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Observation of Self-excited Dust Acoustic Waves (DAW) in Strong-Coupling Regime

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Abstract
Experimental observations of self-excited DAW prorogation in strongly coupled dusty platsma are reported in present work. These DAWs were produced by mixing a small amount of Manganese- Di-Oxide dust with alumina dust grains. The wavelength of the DAW was measured from single frame video images of scattered light from the dust grains. The results are compared with available theories.

1. Introduction

Thus dusty plasmas play a vital role in wide range of phenomenon and are of current research interest for a number of reasons [1-2, 8, 18-19].The investigation of waves in dusty plasma has attracted much interest since many fundamental quantities for the characterization of such plasma can be obtained from the analysis of wave propagation/dispersion. Due to the very high mass of the dust grains with respect to plasma particles (electrons and ions) their response to the electric field is very slow. Thus the resultant waves in the dust plasma are of very low frequency (<50Hz). These types of waves have been studied extensively both experimentally and theoretically and known as dust acoustic wave (DAW) [1-12, 20]. The DAW is a modified version of the usual ion acoustic mode of ordinary plasma but here the inertia is provided by the dust grains and the pressure by the plasma particles (electrons and ions).

Experimentally [3-12, 20] DAW has been studied in a variety of devices. Self-excited and driven DAWs have been studied in both DC [3-8] and RF [9-12, 20] discharges. Barken et.al. [3], observed the formation of self-excited DAW in potassium plasma column of a Q machine. They attributed ion driven instability to be the source of these DAWs. Fortov et. al. [13], observed self-excited DAW in DC glow discharge plasma. They invoked charge dependent forces together with the ion drift effect to be a possible source of instability. For similar observations, Vaulinaet. al. [14] invoked spatial charge gradient of macro-particles as an effective mechanism to excite the instability. In another observation of self-excited DAW in an inductive RF plasma device, Zobninet. al. [15] attributed to the presence of a DC electric field in the dust cloud region as a possible source of mechanism. In their experiment, Pieper [9] found DAW in a horizontally extended crystal, launched by applying a modulated voltage to a wire positioned close to the dust grains. In the technique the confining potential of the plasma crystal and the plasma environment were perturbed due to the presence of wire. Homannet. al. [11] excited DAW in plasma crystals using the radiation pressure of a laser beam. Here the confining potential of plasma crystal and the surrounding plasma environment were not disturbed.

In literature there are many theoretical models to explain DAW. These all model are based on a weakly coupling approximation, i.e. for a coupling parameter$\Gamma<1$. When$\Gamma\geq1$, many interesting effects associated with strong coupling phenomena can set in [2]. For example, for large value of Γ beyond a critical value ($\Gamma>170$), the dust component organize itself to form a crystalline form [16]. In their experiment Pramaniket. al. [8] showed that DAW excitations are also valid in the regime ($1\leq\Gamma\leq10$), where the system is still in strongly coupled fluid state. In this regime correlations, lead to the development of short range order in the system which keeps decaying and reforming in time. In addition these DAW modes occur only below a certain pressure threshold [7, 8]. At high neutral pressures dust-neutral collisions severely damp the mode. At pressure well below the threshold, the dust-neutral collisional damping reduces considerably and the mode can acquire large amplitudes causing nonlinear effects.

In the present experiment we have observed self-excitation of DAW when a mixture of two types dust powder was used rather than individual powder. It is a new and simple technique for the wave excitation in strongly coupled dusty plasma, without perturbing the plasma environment due to external source. For the purpose a small amount of manganese di-oxide (having high dielectric constant) dust grains along with the alumina dust grains was introduced. The presence of this small quantity manganese di oxide enhanced the dust grains levitation. A thick cloud of levitated dust grains was observed even at low discharge voltage and neutral pressure. When the pressure was reduced below a threshold value causes very low frequency (<1Hz) DAW oscillations. These low frequency DAWs oscillations disappeared when neutral gas pressure was

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further reduced and they changed their state from coherent to turbulent.

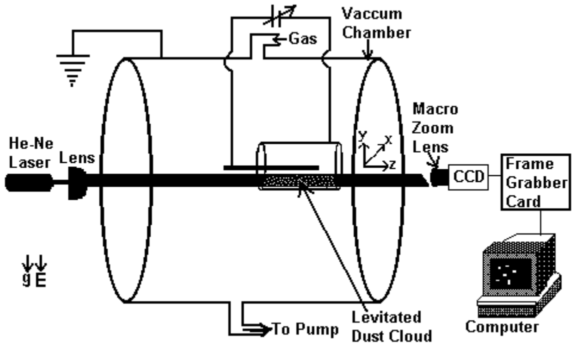

Fig: 1. Schematic Diagram of the Experimental set up

A schematic of experimental assembly used for the propagation of DAW in Coulomb solid is shown in Fig. 1. The anode was a stainless steel wire of 2mm diameter and 40 mm length placed co-axially with the cathode. The DAW propagation was observed in RA geometry (described in details in section [17,18]. In the present experiments solid spherical alumina dust grains of average diameter ~50 µm and density 3.97gm/〖cm〗^3 were used. These alumina grains were spread inside the cathode surface. Over it few grains of manganese di-oxide were sprinkled with the help of drawing brush. The quantity of manganese di oxide grains was much less compared to the alumina grains. To observe and analyze the dust grains dynamics technique discussed in [17] was used. The plasma parameters viz., ion and electron density, temperatures and the floating potential were measured using a Langmuir probe in the absence of dust.

The vacuum chamber was initially evacuated to 0.02mbar and purged with Argon gas at a pressure of 1.0mbar. The chamber was repeatedly evacuated and filled with Argon gas a few times before commencement of the experiment to avoid the impurity of moisture and atmospheric gases. A glow discharge was struck by applying a discharge voltage of 300 V at 0.3mbar pressure.

After striking the discharge the discharge voltage (V_b) was gradually raised to 900V and the neutral pressure was raised to 1.0~mbar. After reaching 900V, neutral pressure was reduced to 0.30mbar and the discharge conditions were maintained for 10minuets. At this condition some dust grains were seen in the sheath region with large thermal vibration. These dust grains were kept accumulating during the course and a highly dense three dimensional dust cloud formed. Although the size of this dust cloud was of few mm. After waiting again the discharge voltage was slowly reduced from900V. It was observed the size of the plasma column decreases and the sheath region expands. With the expansion of sheath region the dust cloud also expands in size.

Simultaneously, the dust thermal motion reduces and they form Coulomb solid. The formation of Coulomb solids is a clear indication of the dust grains entering into a strongly correlated regime. An equilibrium three dimensional dust cloud was observed at a neutral pressure of 0.40mbar and at a discharge voltage of 350V (Fig. 2). The dust grains in this equilibrium cloud were seemed to be at rest and their thermal vibrations were almost negligible.

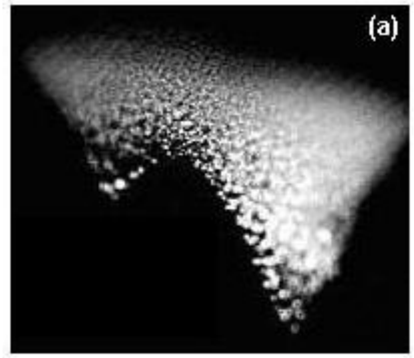

Fig: 2. Picture showing the equilibrium state of the dust cloud at neutral pressure P(Ar)=0.40mbar and discharge voltage V_b=350V.

In Fig. 3 and Fig. 4 represent the pictures of dust cloud when only alumina and only manganese di oxide dust grains were used. These experiments were repeated using the same procedure, described above. From these figures it is clear that very less numbers of dust grains in the cloud levitated compared to the dust cloud (Fig. 2) formed by using the mixed dust.

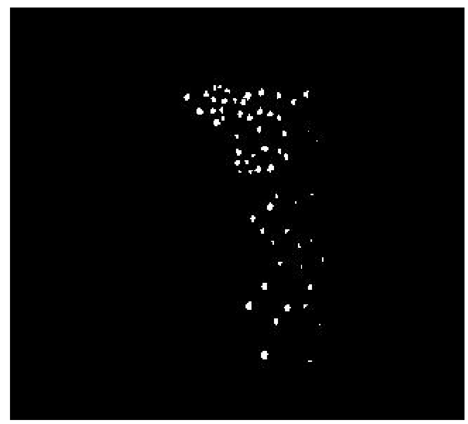

Fig: 3. Picture of dust cloud using only alumina dust at a neutral pressure P(Ar)=0.40mbar and discharge voltage V_b=350V.

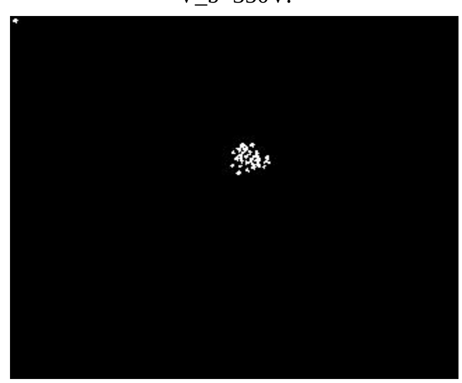

Fig: 4. Picture of dust cloud using only 〖MnO_2 dust at a neutral pressure P(Ar)=0.40mbar and discharge voltage V_b=350V

The idea behind using manganese di oxide dust grains was to enhance the levitation of dust grains in the cloud. Since the di electric constant of manganese di oxide particle

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is higher compared to alumina particle, it was thought they can enhance the levitation of dust grains in plasma by absorbing more number of electrons to its surface. But no such effect observed by using manganese di oxide dust grains alone (Fig. 4). But when a small quantity of it was mixed with alumina dust grains it increased the levitation of dust grains many times. Further when the discharge pressure was reduced in these two cases (pure alumina and pure manganese di oxide) the grains in the dust cloud started making thermal motion, but no wave propagation like phenomenon observed.

When the neutral pressure was reduced progressively from 0.40mbarto 0.30mbar the dust cloud started making spontaneous transverse oscillations (Fig. 5) of the acoustic type. These oscillations were self-excited and no external source was used. The cloud was propagating in the direction from anode to cathode i.e. in the direction of ion drift.

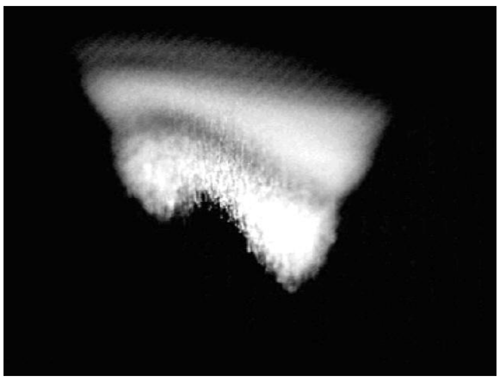

Fig: 5. Picture showing the coherent state of the dust cloud at neutral pressure P(Ar)=0.30mbar and discharge voltage V_b=350V.

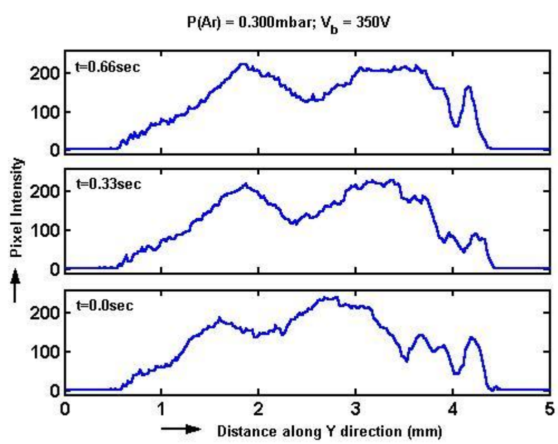

Fig: 6. Phase propagation of coherent mode in y direction at neutral pressure P(Ar)=0.30mbar and discharge voltage V_b=350V.

The propagating bright bands are the wave crests, the regions of higher dust density which produce enhanced light scattering. These self-excited DAW oscillations were similar to those observed previously by Pramanik et.al. [8] and Barkenet. al. [3], in different experimental setup. Video images of these DAW oscillations was captured and analyzed to find their properties. In Fig. 6 three curves between pixel intensity and pixel number at different time scale are shown. To plot these curves first the video image was converted into a series of still images (1sec video image into 30 still images). These still images were converted into a two dimensional arrays of pixel intensity using the MATLAB software. For calculation the same column was selected in these still images. These curves clearly show a phase shift in peak pixel intensity which indicates the propagation of the waves along the direction of gravity.

After forming the self-excited DAW, the neutral pressure was further reduced below 0.30~mbar, the dust neutral collision frequency decreased rapidly and the amplitude of the mode increased. In Fig 7 and 8 two different states of dust cloud at neutral pressure 0.25mbar and 0.17mbar are shown. In their experiments Pramaniket. al. [8], named these states of DAW oscillations were named as intermediate and turbulent states. They also reported excitation of higher frequency modes along with the original DAW mode, when the DAW oscillation state changes from coherent to turbulent. In our experiments, excitations of such higher frequency modes were not observed during the transition of states by pressure reduction.

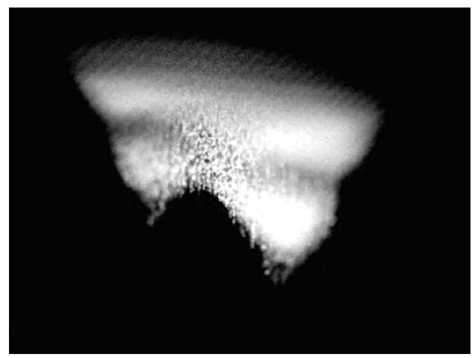

Fig: 7. Picture showing the intermediate state of the dust cloud at neutral pressure P(Ar)=0.25mbar and discharge voltage V_b=350V.

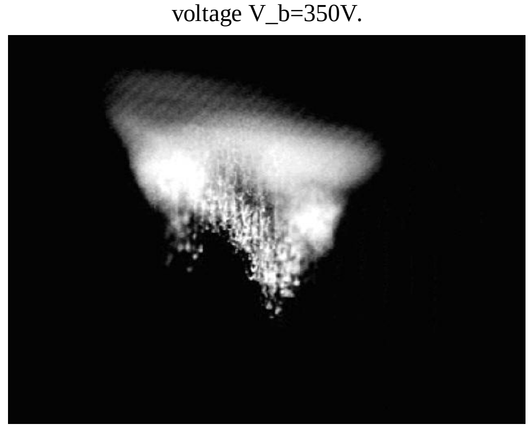

Fig: 8. Picture showing the turbulent state of the dust cloud at neutral pressure P(Ar)=0.17mbar and discharge voltage V_b=350V.

From the captured video frames of DAW oscillations, the wave length and velocity of DAW were measured to be *0.13 cm* and $\sim 5.8 \times 10^{-2}\, cm^{-1}$ respectively, so that the wave frequency was found to be around *0.45 Hz*. The theoretical expression of the phase velocity of the DAW for

$k\,\lambda_p << 1$ is approximately given by $C_{da} \sim \lambda_p \omega_{pd}$. In our experiment the typical measured plasma parameters at a neutral pressure *0.3 mbar* were ion density $n_i \sim 2.5 \times 10^{15} m^{-3}$, ion temperature $T_i \sim 0.03 eV$, electron temperature $T_e \sim 2.0 eV$ while the dust parameters were dust radius $a \sim 25\mu\, m$, dust temperature $T_d \sim 0.03 eV$, dust mass $M_d \sim 2.6 \times 10^{-10} Kg$, no. of electronic charges on dust grain $Z_d \sim 3.5 \times 10^4$ and the calculated value of Coulomb coupling parameter $\Gamma\ was \sim 50$. Thus on an average $\lambda_d \sim 26\mu m$, $\omega_{pd} \sim 17 s^{-1}$ and the phase velocity calculated with these values is $C_{da} \sim 4.4 \times 10^{-2} cm.s^{-1}$. This theoretically calculated value of phase velocity is in close agreement with the experimentally measured value of the phase velocity.

To understand the linear instability, we now estimate the ion drift velocity. For our experimental parameter ion drift velocity $u_i$is $\sim 10^4 cm.s^{-1}$}. Thus the condition $ku_i \gg \omega$ holds good for our experimental observations. In this limit, the linear instability growth rate due to presence of an ion drift $u_i$is given by [13]

$$\gamma_{drift} = \omega_{pd}\sqrt{\frac{\pi}{8}}\frac{u_i}{v_{T_i}}\left(\frac{\lambda_d}{\lambda_{di}}\right)\frac{k\lambda_d}{\left(1+k^2{\lambda_d}^2\right)^{3/2}} \quad \text{….(1)}$$

where v_{T_i} is the ion thermal velocity. For our experimental parameters we get, $\gamma_{drift} \sim 40\ s^{-1}$ at $k \sim 48 cm^{-1}$. Thus ion drift effects, gives a possible mechanism for the linear instability growth for our experimental observation which was also attributed by Barken et. al. [3] and Fortovet. al. [13]

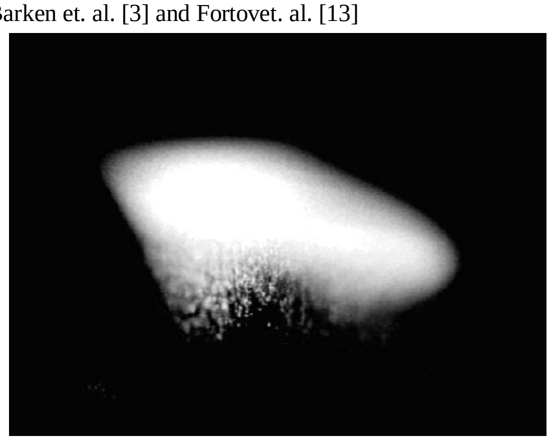

Fig: 9. Picture showing the the dust cloud at neutral pressure P(Ar)=0.30mbar and discharge voltage V_b=400V when the DAW disappears.

In our experiments DAW oscillation were observed to suppress when the discharge voltage was increased beyond $\sim 400\ V$ (Fig. 9). An increase in discharge voltage increases the ion density and hence a decrease in ion Debye length $\left(\lambda_i = \sqrt{T_e/(4\pi\varepsilon_0 n_i e^2}\right)$. This decreased Debye length in turn decrease the growth rate (Eq. 1) of the linear instability and so the wave disappears at higher discharge voltage.

In another model, Vaulina et al. [14] showed that the formation of different self-excited oscillations can be explained by the occurrence of dust charge gradients provided by the disturbance of electro-neutrality in the experimental plasma devices. These mechanisms transform the potential energy of an external field into the kinetic energy of dust grains without requiring any other background sources of energy. This mechanism was also attributed to be one possible source of self-excitation of dust grains rotation [17]. Thus this model provides a possible mechanism for many phenomenon like abnormal dust heating, rotation, regular oscillations etc., occurring in laboratory dust plasma.

In conclusion we have presented experimental observations of very low frequency *(~ 0.45 Hz)* waves propagating in glow discharge plasma which contains significant amounts of negatively charged dust grains. These oscillations have the general features of the self-excited DAW oscillations that have been observed by others [3, 8, 13-14]. In particular the phase velocity obtained from measurements of the dispersion relation was in good agreement with the theoretically predicted one.

These experiments were carried out to investigate the nonlinear state of a self-excited dust acoustic wave in strongly coupled dusty plasma characterized by $1 \leq \Gamma \leq \Gamma_c$. Molotkov et. al. [7] pointed out that dust acoustic instability can be initiated either by decreasing the neutral pressure in the discharge or by increasing the number of macro-particles in the dust cloud. A decrease in neutral pressure in-turn leads to an increase in the ion drift velocity and a decrease in the viscosity of the neutral gas. While by increasing the concentration of macro-particles in the dust cloud creates an additional mechanism for the loss of charges, which in turn increase in the ionization frequency at a fixed discharge current and consequently leads to intensification of the field in the region where the dust grains are found. This in turn, leads to a rise in the ion drift velocity u_i and as a result to an increase in the instability growth rate (Eq. 1). In our experiment first the concentration of macro-particles in the dust cloud was increased by mixing a little amount of manganese di-oxide dust with alumina dust. Afterwards the nonlinear states were obtained by a systematic controlled decrease of the background neutral pressure which concomitantly decreased the wave damping from dust neutral collision processes. The DAW was seen to evolve from an initial coherent state to an increasingly turbulent state. As discussed earlier, these results of excitation of DAW oscillation by decreasing the neutral pressure are in good agreement as observed by Pramaniket. al. [8].

Thus in our experiments we have demonstrated that DAW oscillation can also be excited by mixing of two dust. It is a new and simple technique and do not perturb the plasma environment due to presence of any external source as observed in other experiments [9]. To be best of our knowledge, so far it has not been reported by others.

Comparisons were made of experimental results with the theoretical models. It was attributed that ion driven instability taken along with the spatial charge gradient due to inhomogeneous bulk plasma can give a possible mechanism for the excitation of these DAW oscillations for our dusty plasma system.

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