Dust-Acoustic Waves: Visible Sound Waves

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Abstract. A historical overview of some of the early theoretical and experimental work on dust acoustic waves is given. The basic physics of the dust acoustic wave and some of the theoretical refinements that have been made, including the effects of collisions, plasma absorption, dust charge fluctuations, particle drifts and strong coupling effects are discussed. Some recent experimental findings and outstanding problems are also presented.

Keywords: dusty plasmas, dust acoustic waves
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INTRODUCTION

The term "dust-acoustic wave" first appeared in the 1990 paper by Rao, Shukla and Yu with their announcement that: "We find that a new type of sound wave, namely, the dust-acoustic waves, can appear" [1]. However, the possibility of a wave involving the dust grain dynamics with Boltzmann electron *and* ion distributions was first discussed by Padma Shukla at the First Capri Workshop on Dusty Plasmas in late May and early June of 1989 [2]. This was the genesis of the dust acoustic wave. The discovery of the dust acoustic wave has had a very significant impact on the work of many researchers. An informal inspection of the literature shows that over the past 20 years, an average of 25-30 papers per year have been published on dust acoustic waves and related topics. It is interesting to note that the original Rao, Shulka, Yu paper had already anticipated the need to include the effects of dust charge fluctuations as well as non-linear effects in subsequent treatments of dust acoustic waves [3]. The fact that the grain charge may be affected by the fluctuating wave potential is considered to be one of the unique features of a dusty plasma that distinguishes it from a multi-component plasma.

The motivations for studying dust acoustic waves are quite diverse. Dust-acoustic waves have been discussed in connection with various structures that have been observed in Saturn's rings, such as spokes, braids and clumps [4]. Ion-dust streaming instabilities, which could excite dust-acoustic waves, have been proposed as a mechanism for coupling the solar wind and cometary dust [5]. In astrophysics, dust-acoustic shock waves could trigger condensation of grains in dust molecular clouds. Dust-acoustic waves have been proposed as a diagnostic for dust growth in rf plasma processing reactors [6], and the high resolution images of Saturn's rings taken by the Cassini spacecraft are being scrutinized for evidence of Mach cones (dust-acoustic waves) which could provide information on the physical properties of the ring particles [7]. Finally, since dust-acoustic waves can be observed visually using laser light scattering and CCD video imaging, their study provides a unique opportunity to perform detailed investigations of wave-particle interactions at the level of individual particle dynamics, which is not possible in the study of ordinary plasma waves.

THEORY

When dust particles and plasma merge to form a dusty plasma, the usual plasma wave modes, e.g., ion-acoustic, ion-cyclotron, etc., are modified because a percentage of the electrons become attached to the dust grains so that equilibrium charge neutrality condition becomes

$$n_{io} = n_{eo} + Z_d n_{do} \tag{1}$$

where n_{jo} $(j=i,e,d)$ are the (ion, electron, dust) zero order densities and $Z_d = Q_d/e$ is the dust charge number. For these plasma modes, the relatively massive dust grains do not participate in the wave dynamics and are treated as an immobile negatively charged background distribution. On the other hand, the dust-acoustic mode frequencies are typically well below the electron and ion plasma frequencies, so that both the electrons and ions can be assumed to be in Boltzmann equilibrium.

Physics of the Dust-Acoustic Wave

The simplest model of the dust-acoustic wave is to consider the ions, electrons and dust as a multi-component fluid [1]. The ions, electrons and dust are taken to be at rest and homogeneous in zero order, having constant temperatures T_i, T_e, and T_d, and the dust charge is assumed to be constant. The dust obeys the continuity and momentum equations

$$\frac{\partial n_d}{\partial t} + \frac{\partial}{\partial x}(n_d u_d) \tag{2}$$

$$m_d n_d \left(\frac{\partial u_d}{\partial t} + u_d \frac{\partial u_d}{\partial x} \right) = -\gamma_d k T_d \frac{\partial n_d}{\partial x} + e n_d Z_d \frac{\partial \varphi}{\partial x} \ , \tag{3}$$

where m_d is the mass of the dust particles, u_d is the dust fluid velocity, γ_d is the ratio of specific heats for the dust fluid, and φ is the electrostatic potential. The inertia terms in the electron and ion momentum equations are ignored (Boltzmann)

$$0 = -kT_i \frac{\partial n_i}{\partial x} - e n_i \frac{\partial \varphi}{\partial x} \tag{4}$$

$$0 = -kT_e \frac{\partial n_e}{\partial x} + en_e \frac{\partial \varphi}{\partial x} \quad . \tag{5}$$

The potential, φ, is related to the charge densities by Poisson's equation

$$\frac{\partial^2 \varphi}{\partial x^2} = -\frac{e}{\varepsilon_o}\left(n_i - n_e - Z_d n_d\right). \tag{6}$$

To elucidate the basic physics of the dust-acoustic mode we take the dust to be cold and linearize Eq. (3) to

$$m_d \frac{\partial u_{d1}}{\partial t} = eZ_d \frac{\partial \varphi_1}{\partial x} \tag{7}$$

Where u_{d1} is the first-order dust fluid velocity and φ_1 is the wave potential. Eq. (4), (5) and (1) can be combined into one expression relating the ion and electron pressures, $P_{i1} = kT_i n_{i1}$ and $P_{e1} = kT_e n_{e1}$, to the wave potential φ_1

$$\frac{\partial}{\partial x}\left(P_{i1} + P_{e1}\right) = e\left(n_{eo} - n_{io}\right)\frac{\partial \varphi_1}{\partial x} = -en_{do} Z_d \frac{\partial \varphi_1}{\partial x}, \tag{8}$$

and using Eq. (8) in Eq. (7) we have finally

$$m_d n_{do} \frac{\partial u_{d1}}{\partial t} = -\frac{\partial}{\partial x}\left(P_{i1} + P_{e1}\right). \tag{9}$$

Eq. (9) paints a clear picture of the physics of dust-acoustic wave oscillations in which the dust provides the inertia with the plasma providing the restoring force.

Dispersion Relation

The dispersion relation ω(K) is obtained by combining the linearized forms of Eq. (2) – Eq. (6), and assuming all first-order quantities vary as exp[i(Kx-ωt)]

$$\omega = \left(\frac{kT_d}{m_d} + \frac{\lambda_D^2 \omega_{pd}^2}{1 + K^2 \lambda_D^2}\right)^{\frac{1}{2}} K, \tag{10}$$

where $\lambda_D = \left(\lambda_{De}^{-2} + \lambda_{Di}^{-2}\right)^{-1/2}$, $\lambda_{Dj} = \left(\varepsilon_o kT_j / e^2 n_{jo}\right)^{1/2}$, and $\omega_{pd} = \left(e^2 Z_d^2 n_{do} / \varepsilon_o m_d\right)^{1/2}$. For the case of cold dust ($T_d = 0$) and in the long wavelength limit, the dispersion relation reduces to $\omega/K = C_{DA}$, where C_{DA} is the dust acoustic speed given by

$$C_{DA} = \left(\frac{kT_i}{m_d} \frac{n_{do}}{n_{io}} Z_d^2 \right)^{\frac{1}{2}} . \tag{11}$$

Plots of the dispersion relation, Eq. (10), for typical parameters relevant to dust-acoustic wave experiments are shown in Fig. 1. In most laboratory experiments the wavenumbers lie in the range of 200π m^{-1} to 2000π m^{-1}, so that the typical frequencies are in the range of a few to tens of Hz.

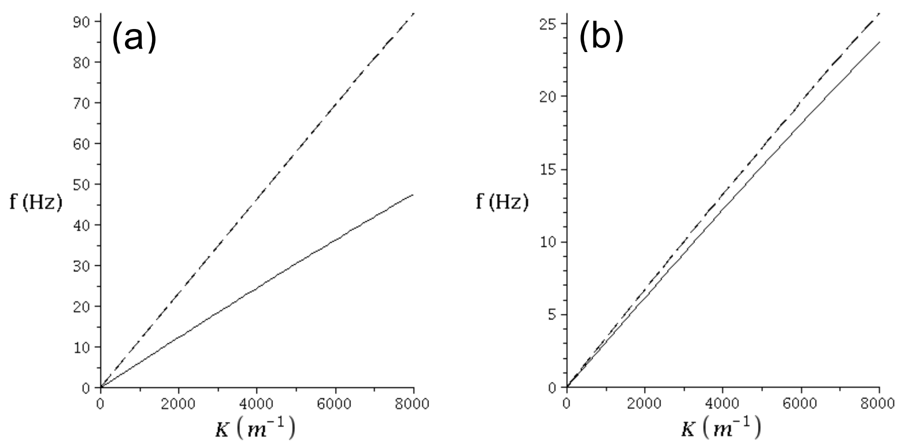

FIGURE 1. Dust-acoustic wave dispersion plots from Eq. (10) showing frequency (f) *vs*. wavenumber (K) for T_e = 2.5 eV, T_i = 0.025 eV, $n_{do}/n_{io} = 10^{-4}$. (a) a = 0.5 μm, Z_d = 2000; (b) a = 2.0 μm, Z_d = 8000. T_d = 0.025 eV (solid line), T_d = 25.0 eV (dashed line).

Current-Driven Dust-Acoustic Instability in a Collisional Dusty Plasma

Laboratory observations of dust acoustic waves have been performed in weakly ionized discharge plasmas. These plasmas are characterized by relatively high neutral pressures and the presence of currents. The analysis of dust-acoustic waves in these plasmas must then include collisions of electrons, ions and dust with the neutral atoms and zero-order drifts. The relative drift between ions and dust particles is the likely cause of the instability that drives the dust-acoustic waves in discharge plasmas. The effects of collisions and particle drifts have been considered in a number of works, using both fluid theory [8 - 12] and kinetic theory [13, 14]. A simple fluid model can be derived using the continuity equation [Eq. (2)] for electrons, ions and dust and the momentum equation [Eq. (3)] including momentum loss terms, $-m_j n_j \nu_{jn} u_j$ due to collisions with the neutrals, where ν_{jn} is the collision frequency between species j and the neutral atoms. A zero-order electric field (E_o) is included to account for the particle drifts, which are determined from $u_{jo} = eZ_j E_o / \nu_{jn} m_j$, $Z_j = +1, -1$, and $-Z_d$, for the ions, electrons and dust, respectively. The continuity and momentum equations along with

Eq. (6) are linearized, and for one-dimensional perturbations of the form $\propto \exp[i(Kx-\omega t)$, the following dispersion relation is obtained

$$1-\sum_{j=i,e,d}\frac{\omega_{pj}^2}{\left(\omega-Ku_{jo}\right)\left(\omega-Ku_{jo}+i\nu_{jn}\right)-K^2V_{j,th}^2}=0 \qquad (12)$$

where $\omega_{pj}=\left(n_je^2Z_j^2/\varepsilon_o m_j\right)^{1/2}$ and $V_{j,th}=\left(kT_j/m_j\right)^{1/2}$. Note that Eq. 12 contains the effects of finite ion and electron inertia. The dust-neutral collision frequency is given by the Epstein formula, $\nu_{dn}=4\pi a^2 N m_n V_{n,th}/3m_d$, where a is the radius of the dust grains, m_n is the mass of the neutral atoms, and $V_{n,th}=(kT_n/m_n)^{1/2}$ is the thermal speed of the neutral atoms at the temperature T_n.

Other Effects Unique to Dusty Plasmas

We include, for completeness a brief discussion of some of the other important effects that have been included in various analyses of dust-acoustic waves. In a sense, these are the effects which are novel to dusty plasmas and which differentiate it from the study of multi-component plasmas.

The Effect of Grain Charge Fluctuations

In a three month period from October 1992 to January 1993, groups at the Auroral Observatory in Tromsø, Norway [15], Ruhr University in Bochum, Germany [16], and the Institute for Plasma Research in Bhat, Gandhinagar, India [17], submitted papers which analyzed the effect of a time-dependent variation of the grain charge on electrostatic oscillations in a dusty plasma. This effect arises due to the fact that the charging currents to a dust grain depend on the grain surface potential relative to the plasma potential. In the presence of fluctuating wave potentials the plasma currents to the grain must also fluctuate. The importance of this effect depends on the wave frequency relative to the so-called charging frequency, which is the inverse grain charging time. It was shown that a phase difference between the dust charge variation and the wave can lead to a strong (collisionless) damping of the wave.

Strong Coupling Effects

In some laboratory dusty plasmas that are operated at relatively high neutral pressures (>> 1 Pa) the coupling parameter, $\Gamma=e^2Z_d^2/4\pi\varepsilon_o d kT_d$ can be much larger than 1, indicating that the dust is in a strongly interacting state. Here $d=\left(3/4\pi n_{do}\right)^{1/3}$ is the intergrain spacing. Even for $\Gamma\sim 1$, in which the dust is in a liquid-like state, the question arose as to whether or not the standard continuum treatments of dust-acoustic waves were valid. A number of groups grappled with how to include strong correlations in the wave formalisms, and various approaches have been considered including the quasi-localized charge approximation [18], the generalized hydrodynamic approach [19], and the generalized thermodynamic approach [20]. Melandsø [21] performed three-dimensional particle simulations taking into account hexagonal crystal structures with plasma flows using interparticle forces generated self-consistently by the plasma flow. These investigations showed that there are important modifications to the dust-acoustic wave dispersion relation, such as a decrease in the phase speed and new dispersive corrections, when the strong coupling effects are included. An experimental study of the dispersion of dust-acoustic waves in the strong coupling regime was carried out by Pieper and Goree [22].

A novel result that arose from the inclusion of strong coupling effects was the realization that a strongly couple dusty plasma could sustain, in addition to the longitudinal dust-acoustic mode, a low-frequency transverse mode. The transverse shear waves have been observed by Nunomura et al. [23], and Pramanik et al. [24].

Effect of Plasma Absorption on Dust

In the dust charging process, electrons and ions are removed from the plasma. To compensate these losses, an ionization source is required to maintain the plasma densities constant. This is a major distinguishing feature of a dust plasma as compared with a multi-component plasma. Thus the basic equilibrium state upon which wave perturbations are imposed is altered by the presence of dust. The corrections to the dispersion relation for the dust-acoustic wave that are introduced by this effect were analyzed by Tsytovich and Watanabe [25] who also took into account the neutral drag force on the dust and the dust charge variation. Their analysis showed that the modifications to the dispersion relation appear in combination with the effects of the drag force and dust charge variation, so that the effects of plasma absorption on the dust are important only if the drag and charge variation effects are included. It is argued [26], that these effects can give rise to a type of 'universal instability' in dusty plasmas that is driven by the external energy supplied to maintain the ionization source. These instabilities can occur even in the absence of the usual instability mechanisms, such as the presence of non-equilibrium particle distributions.

FIRST EXPERIMENTAL OBSERVATIONS OF THE DUST-ACOUSTIC WAVE

Some Historical Observations on Developments in Dusty Plasmas

The study of dusty plasmas developed along two parallel paths. Prior to 1990, a considerable amount of experimental work had been done by researchers concerned with the dust contamination problem in the plasma processing industry. The realization that dust particles were actually being grown or produced by sputtering in-situ in the processing reactors launched a concerted effort to understand the physics of the dust-plasma interaction [27] with the goal of devising ways to eliminate or at least control the dust in these plasmas. This was a significant milestone in the study of dusty plasmas. The other milestone came in 1981 and 82 with the Voyager observations of radial spokes in Saturn's B ring [28]. This discovery launched a flurry of activity in dusty plasmas from researchers mainly in the fields of space physics and astrophysics [29]. Of course, the role of dust in astrophysics was known for some time [30], but the awareness of the fact that the dust was likely to be charged significantly boosted the level of research activity in this field. Until roughly the mid 90's the two communities investigating dusty plasmas (industrial and space–motivated) continued to develop along parallel and for the most part non-intersecting paths.

The theoretical prediction of the dust-acoustic wave appeared in 1990 [1], but the first experimental observations were not made until 1994 and 1995. By 1993, there were already many theoretical papers on dusty plasmas but very few experimental papers. The formalism for including additional species in theoretical calculations was already in place, since multi-component plasmas had been studied for some time. However, figuring out how to get dust particles into plasmas, so that their properties could be studied, proved to be a difficult task for experimentalists. Once this was accomplished, devising diagnostics for dusty plasmas was even more challenging. Some experimentalists (the author included) were quite skeptical about our ability to make reliable measurements in a dusty plasma. Even when dusty plasma devices became available, there were no experimental plans (at least to my knowledge) to look for the dust acoustic wave. In our laboratory at the University of Iowa, our main interest was to study the effects of dust on the plasma modes that we were already familiar with, such as the electrostatic ion cyclotron wave and the dust acoustic wave. This was a simpler task that did not require having a confined dust cloud. We devised a method of dispersing dust into a magnetize plasma column, allowed it to fall through the plasmas where it became charged. Because the waves we studied were at frequencies well above the frequencies at which the dust could respond, the dust amounted to an immobile negatively charged background [31].

Coulomb Solids and Low-Frequency Fluctuations in RF Dusty Plasmas

In 1994, Chu, Du and I [32], reported on experiments in an RF hollow post magnetron system operated with an $SiH_4/O_2/Ar$ gas mixture. In this device, which was previously used for plasma chemical vapor deposition studies, SiO_2 particles are generated through gas-phase chemical reactions. The size of the particles was controlled by the on-time and pressure of the reactive gas. Negatively charged particles were suspended near the bottom of the discharge vessel by a strong electrostatic field. At high neutral pressure (300 mTorr) where the discharge fluctuations were suppressed, Coulomb solids composed of particles of about 10 μm diameter were observed using HeNe laser illumination. At lower pressures, low-frequency fluctuations (~ 12 Hz) were observed both in the plasma emission and in the scattered light emission. The fluctuations had a typical wavelength of 0.5 cm. It was noted that the plasma emission fluctuations and fluctuations in scattered light emission from the dust were out of phase, suggesting that the wave was a dust density wave. These observations were later interpreted by D'Angelo [33] as dust acoustic waves.

Laboratory Observation of the Dust-Acoustic Wave Mode at Iowa

Our observation of the dust-acoustic wave at the University of Iowa in 1995 [34] came about not as a matter of experimental design, but as often occurs, as a matter of happenstance. We were searching for a way to trap dust particles in the plasma. The common technique that was being used at that time was the parallel plate (GEC) RF discharge in which dust particles could be suspended in the sheath above the lower electrode. This method, however, suspends a few horizontal layers of particles, and our goal was to confine a three-dimensional dust cloud.

We modified our existing dusty plasma device, which was a single-ended Q machine with a rotating dust dispenser [31], by biasing the end plate at +200 V and raising the background neutral pressure of N_2 or Ar to about 1-10 mTorr. This configuration (shown in Fig. 3) forms an anode glow plasma within the existing K plasma column [34]. Since the plasma is magnetized, the anode glow is elongated along the magnetic field (we call this a 'firerod') and the interior of this secondary discharge plasma is at a relatively high potential relative to the background plasmas. The radial electric fields of the double layer provide the electrostatic trap for the charged dust particles. When the anode is in position 1 near the end of the rotating dust dispenser, dust grains could be trapped and confined indefinitely in the anode double layer. The dust particles formed a stable spherical structure (dust ball) a few centimeters in front of the anode. The dust particles were seen visually due to the illumination provided by the light from the Q machine hot plate. Initially, the dust ball rotated as a rigid object, but gradually over a period of seconds relaxed to the point where individual particles could be observed. If the voltage on the anode was suddenly turned off, the dust apparently retained at least a large fraction of its charge and the ball 'exploded'. These observations are described in more detail in ref. [35].

In order to provide a larger field of view to image the dust ball, we moved the anode back into the region of diverging magnetic field (position 2). However, much to our surprise, this completely changed the configuration so that instead of a dust ball, we were able to form a large, elongated dust cloud. This cloud contained spontaneously excited, visible vertical striations that propagated away from the anode. The fluctuations were imaged and recorded using a video camera and it was determined that the wave speed was 9 cm/s and the wavelength was 0.6 cm, so that the frequency $f = 15$ Hz. A single-frame image of the dust-acoustic wave is shown in the cutout in Fig. 1. The measured wave parameters were consistent with a dust-acoustic wave consisting of grains of ~5μm diameter, $Z \approx 4\times10^4$, and $n_{do}/n_{io} \approx 10^{-4}$. It was noted that the wave amplitude $n_{d1}/n_{do} = e\varphi_1/kT_i$ often approached 100% [34].

Because the dust-acoustic waves were self-excited in the experiment just described, it was not possible to determine the dispersion relation. We performed a measurement of the dispersion relation in a dc glow discharge plasmas device [36]. In this device a dc glow discharge was produced on a 3 cm diameter anode disk located in the center of a large, grounded vacuum vessel under an argon pressure of ~ 100 mTorr. Fine kaolin powder was incorporated into the plasma from a tray located beneath the anode. When the discharge was turned on, some of the dust on the tray was attracted up into the glow plasma where it was suspended by the electric fields associated with the anode glow.

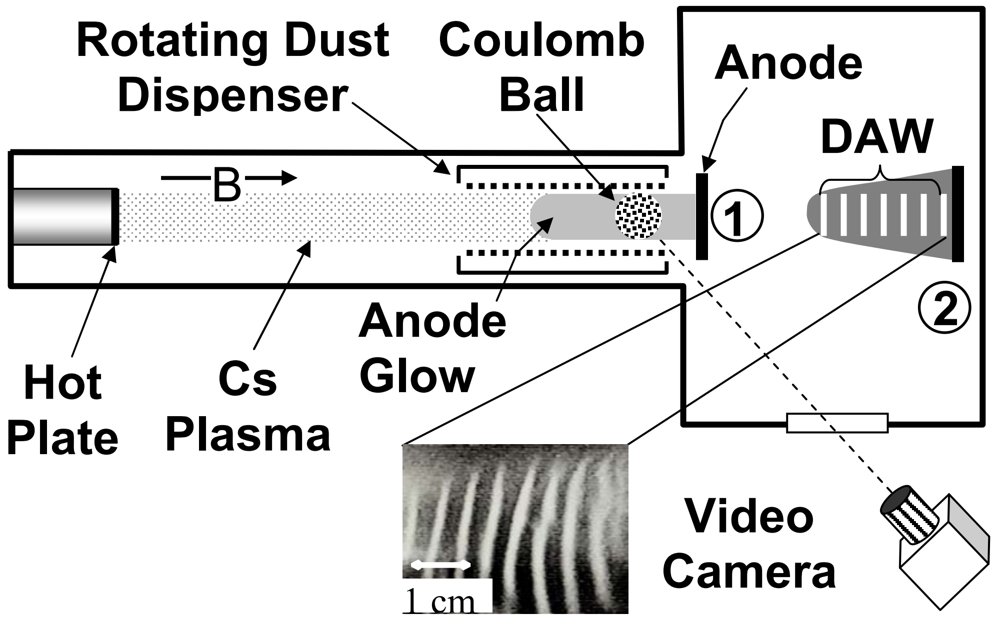

FIGURE 2. Schematic of the device used to observe dust-acoustic waves. Dust is trapped in an anode glow plasma. Dust (Coulomb) balls are observed when the anode is in position 1 and dust-acoustic waves are observed when the anode was moved to position 2.

The determination of the dispersion relation requires that the wave frequency be varied and the wavelength measured. The wave frequency was varied by applying a sinusoidal modulation voltage to the anode in series with the DC bias. The modulation frequencies were in the range of 5–30 Hz. The waves were observed using a video camera and the wavelengths were measured from single frame images. The wave speed derived from the dispersion plot shown in Fig. 3 is ~ 15 cm/s. The measured phase

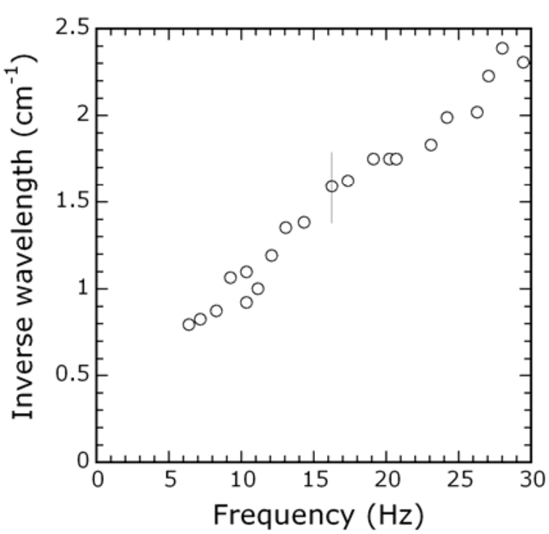

FIGURE 3. Measured dispersion relation for dust-acoustic waves [adapted from ref. 36].

speed was in agreement with the theoretical value obtained Eq. [11] using the experimental values of the dust and plasma parameters. Notice that in Fig. 3, the data points do not extrapolate to $1/\lambda = 0$ as $f \rightarrow 0$. This result was shown later to be due to the effects of dust-neutral collisions [37]. When ω is externally synchronized, the real part of the wavenumber is given by

$$K_r = \left[\omega \left(\omega + \sqrt{\omega^2 + \nu_{dn}^2} \right) \Big/ 2C_{DA}^2 \right]^{1/2} \qquad [13]$$

which gives rise to an 'offset' in the K vs. ω plot.

Other Effects Observed with Dust-Acoustic Waves

Although quite a lot of research has been done on dust-acoustic waves, there are outstanding issues. An observation that has been noted many times is that dust-acoustic waves observed in the laboratory tend to have very high amplitudes, so that the waves are clearly non-linear. To given an example, we show in Fig. 1 the spatial profile of scattered laser light intensity derived from the analysis of a single frame video image of a dust-acoustic wave. The scattered light intensity is proportional to the dust density.

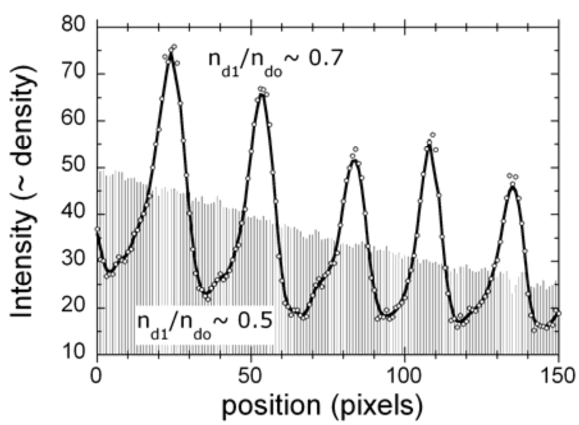

FIGURE 4. Spatial profile of the scattered light intensity (~dust density) in a dust-acoustic wave. The vertical lines represent the average intensity.

The average scattered light intensity (vertical lines) is obtained by averaging over a very long sequence of video frames. The wave amplitudes, n_{d1}/n_{do} corresponding to a wave trough and a wave crest are indicated. Two points are evident: First, the wave amplitudes are very high, and secondly the wave amplitude of the wave crest (compression) is larger than that of the trough (rarefaction). This latter effect is observed fairly regularly. In general, the peaks in the compressional part of the wave tend to be sharper compared to the troughs which tend to be more rounded. This effect could be due to the effect of a reduction in the dust charge that would accompany the increase in dust density in the wave crest. The reduction in dust charge in the compressional zone of the wave could lead to further compression.

Another unusual aspect that we have observed with dust acoustic waves are topological anomalies in the wave fronts. An example of this phenomenon is shown in Fig. 5. The wavefronts are often non-planar and may contain bifurcations or other defects, as indicated by the arrow. We have also observed wavefronts that split and reconnect to other wavefronts.

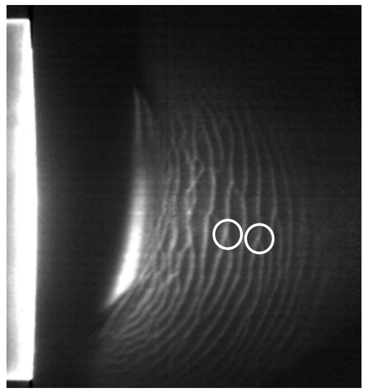

FIGURE 5. A single-frame video image, taken at 500 fps, of dust- acoustic waves showing topological anomalies (indicated by the circles) in the wavefronts.

CONCLUDING REMARKS

We have reviewed some of the historical developments in theoretical and experimental dust-acoustic wave research. Dust-acoustic waves seem to be a ubiquitous feature of dusty plasmas produced in discharge plasmas. This is most likely due to the fact that discharges are maintained by currents so that there is a relative drift between the ions and dust particles. The ion-dust streaming instability is the likely excitation mechanism of the dust-acoustic waves.

Some of the outstanding issues in dust-acoustic wave research have been briefly mentioned. Dust-acoustic waves tend to be non-linear and topological defects in the wavefronts are also a common feature. In future work on dust acoustic waves, we plan to investigate dusty plasmas with ferromagnetic dust particles, allowing for the possibility of a long-range attractive magnetic dipole-dipole interaction in addition to the usual repulsive shielded Coulomb interaction between particles [38].

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