Novel experiments on the heartbeat instability in complex (dusty) plasmas and hypothesis on its physical mechanism

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A series of new ground-based experiments on the heartbeat instability in complex (dusty) plasmas was conducted. The experiments included the investigation of a stability diagram of a dust cloud in a RF discharge, time-resolved measurement of the plasma emission during the heartbeat instability, control of the instability by means of a modulated laser beam, whose wavelength was tuned to an atomic transition of a working gas. As an outcome of the experiments, a hypothesis on the physical mechanism generating the heartbeat instability was suggested. According to this hypothesis, the instability occurs due to the periodically repeated formation of the sheath on the boundary between the microparticle-free area (void) and the complex plasma. The origin of this transformation is the loss of the plasma on microparticles surrounding the void. We have shown that this hypothesis is consistent with all the available experimental data on the heartbeat instability.

1. Introduction

Electronegative plasmas are known to exhibit numerous types of instabilities [1, 2]. Complex (dusty) plasmas can in principle also be considered as plasmas with very heavy negative ions. However, due to the macroscopic nature of microparticles, complex plasmas exhibit two features which make them remarkably distinct from regular electronegative plasmas: (1) The charge of a microparticle is determined by the dynamic balance of the ion and electron fluxes on its surface, which represents therefore a volumetric sink for a plasma. (2) The ion drag force, acting on microparticles, becomes important, leading to the formation of so-called voids, i.e., microparticle-free regions. Such plasmas can no longer be treated as homogeneous.

This determines specific properties of the instabilities in complex plasmas. In the first microgravity experiments with complex plasmas, a spontaneous periodic contraction of the void boundary was reported [3]. Because of its characteristic appearance as well as due to very low repetition frequency (from single contractions to hundreds Hz), this phenomenon was termed “heartbeat” instability [4]. Several years after the discovery, it was shown in ground-based experiments that the heartbeat instability cannot be reduced to the dynamics of microparticles only [5]. The global characteristics of the discharge (e.g., rf current) were found to be modulated with the low frequency of the instability. High-speed real time imaging of the discharge showed that the contraction of the void is preceded by a steep increase of the glow intensity inside it. Physical mechanisms leading to such a behavior of the plasma are not understood until now.

We present here a hypothesis based on the results of the new ground-based experiments, which employs both specific features of complex plasmas – heterogeneity and presence of the volumetric sink of plasma.

2. Experimental setup

Our experiments were performed in a PK-3+ chamber [6], which is a symmetrically driven parallel plate capacitively-coupled rf reactor (see Fig. 1). The discharge was created by applying 13.56 MHz voltage to the disc-shaped electrodes of 6 cm in diameter, separated by a 3 cm gap. As a working gas, we used argon in a pressure range of 10–50 Pa.

Melamine formaldehyde plastic spheres with the diameter 1.95 μm were injected into the discharge and levitated in the vicinity of the bottom electrode. By heating up the bottom electrode and thus compensating the gravitational force by thermophoresis, a significant part of the discharge volume was filled with microparticles forming a void almost in the center of the chamber. The microparticles were illuminated by a vertical sheet of green (532 nm) laser light and observed from the side with a CMOS video camera at a frame rate of 1000 fps.

At two radial positions - one inside the void and the other outside it, on the periphery of the microparticle cloud (see Fig. 1) - the light from the plasma was collected by two lenses and by means of optic fibers transmitted to the two respective
Along with the observation of the sporadically triggered heartbeat instability, we used a tunable diode laser to excite it "on purpose." The wavelength of the laser was set to the center of the Doppler profile of 772.38 nm spectral line of argon. This light is resonantly absorbed by argon atoms in the $1s_5$ metastable state, causing the excitation into the $2p_7$ radiative state. The 2.4 mm diameter cylindrical beam from the tunable laser with the maximal power of 8 mW was modulated by a mechanical chopper. It was possible to move the beam vertically. The laser power entering the chamber was varied by attenuating the beam with the neutral density filters. Due to their long lifetime, argon metastable atoms contribute to the ionization. Therefore, by modulating the tunable laser beam, we were able to modulate the ionization rate in our discharge.

3. Results

First of all, the stability range was studied for a fixed number of levitating microparticles. The results are presented in Fig. 1. At a fixed pressure, the instability exists in a fixed range of discharge power. Also, there is a threshold pressure, above which the instability cannot be triggered.

Next, the temporal evolution of the plasma emission was measured by the two PMT modules (Fig. 2). It was shown that emission inside and outside the void evolves opposite in phase. Also the initial increase of the emission occurs typically within 0.2 ms.

The excitation of the heartbeat instability by a modulated beam of a tunable laser exhibited resonance properties. It was always observed in quite a narrow band of the beam modulation frequency around 40–60 Hz. The frequency of the heartbeat can be used as a measure of the "strength" of the instability. The laser-excited heartbeat instability becomes stronger with the increase of laser power. It also varies with the vertical position of the laser beam: it is the strongest if the beam crosses the center of the void and completely disappears as the beam is moved out of the void. The effect of laser excitation disappears if the wavelength of the laser is detuned from the argon atomic transition line.

4. Proposed mechanism of the instability.

Importance of the void boundary for the heartbeat instability is substantiated by three independent observations: (1) Instability never occurs without the void. (2) During the instability the plasma emission varies in opposite phases inside and outside the void. (3) Tunable laser excitation of the heartbeat instability is only possible if the laser beam crosses the void.

Therefore we suppose that the instability occurs due to a critical phenomenon on the void boundary. Our suggestion is that this critical phenomenon is the formation of the sheath on the void boundary. The reason for the sheath formation is evident: under certain condition the loss of the plasma on the void boundary may become so high, that the ions will have to be accelerated to the Bohm velocity in order to sustain the ionization balance.

An immediate consequence of such a transformation would be the gradual increase of the
electric field on the void boundary, pushing the microparticles towards the void center (Fig. 3).

A dimensionless parameter controlling the triggering of the heartbeat instability is then the ratio of the actual diffusion flux \( Q_{\text{diff}} \) to the Bohm flux \( Q_{\text{B}} \):

\[
C = \frac{Q_{\text{diff}}}{Q_{\text{B}}} \propto \sqrt{\frac{T_e}{pR_v}} \propto \sqrt{k_i(T_e)}, \tag{1}
\]

where \( T_e \) is the electron temperature, \( p \) – argon pressure, \( R_v \) – void size, \( k_i \) – the ionization rate constant. Formally, if \( C<1 \) the void boundary should be stable and \( C=1 \) would mean sheath formation and therefore onset of the instability. Qualitatively this criterion does not contradict to any known experiments.

5. Conclusion

A hypothesis explaining the triggering of the heartbeat instability is suggested. Formation of a sheath on the void boundary is supposed to be the critical phenomenon leading to the observed collapse of the void. Although no major contradictions of this hypothesis to the available experimental data are found, it requires a more direct confirmation.

5. References


Fig. 3. Schematic illustration of the sheath formation on the void boundary.