Electromechanical effect in complex plasmas

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Experimental results on an auto-oscillatory pattern observed in a complex plasma are presented.

The experiments are performed with an argon plasma which is produced under microgravity conditions using a capacitively-coupled rf discharge at low power and gas pressure. The observed intense wave activity in the complex plasma cloud correlates well with the low-frequency modulation of the discharge voltage and current and is initiated by periodic void contractions. Particle migrations forced by the waves are of long-range repulsive and attractive character.

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In this letter we address the electromechanical effect and associated self-sustained oscillatory and wave patterns observed in complex plasmas with the PK-3 Plus setup on board the ISS \cite{1, 2}. These active experiments (including as an item wave excitations \cite{3}) have been performed recently in a particularly wide range of plasma parameters \cite{2}. With a complex plasma in an active state an activation of the particle cloud-plasma feedback mechanism leading to self-sustained oscillations is quite natural.

Complex plasmas are low pressure low temperature plasmas containing microparticles. These particles can be visualized individually with a laser beam, the light of which is scattered by the particles and then recorded with a CCD camera. Under microgravity conditions in experiments on board the ISS \cite{2} or in parabolic flight experiments \cite{3}, the recorded particle clouds are essentially three-dimensional structures more or less homogeneous, albeit inside commonly containing a void – a 'visibly empty region' free of particles \cite{4}. (For the last decade 'void closure' was a long-standing challenge of complex plasma investigations \cite{4}.)

The system 'complex plasma with a void' (CPV) is one of the most intriguing phenomena detected in experiments with complex plasmas: the CPV gives rise to self-excited macroscopic motions – it sets the paradigm of a dissipative system capable of auto-oscillations. (This stable auto-oscillating CPV should not be confused with cyclic spatio-temporal microparticle generations \cite{7}, and the heart-beat instability \cite{8} studied in detail in dust forming plasmas.) Depending on discharge conditions and plasma parameters, the CPV could be kept stable, or excited externally into an oscillatory state, which even in the presence of damping remains autonomically excited.

There are a few useful analogies which help to identify the main features of the self-excitation’ mechanism.

An ability to self-sustain oscillations is typical for auto-oscillation systems with inertial self-excitation such as the Helmholz resonator well known in acoustics, and many others \cite{3}.

We associate low-frequency current and voltage self-pulsations, and the accompanying particle oscillations in complex plasmas, with the negative differential conductivity (NDC–see \cite{10}). In this sense the CPV exhibits properties similar to some type of photoconductors \cite{10}, semiconductors \cite{11}, semi-metals \cite{12}, ferroelectric liquid-crystalline films \cite{13}, carbon nanotubes \cite{14}, nanocrystalline heterostructures \cite{15} and other microelectromechanical systems \cite{16, 17}.

The non-linear dissipative compact formations in the patterns seen in CPV remotely resemble oscillons. These standing undulations can be produced on the free surface of a liquid (so-called Faraday’s waves \cite{18}), a granular medium (in this case localized excitations can self-organize with possible assembly into ’molecular’ and ’crystalline’ structures \cite{19}), or nonlinear electrostatic oscillations on a plasma boundary \cite{20}. Oscillons ”feed” from external shaking of the system and dissipation seems to be inherent for their existence, likewise in our case. There remain still many open questions in explaining the physical mechanism of oscillons.

Hydrodynamic (or hydrodynamic-like) systems provide other examples of oscillatory patterns fed by streaming in the system: a flow-acoustic resonance \cite{21}, hydrothermal \cite{22} and plastic deformation flows \cite{23}, mobile dunes \cite{24}, surface tension auto-oscillations \cite{25}, oscillating domains in planar discharges \cite{26}, self-excited dust density waves \cite{27}, and many others.

The usual assumption is that auto-oscillations are maintained by a sufficiently powerful instability allow-
ing recirculation (hysteresis) in phase space \[28, 29\]. By providing investigations of micro-particle migrations at the atomistic level, experiments with the CPV may help us to understand the fundamental nature of inanimate auto-oscillations and the intrinsic dynamics of highly dissipative non-linear structures.

Streaming ions may act as an activator of the instability in the CPV (see, e.g. \[24\]). The formation of a void itself is explained frequently by the counteraction of the confinement force and the ion drag force \[30, 31\]. Void vibrations in an energized CPV are believed to be due to the heart beat instability the free energy of which may arise from streaming ions \[8\]. There are a number of direct observations of the interaction of streaming ions and dust particles \[31, 32, 33\].

Since straightforward measurements of flowing ions in complex plasmas are not possible to perform without perturbing the particle cloud structure \[24\], evidence might be extricated from the direct observations of particle vibrations. There are two possible options: (i) elucidate the long-range character of particle vibrations; (ii) decode the patterns of the secondary wavefronts. Fortunately, both options are realizable as has been proven by the given experiments.

We performed our experiments in a PK-3 Plus chamber \[1, 2\]. The parallel plate capacitively coupled rf discharge is symmetrically driven by two electrodes, which have a diameter of 6 cm and are separated by 3 cm (measured voltage asymmetry does not exceed \(\pm 2\%\); all measured electrotechnical values shown below are arithmetic means). The electrodes are surrounded by a grounded ring of 9 cm diameter and 1.5 cm width. (More technical details of the setup can be found in \[2\]). Particle vibrations were recorded at a rate 50 fps and a spatial resolution of 0.41 Mpixel at 45.05 Mpixel (49.6 \(\mu\)m/pixel) in the vertical (horizontal) direction. The sample rate of the low-frequency electrotechnical measurements was 10 Hz at the stage of stable vibrations.

The experiment, we address here, was performed in Argon at a pressure of 9 Pa and was arranged in two stages (Fig.1). In the first stage the discharge was ignited with a peak-to-peak voltage of 37 V at an applied (rms) power of 0.181 W (the discharge power factor for the entire circuitry was estimated as about 45-60%). Melamine-formaldehyde particles with a diameter of 9.2 \(\pm 1\) \(\mu\)m and a mass density of 1.51 g/cm\(^3\) were inserted into the chamber. \(^1\) They formed a cloud stretched horizontally (the aspect ratio width/height \(\equiv D/H \approx 64 \text{ mm}/15 \text{ mm}\) with a visually pulsating elliptically-shaped void (see Fig.2 in the maximal "stretched" phase the void is \(\sim 7 \times 3 \text{ mm}^2\)). This discharge regime allows us to observe stable oscillations at a frequency 3-15 Hz and to perform statistically relevant measurements during \(\sim 150\) s. The estimated gas damping rate, attenuating particle motion, was 10.7 s\(^{-1}\). Unlike \[8\], no contaminating (sputtering) components affected the discharge.

Next the applied power was lowered to 0.12 W, and another form of the heart-beat instability with its almost irregular large-amplitude void constrictions started. The

\[\begin{align*}
\text{FIG. 1: The (rms) discharge voltage, the current and the applied power measured during the two-stage experiment. The numbers indicate the main phases: } & 1 - \text{stochastic stabilization, } 2 - \text{first round of short-time pulses, } 3 - \text{stable free oscillations at a higher applied power, } 4 - \text{second round of short-time pulses, } 5 - \text{free oscillations at a lower applied power.}
\end{align*}\]

\[\begin{align*}
\text{FIG. 2: 10 superimposed images shifted by one period in time are shown to reveal the global dynamical pattern of the CPV. The main elements of this 'dynamo-machine' are: a void (the dark elliptic-shaped area to the right, at this active stage open), a quasi-spherical halo (highlighted by the dash-dotted line) with concentric waves spreading around the vibrating void, two horizontal counter-rotating global vortices with angular velocity } & \approx 0.2 \text{ s}^{-1}, \text{ and horizontal radius } \approx 7.5 \text{ mm, and an edge 'buffer' zone to the left. The boundaries of the vortices form a 'waveguide' for oscillons in-between (oscillons are identified in the middle as a few brighter vertical stripes). For the given half-cycle the dominant particle motion is as indicated by the arrows. The semi-transparent arrows indicate general particle drifts. The dashed lines cross at the position of the void center. The field of view is } 17.6 \times 34.7 \text{ mm}^2. \text{ The illuminating laser sheet FWHM is about } 80 \mu\text{m.}
\end{align*}\]
FIG. 3: Periodgram showing horizontal oscillations of the cloud. The brighter spikes in the middle (indicating enhanced particle density) are oscillons (see also Fig.2) slowly propagating towards the outer edge of the cloud (to the left) away from the pulsating void (the horizontal periodic dark stripes to the right) at an approximately constant speed of 0.4 mm/s. The dashed line indicates the position of the void center. The lifetime of the oscillons is $\approx 20$ s, i.e. about 200 damping times. Oscillons are "fed" by the CPV oscillatory energy. The faster edge wave-ridges (see [3]) are also clearly seen at $x > 25$ mm.

stable oscillation phase we address here would seem to be a completely different phenomenon. Details on the unstable (heart beat) phase will be published elsewhere.

The experiment started out from the stochastically stabilized complex plasma (t=0 in Fig.1; for details of stochastic stabilization see [2]). At 20 s the external stabilization was turned off and after $\Delta t \approx 1$ s delay the auto-oscillations appeared. Next at 31 s the plasma was stimulated by a series of six short-time voltage pulses produced by the function generator. The pulses, with a negative amplitude of -50 V, were applied to the bottom electrode through a 20kOhm feed resistor. This produces short-time DC voltage shifts of a few volts which leads to shock compression of the particle cloud. This technique can also be used as a stability test: The CPV reverted rapidly to its former stable condition after each applied pulse. After this the CPV was observed to freely oscillate for $\approx 83$ s without external forcing.

Fig.2 visualizes the dynamical activity. Surprisingly the "shaking" divides the particle cloud into two counter-moving parts which forms a stagnation zone with nearly zero particle velocity at the interface. Outside the stagnation zone the particles are seen to move along the axis at nearly constant velocity (in this particular half cycle) as if they were attracted by the void. Apparently, in this phase the void behaves like a negatively charged probe, and long range attraction is due to the ion collection effect [33]. (In the next half a cycle, as the void tends to close, the particles are repelled from the center). Simple estimates based on particle behavior analysis show a rather weak plasma charge oscillation with maximal decompensation of the order of $\delta n/n = 5 \cdot 10^{-3}$.

The periodic auto-oscillation pattern formed by particle horizontal vibrations is shown in Fig.3. For depicting the oscillation pattern, we follow a simple procedure proposed in [27]. From each image of the recorded sequence a narrow slab of size 35x5 mm$^2$ centered over the void vertical position is extracted. Then the slab is 'compressed' into a line by adding up the pixel intensities perpendicular to its longer side. The result is plotted (as a periodgram) for every frame as shown in Fig.3 forming a $(x, t)$ map. The brighter regions of this map correspond to higher particle densities. The darkest regions are particle-free, that means that the void is maximally open. The fundamental oscillation frequency shown by the cloud is

$$f_{osc} = 2.81 \pm 0.03 \text{ Hz.}$$  \hspace{1cm} (1)

Fig.4 shows a correlation between vertical cloud oscillations and rf current, rf voltage, and applied (forward) rf power vs. reduced time ($f_{osc} t$). Two "reconstructed" oscillation periods are shown. Reconstruction, based on superposition of the data points taken over 20 consecutive periods (phase 3 in Fig.1), demonstrates clearly local quasi-periodicity of the discharge electrical signals (periodicity time is limited by slowly drifting oscillons). Lack of any periodicity in the applied power signal is also evident. (The forward power is held constant by a servo control loop inside the rf generator.)
lations and all electrical signals. There is no correlation with the applied power. To depict the pattern of vertical oscillations the aforementioned procedure is carried out over a narrow vertical slab of size 2x20 mm². The result is shown in Fig[4], as a superposition of consecutive periods.

Comparison with the oscillatory components of the effective voltage and current (Fig[1,b,c]) show an almost anti-phase behaviour that is typical to pattern-creating gas discharges (see, e.g., [30]). Mean components of these signals (corrected to measurement offset errors) are

\[ < I > = 3.24 \pm 0.03 \text{ mA}, \quad < U > = 12.70 \pm 0.02 \text{ V}. \]  

(2)

From this we obtain an average ohmic discharge resistance of \( \approx 4 \text{ kOhm}. \) (Without particles the plasma resistance was \( \approx 3.4 \text{ kOhm}. \) This value agrees well with that estimated from [31].)

Note that sharp current minima (voltage maxima) are apparently linked to the vertical cloud compression, whereas the void opening relates to a weak rise in the current. All this suggests an association with the variation of the discharge capacitance – an "electromechanical effect". In this sense the CPV might resemble a varicap, a device whose capacitance varies under the applied voltage.

Based on this analogy and using an equivalent circuit model [27] it is easy to show that the expected variation of the rms current is of the order of the

\[ \frac{\delta I}{< I >} \approx -\eta \frac{C_{\text{cloud}}}{C}, \quad \eta = \frac{\omega^2 \tau^2}{1 + \omega^2 \tau^2}, \quad \tau = RC, \]  

(3)

where \( R \) is the discharge resistance, \( C \) the discharge capacitance, \( C_{\text{cloud}} \) the CPV capacitance. Assuming \( \tau \approx 1 \) we estimate \( C \approx 3 \text{ pF}. \) Hence, the observed oscillation amplitude would be explained if \( C_{\text{cloud}} \approx 0.4 \text{ pF} \), which is quite reasonable.

Note also that the active oscillatory state of the CPV is accompanied by a periodic pulsation in the discharge glow as well.

Extrapolating probe measurements [38] we estimate the plasma parameters as \( n_e \approx 10^8 \text{ cm}^{-3}, \ T_e \approx 2 - 3 \text{ eV} \). Interparticle separation averaged over the entire cloud area (Fig[2]) is \( < \Delta > \approx 230 \mu \text{m}. \) The highest compression occurs at the spikes (Fig[3], \( \Delta_{\text{min}} = 173 \pm 16 \mu \text{m}. \) Outside the spikes compression is less, \( < \Delta > = 300 - 350 \mu \text{m}. \) At the kinetic level we see that particles are first accelerated to high speeds (\( v_{\text{max}} = 18.9 \pm 0.4 \text{ mm/s} \)), then they are decelerated forming spikes – oscillations which are clearly seen in Fig[2] as vertically elongated constrictions. Following [27], we estimate the particle charge \( Z_{d} \sim 9000 \text{e}, \) the dust sound speed \( C_{\text{Daw}} \sim 6 - 7 \text{ mm/s}, \) and the dust plasma frequency \( \omega_{dust} = \omega_{dust}/2\pi \approx 70 \text{ Hz}. \)

The origin of the proposed electromechanical effect could be due to the cloud stretching, multiplication or selective harmonic amplification of coupled oscillations of the particles and the electrical circuitry feeding the discharge. In the case studied here it is a self-sustained low frequency resonant oscillator. We conclude that the self-excitation leading to the regular repeatable constrictions of the void in the particle cloud is due to the free energy in plasma ions drifting relative to the microparticles.

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