Circulation’ dynamo in complex plasma

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Abstract. In ground based experiments (performed in Ar using a radio frequency (rf)-discharge), we observe the interaction of individual agglomerated particles with a monodisperse (bulk) complex plasma cloud containing (melamine-formaldehyde (MF)) microparticles of 7.17 µm ± 3% diameter. The particles are levitated by thermophoresis. For this purpose, a gas temperature gradient of 2000 K m⁻¹ is applied. The particle cloud has a complicated ‘sandwich-like’ vertical structure of two dense slabs (filled by particles), separated by a void, a central particle-free region. The void is impenetrable for small particles, but not for heavier and/or accelerated agglomerates, which may slide through the entire void and therefore can be used as natural test particles for determination of the force acting inside the void. The bulk particles remain in quasi-equilibrium for a long time and are dynamically active, e.g., intense edge rotations (vortices) and nonlinear vertical waves. We traced particle motions in detail and studied the correlation of particle vibrations inside the clouds and the motion of agglomerates and/or accelerated particles penetrating through the void. A possible physical explanation of the cloud’s activity is based on the assumption that the phenomenon can be considered as a consequence of the non-Hamiltonian character of complex plasmas.

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1. Introduction

Complex plasmas are multi component systems. Their dynamical behaviour is strongly dependent on the number of components. Another problem is the complexity of the equations used for their description. The microparticles induce a dynamical pattern of new quality. For instance, the suspended micro-particle component in a weakly ionized plasma (normally consisting of electrons, ions, and neutral gas atoms (as a background)) reveals a new state of matter—a complex plasma—which has the ability to crystallize showing phase transitions [1]–[4].

Investigations carried out in the past decade have shown that complex plasmas can serve as powerful tools to study a variety of phenomena at the kinetic level: wave excitations [5]–[9] (for details see, e.g., [10]); viscosity [11], heat transfer [12], diffusion [8], [13]–[15] parametric and other instabilities [17]–[22].

Space complex plasmas (Saturn rings, for example [23]), complex plasmas under microgravity conditions [24]–[26] and in laboratory experiments, such as plasmas in radio frequency (rf)-discharges [17], nuclear excited plasmas [27], plasmas in shock discharges into air [28] and plasmas produced by proton beams [29] also reveal the ability to create and self-sustain large-scale dynamical structures, such as global rotations [17, 26], [30]–[33]. The origin of these different activities is still an open issue.

In [17] a stable vortex flow was observed and was explained by the introduction of an artificial driving force. In [24] the ion drag force was considered as the main force inducing particles to circulate. In [26] the rotation was claimed to be due to the presence of a particle charge gradient and a non-electrostatic force (such as gravity, thermophoretic force, or ion drag force). These studies show that with the assumption of an ion drag force, small gradients of dust charges can provide dust vortex formation in microgravity and large-scale dust rotation. The influence of the thermophoretic force was not studied. (No special gas heating was applied in these experiments.)

In [30] it was claimed that ‘the generation of the vortices can be ascribed to a nonzero rotation of the net global force vector field, which is the sum of the ion drag force, the electric force and the thermophoretic force’. In [31] it was discussed that the excitation of gravitation induced Rayleigh–Taylor-like instability for a charged dust cloud arises as a result of inverse stratification of the dust mass/number density. This is, evidently, not the universal situation in...
experiments (in microgravity, for instance). In [32] it was assumed that the vortices are excited due to the voids, whereas in [33] they are due to the shear instability. The latter, evidently, may not explain the global structure rather than the set of local vortices of a size of a shear in the same way as in the stratified atmosphere of Jupiter.

In laboratory experiments, where thermophoresis counteracts gravity [17, 34], (and the given study below) it seems natural to explain the dust rotations by considering gas convection [35]. Unfortunately, in the Rayleigh–Benard convection in a classical fluid [36] and its compressible modifications [37], the critical Rayleigh number for the onset of gas convection in a several centimetre thick layer at low gas pressures (10–100 Pa) is too big. However, an interesting source for convection comes from the physics of so-called granular gases [38]: classical fluid convection requires an externally imposed temperature gradient opposite to gravity. In a vibrofluidized granular medium, a negative temperature gradient sets in spontaneously, because of the energy loss by inelastic collisions. Convection develops when the absolute value of the temperature gradient is large enough. This process links the thermal instability of the dust cloud with the particle vibrations (or waves). There are some problems with this analogy, however. It is not clear whether the dust cloud can be treated as a granular medium or not, and the experiments performed in our study have shown that edge circulations are activated without any noticeable wave or vibration activity in the main cloud. Hence, in complex plasmas, these phenomena may differ in origin.

In this paper, we focus our attention on the physical mechanism of particle rotations, which we have termed ‘a circulation’ dynamo’. It has been observed and investigated for the first time at the kinetic level in laboratory experiments in a dusty plasma, where gravity was compensated by an opposite temperature gradient. A possible physical explanation suggests that the phenomenon can be considered as a consequence of the non-Hamiltonian character of complex plasmas [39]–[41].

2. Observation conditions

The experiment was carried out in the PK-3 Plus rf plasma chamber, under conditions similar to that in [17, 34] at low gas pressure (Ar, 16 Pa). Additionally, thermophoresis was used to compensate gravity. The installation allows us to perform experiments in a wide range of parameters (gas pressure, temperature gradient, particle contamination, etc). Detailed investigations will be published elsewhere.

Here, we focus on a particular case which is most suitable for the main aim of this study. Melamine-formaldehyde (MF) microparticles are injected into the discharge chamber, where they self-organize in a complicated ‘sandwich-like’ vertical structure of two dense clouds separated by a void and a central particle-free region (see figure 1). For particle levitation, a gas temperature gradient of 2016 K m$^{-1}$ was applied (the upper electrode was kept at 27 $^\circ$C, the temperature difference between the lower and upper metal electrodes is $\Delta T = 61.5$ $^\circ$C, the distance between the electrodes is 30.5 mm). The particles are visualized with reflected light from a laser sheet, which illuminates a vertical plane of $\sim 100 \mu$m thickness through the chamber axis. The cloud’s dynamics was recorded with a charge-coupled device camera at a rate of 17.34 Hz. Size, form and position of the void changed when the discharge parameters and temperature gradient were changed (for details, see [17, 34]).
Figure 1. Particles inside the clouds, edge vortices, vertical waves and ‘void-penetrator-particles’ are shown as a superposition of 42 colour-coded images consecutive in time (colour varies from dark blue, light blue, green, yellow to red). The size of the field of view is $42.9 \times 56.7 \, \text{mm}^2$. Only particles within the vertical $\sim 100 \, \mu\text{m}$ laser sheet are visible. The penetrators are shown as relatively long multi-coloured ‘streaks’, whereas the strongly coupled particles in the cloud appear round. This shows that these particles are practically immobile during the total observation period of $\sim 2.5$ s. Circulations with closed (or quasi-closed) particle trajectories concentrate at the edges of the bottom cloud. The experiment conditions are: gas Ar at 16 Pa, 7.17 $\mu\text{m}$ MF particles, $\Delta T = 61.5 \, ^\circ\text{C}$, electrode separation $\Delta y = 30.5$ mm.

Under certain conditions the lower part of the cloud became ‘vertically’ unstable and density waves were self-excited and propagated through the cloud. Normally, wave propagation is accompanied by particle rotations, localized at the edges of the cloud. For the chosen conditions, these features are well pronounced and suitable for registration. This is illustrated in figure 1. We superimposed and colour-coded 42 consecutive images to demonstrate the particle motion. Rotating particles are visualized as two large circulations separated by a slab of oscillating, but not rotating particles, through which vertical waves propagate. (The waves can be seen in the figure as two long parallel strips slightly curved at the edges). Rotating particles (‘true circles’ with closed flow lines and constant angular velocity) and vibrating particles (‘a stagnation zone’) are separated from each other by a transition zone of an angular velocity gradient. The top boundary of the bottom cloud is surprisingly flat (probably because this corresponds approximately to the chamber centre). In the upper layer of this cloud, the particles vibrate a little; the mean particle separation is 300–400 $\mu\text{m}$. The top cloud is curved at the edges to a layer of one to two particles in width revealing the void geometry.

The void is impenetrable for all low energy particles of the main complex plasma cloud. Heavier agglomerates and accelerated particles can penetrate through the void. In figure 1, their trajectories can be seen as vertical dashed lines connecting top and bottom clouds. These agglomerates and accelerated microspheres are natural test particles for the investigation of the
force distribution inside the void \cite{42}. The source of penetrating particles is at the top $\sim 8$ mm above the boundary of the lower cloud.

3. Dynamical parameters of the particle clouds

It is convenient to summarize the main parameters of the particle clouds separately, because we will refer to these estimates throughout the whole paper. The size, mass density and mass of a particle are

\[ a = 3.59 \mu m, \quad \rho = 1.51 \text{ g cm}^{-3}, \quad M = 2.9 \times 10^{-10} \text{ g}. \]  \hspace{1cm} (1)

For Argon at a gas pressure of 16 Pa the Epstein drag coefficient \cite{43} is

\[ \gamma = 26.5 \text{ s}^{-1}. \]  \hspace{1cm} (2)

It defines the friction force according to the relationship

\[ F_{fr} = -M\gamma V, \] \hspace{1cm} (3)

where $V$ is the particle velocity (relative to that for gas atoms). The thermophoretic force can be estimated as

\[ F_T = \alpha \frac{dT}{dy}, \quad \alpha = 3.33ka^2/\sigma, \] \hspace{1cm} (4)

where $a$ is the particle size, $k$ is the Boltzmann coefficient, $dT/dy$ is the temperature gradient and $\sigma$ is the corresponding gas kinetic cross-section \cite{34}. (The numerical coefficient in this relationship was verified in \cite{34} experimentally.) For our conditions ($dT/dy = 61.5 \text{ K}/30.5 \text{ mm} = 2016 \text{ K m}^{-1}$) it yields

\[ F_T = 2.83 \times 10^{-7} \text{ dyne}. \] \hspace{1cm} (5)

The equilibrium of clouds is determined mainly by a balance of gravity and thermophoretic force

\[ F_T \approx Mg = 2.86 \times 10^{-7} \text{ dyne}. \] \hspace{1cm} (6)

This result is valid for the particles which concentrate on top of the lower cloud, where the discharge electric field is weaker. Further down, deeper in the cloud, the external electric field enhances and strongly affects the cloud structure.
Figure 2. Regular waves in the cloud. Shown are five panels, which were obtained by superposition of eight images, temporally displaced by $2/17.34 \text{s}$ to demonstrate the propagation. The top of the cloud is almost motionless; the bright horizontal strips below demonstrate propagating waves.

4. Regular density waves in the bulk of the cloud

Experiments with heavier particles are convenient because in this case it is easier to visualize the regular periodic motions and rotations, because the corresponding velocity is smaller.

After a critical temperature gradient is established, intense self-excited waves propagate through the cloud. They can be clearly seen in individual still pictures and their traces can be visualized in superimposed images (figure 1).

To investigate these waves, we introduced a simple image filter, which is based on the assumption that the images repeat periodically, because the waves are regularly propagating. In a set of two images from a sequence, repeatable elements would be contrasted (and non-periodic ones would dissolve), when the images are superimposed and renormalized. The contrast of repeatable details depends on the number of superimposed images. The result of this procedure is shown in figure 2.

After some calculations, we obtain the wavelength $\lambda$, the frequency $\nu$ and the phase velocity $V_{ph}$ from the data

$$\lambda = (2.2 \pm 0.4) \text{ mm}, \quad \nu = (2.1 \pm 0.3) \text{ Hz}, \quad V_{ph} = (4.6 \pm 1.6) \text{ mm s}^{-1}. \quad (7)$$

In order to prove the periodicity, each 7th and each 9th image from the same image sequence was superimposed. The results confirmed that the periodic structures were dissolved.

5. Circulating particles

Since the particle clouds are extremely dense, and rotating particles vibrate quickly, only a few single particle trajectories could be traced (see figure 3(a)). First, we suppose that these particles go through similar stages, and their trajectories form a family of a simple fabric. We plotted the so called pedal curve, which was introduced first by Colin MacLaurin (1718), who first studied this group of curves [44] for the trajectories shown in figure 3(a). Surprisingly, it turns out to be a simple circle (figure 3(b)). Plotting the velocity profiles also supports this idea (figures 3(c) and (d)). Simple fitting allows a quantitative characterization.
Figure 3. Particles inside the vortices: (a) examples of trajectories, (b) pedal curve corresponding to the circling particles, and particle velocities: (c) vertical component $V_y$ versus horizontal position $x$, and (d) horizontal component $V_x$ versus vertical position $y$, demonstrating the rotations. Cross ($x_c = 7.47$ mm, $y_c = 19.14$ mm) marks the position of the rotation centre (the latter is determined by the relationships: $V_x = 0$, $V_y = 0$). Dashed lines are the results of the least squares fit: (b) $(x - x_0)^2 + (y - y_0)^2 = R^2$, $x_0 = 3.04$ mm, $y_0 = 9.66$ mm, $R = 10.23$ mm; (c) $\delta V_y/\delta x = -0.62$ s$^{-1}$, (d) $\delta V_x/\delta y = 0.96$ s$^{-1}$.

By determining the position of the rotation centre (figure 3(a)) we can calculate the slopes of the velocity profiles

$$\delta V_y/\delta x = -0.62 \text{ s}^{-1}, \quad \delta V_x/\delta y = 0.96 \text{ s}^{-1}.$$  \hspace{1cm} (8)

The sign indicates the direction of rotation; it is clockwise from bottom left and then upward (see left vortex in figure 1). It is approximately rigid body rotation with angular velocity

$$\omega = \left[ |\delta V_y/\delta x| \times |\delta V_x/\delta y| \right]^{1/2} \approx 0.8 \text{ rad} \text{ s}^{-1},$$  \hspace{1cm} (9)

and ellipticity factor

$$\epsilon = \left[ |\delta V_y/\delta x| |\delta V_x/\delta y| \right]^{-1/2} \approx 1.2.$$  \hspace{1cm} (10)
The ellipticity is not large, but also not vanishing; it means that ‘on average’ the vortex is deformed a little (compressed in one direction, see figure 1).

Since the maximal particle velocities are of the order of \( V_m \sim 2.5–3 \, \text{mm s}^{-1} \), we can obtain a rough estimate to the size of the rotating area

\[
R_c \approx \frac{V_m}{\omega} \sim 3–4 \, \text{cm}.
\]  

(11)

This result is in a fairly good agreement with observations (figure 1).

The zone of intense circulations has a complicated flow structure. Outside the vortex area there is a buffer zone, where rotations and vertical waves join. The interaction is so strong here, that periodical shock-like disturbances are excited (see figure 4). The interaction of the regular wave front and the shock results in a visible bending of the front in the transition area, as can be clearly seen in figure 4. From the traces of shock front displacements (traces are clearly visible in figure 4 as alignments due to their enhanced brightness), we estimate the shock speed and the shock repetition frequency

\[
V_{\text{shock front}} = 15–19 \, \text{mm s}^{-1}, \quad \nu_{\text{shock}} \sim \frac{17.34}{3} \approx 6 \, \text{Hz}.
\]  

(12)

The shock front propagates downward and is destroyed when it reaches the bottom of the cloud; the particles from shocks are pushed apart and away from this area horizontally (see first column on the left in figure 4). Hence, the energy of shocks may partly feed the rotations. If we assume that all the kinetic energy of particles in a single shock is transformed into energy which is dissipated (due to friction) by the particles whilst traversing a half circle (with radius \( R \)), we find the relation

\[
\frac{1}{2}MV_s^2N_s \sim \pi R\gamma V_rN_r,
\]  

(13)

where \( M, N_s, V_s, V_r \) are the particle mass, the number of particles and the velocities, with subscripts \( s = \text{shock}, \ r = \text{rotation} \), and \( \gamma \) is the damping rate coefficient (2). This expression can be
rewritten for our particular conditions as

\[ N_r / N_s \sim V_s^2 / (\pi R \gamma V_t) \sim 1/3 - 1/2. \]  

(14)

We see that the high dissipation rate of a single shock, does not leave energy to drive the particle rotation. However, for a series of shocks, this value has to be multiplied by a frequency factor, which in our case is equal to

\[ \frac{1}{2} v_s / v_t \sim 24. \]  

(15)

This means that each individual shock particle (at the observed repetition frequency!) has enough energy to drive 5–10 particles to rotate in the cloud, and hence the ‘perpetual’ motion could be self-sustained. Still we need a mechanism (a dynamo), which triggers these circulations.

6. Possible origin of circulations

A simple way to learn about the origin of particle rotations is to consider the equations of motion

\[ \Omega = \text{curl} \, \mathbf{v}, \]

\[ \dot{\mathbf{v}} = \partial_t \mathbf{v} + \frac{1}{2} \nabla \mathbf{v}^2 - \mathbf{v} \times \Omega = -\frac{Q}{M} \nabla \phi - \frac{1}{\rho} \nabla p - \frac{\alpha}{M} \nabla T + g - \gamma \mathbf{v}. \]  

(16)

We follow the approach proposed in [29], simplifying the description. All the main forces, the electrostatic force (including the ion drag force), thermophoretic force, gravity, pressure and friction are taken into account. Taking the \( \text{curl} \) of both sides of equation (16) yields

\[ \partial_t \Omega + \gamma \Omega = \text{curl} (\mathbf{v} \times \Omega) - \nabla \frac{Q}{M} \times \nabla \phi - \nabla \frac{\alpha}{M} \times \nabla T - \nabla \gamma \times \mathbf{v} - \nabla \frac{1}{\rho} \times \nabla p. \]  

(17)

This establishes the relationship between sources and losses of rotation. Generation of a vortex is only possible if the source terms on the right hand side are not vanishing, and are intense enough to overcome the frictional dissipation (second term on the left hand side). This is in agreement with simulation results [30], where generation of vortex-like configurations was demonstrated assuming that the energy loss due to friction with the background gas might be compensated by energy gain from the force \( \mathbf{\tau} \) exerted by the discharge in such a way that \( \nabla \times \mathbf{\tau} \neq 0 \). Note that a possible reason for inhomogeneity is the particle size dispersion (particles used in the experiment have a 3% dispersion).

If gravity (totally compensated by thermophoresis for almost all the particles, see section 4) and the electrostatic force are dominating in the balance, then the following simple estimate must be valid

\[ g_{\text{eff}} \sim \left| \frac{Q}{M} \nabla_{||} \phi \right|, \quad g_{\text{eff}} = g \frac{\delta a}{a}, \quad \Omega \sim \left| \nabla_{||} \frac{Q}{M} \cdot \nabla_{\perp} \phi \right|, \quad g_{\text{eff}} \gamma \sim \frac{E_{\perp}}{E_{||}} \frac{g}{\gamma L Q} \frac{\delta a}{a}. \]  

(18)
where symbols $\parallel$ and $\perp$ mark vertical and horizontal components, $\varphi$ is the electric field potential, $E$ is the strength of the electric field and $L_Q$ is the scale of vertical inhomogeneity of charge distribution, $\Omega$ is the angular velocity.

The cloud of dust particles is confined horizontally (figure (1)) due to the presence of the horizontal component of the electric field. Usually it forms bowl-like equipotentials above the rim at the lower electrode, and is weak [45] (does not exceed several percent of the strength of the vertical component). In our case, when gravity is closely compensated by thermophoresis, it is natural to assume (in view of electric field pressure balance)

$$\frac{E_\perp}{E_\parallel} \sim \frac{1}{2} \frac{L_\parallel}{L_\perp}.$$ (19)

where $2L_\perp/L_\parallel$ is the ratio of horizontal to vertical size of the cloud. For our geometry (see figure (1)) this yields $E_\perp/E_\parallel \sim 0.08$. Since $L_Q \approx 8 \text{ mm}$, $\delta a/a = 0.03$, we estimate that $\Omega \sim 0.1 \text{ rad s}^{-1}$, much less than the measured value (equation (9)). Therefore, this mechanism is not powerful enough in our conditions; the charge inhomogeneity mainly affects the particle oscillations [29], rather than creating intense rotations.

Experimentally, it is well known that particle clouds containing particles of different sizes tend to sediment in such a way that larger particles are accumulated mainly at the outside edges. This can create horizontal gradients of charge and/or mass density as well. Hence, according to (17) it might be possible to activate rotations induced by temperature gradients. For rotations induced by temperature gradients, we may write in analogy with (18)

$$g \sim \frac{\alpha}{M} |\nabla T|, \quad \Omega \sim \frac{\delta a}{a} \frac{g}{\gamma L_a}.$$ (20)

Assuming now that the inhomogeneity scale is of the order of the circle size, $L_a \sim R_c \sim 3-4 \text{ mm}$ (equation (11)), we can estimate at which steady-state level of size variations it is possible to create the needed rotation $\Omega \sim \omega \approx 0.8 \text{ rad s}^{-1}$. This turns out to be

$$\frac{\delta a}{a} \sim 0.01 < 0.03.$$ (21)

Since it is lower than 3% of the levels guaranteed by the manufacturer for these particles, it seems reasonable that this mechanism could be responsible for the creation of particle circulation.

The last term $\nabla \frac{1}{\rho} \times \nabla p$ on the right-hand-side of equation (17) could also be responsible for circulation if dust particles are distributed non-uniformly upon dust isobars. We observe strong spatial variation of density (with a space scale $\sim \lambda$ (7)) inside regions where intense waves are self-excited (lower central part of the cloud, see figure 1). Due to wave heating, expected temperature gradients are even stronger here. Nonetheless, generation of intense rotations is not possible because the temperature $T_d$ varies dominantly across the cloud as the density $\rho$ does. However, it is reasonable to consider this mechanism in addition to that discussed above: strong localized cross-gradients of density and temperature may appear in the transition zones (see section 5).

Steady state rotations (alone with the stationary shear dust flow) in a cloud of particles with diameters of $2a = 3.7 \mu\text{m}$ have been observed in [17]. The size of vortices ($\sim 10 \div 20 \Delta \simeq 1 \div 2 \text{ mm}$) was lower than in our case. Small vortices of the size $\lesssim 5 \text{ mm}$ were observed also in

New Journal of Physics 9 (2007) 39 (http://www.njp.org/)
[24] in a cloud of bigger particles with \( 2a = 14.9 \mu\text{m} \) (vortices merged into one large one as the rf power was increased). Angular velocities were not reported in [17, 24]. Rotation velocities for clouds containing small dust particles \( (a = 1.7 \mu\text{m}) \) have been measured in [26]. For different gas pressures 0.36–0.98 mbar \( \omega \) was in the range 0.1–0.16 s\(^{-1}\), which is 5–8 times lower than that we observe. This is because the damping was much stronger \( (\gamma = 120–330 \text{s}^{-1}) \) compared to our conditions (2). Note also that we observe elongated vortices. This corresponds qualitatively to that predicted in theory [31] and in simulations [30].

7. Particles outside of the clouds

The unique feature of the given experiment is a great opportunity to observe in situ the interaction of agglomerates with complex plasma clouds. A heavier particle appears first in the upper cloud (above the void), then penetrates into the void and slides through, collides with the lower cloud beneath the void and damages it to create caverns. The size of the caverns and the restoring time are useful to estimate the cloud parameters as well.

The projectile–cloud collision is a complicated process. Generally it is inelastic, because the primary projectile, in turn, is ‘swallowed’ by the cloud. Nonetheless, at least at the beginning, the interaction looks as if it is a quasi-elastic process. We sometimes observe that shortly after the projectile crosses the cloud boundary, (i.e. a collision has ensued) a new particle directed oppositely leaves the cloud (figure 5). It might be the original particle scattered back, or one of the cloud’s particles which has been ejected and penetrates deep into the void. In this case, the interaction could be interpreted qualitatively as a ‘sputtering event’ though the situation is not quite similar to usual sputtering which occurs, for instance, during the ion bombardment of solid body surfaces. We cannot solve that dilemma directly, because it is not possible to trace an individual particle in a dense cloud, such as for our conditions.

It is important that we can trace the secondary particle inside the void. A simple analysis demonstrates that this particle loses energy along its trajectory, but it is less than that predicted by standard gas drag theory. We suppose that this kind of ‘super fluidity’ is due to acceleration by the oscillatory field induced by the dynamics of the void plasma (according to [29, 30] the force field of the void plasma could be responsible for a driving force at least of low frequency oscillations) or by the dynamics of the particle cloud beneath the void. The bottom part of the lower cloud is in an active state (particles in the bottom oscillate vertically, revealing visible waves propagating down, see section 3). Hence, the electric field may contain a non-potential component.

To test if this is the case, we fitted the velocity distributions of traced particles by the sum of the zeroth, first and second harmonics. Fitting results are accumulated in table 1 and shown in figure 5. Actually, fitting results are in a fairly good agreement with those reported above in section 4: the frequency of the accelerating field has to be \( v = 1.4–1.6\text{Hz} \), which corresponds to that shown in equation (7), within the accuracy of the measurements.

8. Conclusion

We have investigated dynamical properties of a complex plasma cloud compensated against gravity by the thermophoretic force. We have found the dynamical activity in such a cloud: an excitation of circulations (rotations) and regular waves.
Figure 5. Particles inside the void. (a) Vertical positions, (b) particle velocities. The dashed lines are the void boundaries; the dotted lines are harmonic fits to velocity distributions. The first two trajectories are from the particles crossing the void. The last one belongs to a particle kicked out of the lower cloud through the collision of the second particle (at $t \approx 1.9$ s) with the surface of the cloud. The traced trajectory of this ‘jumping’ particle is shown in the lower panel in more detail.

Table 1. Fitting parameters. Trajectory number corresponds to those shown in figure 5; $V_{0,1,2}$ are the amplitudes of the harmonics constituting the velocity fit.

| Trajectory | 1       | 2       | 3       |
|------------|---------|---------|---------|
| $V_0$ (mm s$^{-1}$) | $-18.6 \pm 0.6$ | $-18.3 \pm 0.4$ | $0.21 \pm 0.16$ |
| $V_1$ (mm s$^{-1}$) | $11.5 \pm 0.6$ | $17.1 \pm 0.4$ | $30.5 \pm 0.2$ |
| $V_2$ (mm s$^{-1}$) | $5.5 \pm 0.7$ | $1.7 \pm 0.6$ | $9.5 \pm 0.5$ |
| $\omega$ (rad s$^{-1}$) | $8.8 \pm 0.6$ | $8.8 \pm 0.5$ | $10.2 \pm 0.1$ |

We proposed a possible mechanism which would produce such a ‘circulation’ dynamo’ based on the non-Hamiltonian character of complex plasmas.

Having traced the particles inside the void (above the cloud), we also have shown that there could be a correlation between the dynamic activity inside the cloud and the behaviour of the particle trajectory through the void.
We have experimentally measured the parameters of different dynamical activities and demonstrated a fairly good agreement between them.

The obtained results and interpretations represent a first step towards understanding the surprising and amazing property of complex plasmas to generate and self-sustain regular dynamical patterns.

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