gas, the gas starts moving along the body *in the direction* of the temperature gradient [20–22]. This phenomenon is referred to as *thermal gas creep* (or *thermal gas slip*). It was predicted theoretically by Maxwell [23] and verified experimentally by Reynolds [24] and is governed by the relation

$$V_{\mathrm{TC}} = K_{\mathrm{TC}} \nu \nabla_{\parallel} \ln T_W, \tag{4}$$

where V_{TC} is the velocity of creep at the body surface, ν is the kinematic viscosity of the gas, T_W is the temperature of

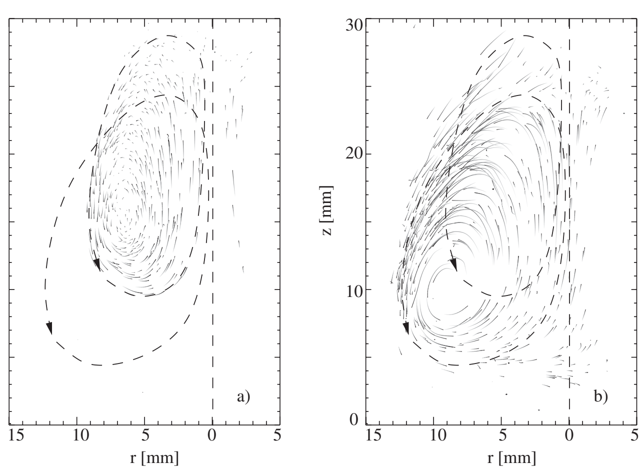

FIG. 4. Convective dust clouds of $r_p = 3.05$ μm particles at a pressure of 50 Pa for cases (a) "plasma on" and (b) "plasma off." The shape of the cloud and direction of the rotation in the "on" and "off" cases are indicated by the upper and lower loops, respectively, and their overlap shows the region used for the reconstruction of radial electric force (see Fig. 6). The vertical dashed lines show the center of the tube.

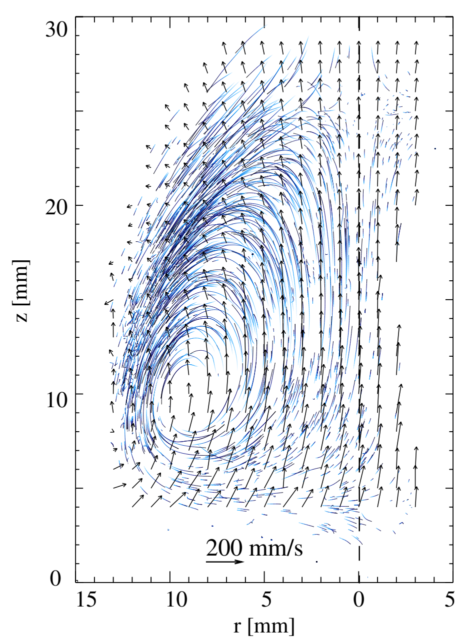

FIG. 5 (color online). Averaged gas flow velocity field (vectors) superimposed with particle trajectories. The vertical dashed line indicates the center of the tube.

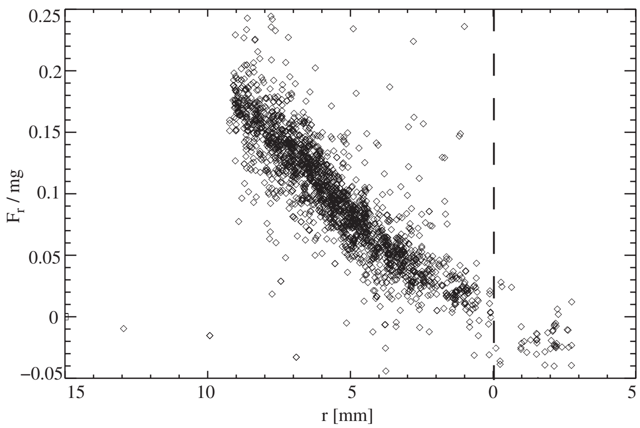

FIG. 6. Reconstructed radial force for the overlapping region. The vertical dashed line indicates the center of the tube.

the heated body, i.e., the glass walls in our case, and $\|$ indicates the component of the gradient along the surface. For a long tube, the radial distribution of the (longitudinal) velocities is well known: $v_z = V_{TC}(2r^2/R^2 - 1)$ [22]. In our geometry, the vertical temperature gradient is negative: $dT_W/dz < 0$ (see Fig. 2). Hence, the gas should flow downwards along the tube walls with $v_z(R) = V_{TC}$ and upwards near the tube axis with $v_z(0) = -V_{TC}$, which is in agreement with our observations (see Fig. 5). For a quantitative comparison with the experiment, we rewrite Eq. (4) in the following form: $K_{TC} = |V_{TC}/\nu\nabla_z \ln T_W|$. Based on the experimental data shown in Figs. 2 and 5, we get $K_{TC} \simeq 1$, which coincides with theoretical expectations (K_{TC} should be in the range of 0.7–1.2 [21]). Moreover, the magnitude of the convection velocity decreases monotonically with pressure, which is also in line with theory: Combining Eqs. (3) and (4), we obtain that the velocity should scale as $\propto p^{-1}$, which is in good agreement with our measurements shown in Fig. 7. (Note that the conventional Rayleigh mechanism predicts the opposite tendency, when the velocity increases with pressure.)

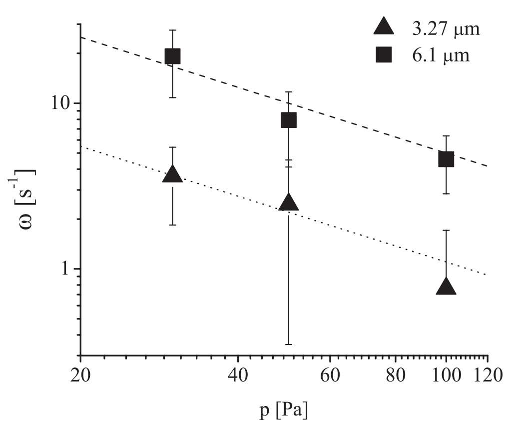

FIG. 7. Angular velocity (vorticity) of the rotating particles versus gas pressure The dashed line $\omega[\mathrm{s}^{-1}] = 500(p[\mathrm{Pa}])^{-1}$ and the dotted line $\omega[\mathrm{s}^{-1}] = 110(p[\mathrm{Pa}])^{-1}$ indicate a dependence proportional to p^{-1} of the cloud vorticity.

In conclusion, we observed steady-state particle clouds levitating in a vertical glass tube, above a heated wire. The particles exhibited a global convective flow. We showed that the particle vortices were induced by the convection of neutral gas, analogously to convective clouds in the atmosphere. The mechanism responsible for the gas convection was the thermal creep along the inhomogeneously heated tube walls. The phenomenon of thermal creep, which commonly occurs in rarefied gases under the presence of thermal gradients, has never been taken into account in experiments with complex plasmas. We believe that this phenomenon should generally play a substantial role in the experiments, because (i) the resulting convection can be triggered in the absence of gravity, (ii) it operates in the pressure range typical for complex plasmas, and (iii) it does not require substantial temperature gradients and hence might be triggered due to natural temperature inhomogeneities always present in experiments.

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