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25 years of dust acoustic waves

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The dust acoustic wave (DAW) was first discussed by P. K. Shukla in May of 1989 at the First Capri Workshop on Dusty Plasmas. In the past 25 years, the subsequent publication of the linear and nonlinear properties of the DAW (Rao, N. N., Shukla, P. K. and Yu, M. Y. 1990 *Planet. Space Sci.* **38**, 543) has generated and sustained a large body of theoretical and experimental research that has clarified the physics of collective effects in dusty plasmas. A unique feature of the DAW is that it can be observed (literally) using laser illumination and high-speed videography, revealing details of wave-particle interactions at an unprecedented single particle level. This paper attempts to review some of the contributions and extensions of dust acoustic wave physics, as well as identify recent findings that illustrate the potential importance of this dust wave in the agglomeration of dust particles.

1. Introduction

2014 marks the 25$^{\text{th}}$ anniversary of the theoretical discovery of the dust acoustic wave (DAW) by Padma K. Shukla. Toward the end of the First Capri Workshop on Dusty Plasmas in May of 1989, Shukla discussed with Umberto de Angelis (private communication, 2009) the possibility that a dusty plasma might support a very low frequency mode that involved the dynamics of the heavy, charged dust particles. Prior to this point, only the effect of immobile dust on ion waves had been considered (de Angelis et al. 1988). The issue was how to model the charged dust. Shukla suggested that a dusty plasma could be treated as a multicomponent plasma using fluid theory. Furthermore, due to the extreme disparity of the masses, both the electrons *and* ions could be modelled using the Boltzmann distribution. The details were worked out later in Bochum and published in Planetary and Space Science (Rao et al. 1990).

This paper will review some of the early theoretical and experimental work on DAWs as well as the refinements to the basic theory and the more detailed measurements that were made as improved laser diagnostics and image processing techniques became available. The focus is mainly on DAWs observed in dusty plasmas in the gaseous or liquid state. It must be pointed out that this article deals with longitudinal (compressional) dust waves which are referred to as DAWs, although others refer to these more generically as dust density waves (DDWs).

2. Dust acoustic wave theory

2.1. *Linear dispersion relation*

The simplest theory of the DAW is obtained from the linearized continuity and momentum equations for cold, collisionless, non-flowing dust with particle mass m_d

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and constant charge number Z_d. Let the perturbed (first order) dust density and velocity be designated respectively as n_d and v_d, with n_{d0} the zero-order dust density. The linearized continuity and momentum equations for wave propagation in the x-direction are respectively,

$$\frac{\partial n_d}{\partial t} = -n_{d0}\frac{\partial v_d}{\partial x} \tag{1}$$

$$\frac{\partial v_d}{\partial t} = \frac{eZ_d}{m_d}\frac{\partial \varphi}{\partial x}, \tag{2}$$

where φ is the first-order electrostatic potential. The linearized Boltzmann relations for the ions and electrons are $n_{(i,e)} \approx \mp n_{(i,e)0}\left(e\varphi/k_B T_{(i,e)}\right)$. In the long wavelength limit, $\lambda \gg \lambda_{Di}$, where λ_{Di} is the ion Debye length, the quasineutrality condition can be used, so that $n_i \approx n_e + Z_d n_d$,where it is assumed that the dust is negatively charged. Combining the quasineutrality condition and the Boltzmann relations relates the dust density to the electrostatic wave potential as

$$n_d = -\frac{\varepsilon_o}{eZ_d\lambda_{D,eff}^2}\varphi, \tag{3}$$

where $\lambda_{D,eff}$is the "effective Debye length" defined by $\lambda_{D,eff}^{-2} = \lambda_{Di}^{-2} + \lambda_{De}^{-2}$, where $\lambda_{D(i,e)}$ is the (ion, electron) Debye length. Taking $\partial/\partial t$ on (1) and $\partial/\partial x$ on (2), equating the mixed partial derivatives of v_d, and using (3) we obtain the one-dimensional dust acoustic wave equation

$$\frac{\partial^2 n_d}{\partial x^2} = \frac{1}{C_{DA}^2}\frac{\partial^2 n_d}{\partial t^2}, \tag{4}$$

where $C_{DA} = \omega_{pd}\lambda_{D,eff}$ is the DA wave velocity, with $\omega_{pd} = (n_{d0}e^2 Z_d^2/\varepsilon_0 m_d)^{1/2}$ the dust plasma frequency. Equation (4) admits plane wave solutions $n_d(x,t) = \tilde{n}_{d0}\exp[i(Kx-\omega t)]$, where ω and K are the angular frequency and wavenumber, which are related by $\omega/K = C_{DA}$. For typical laboratory dusty plasma conditions, $T_i \ll T_e$, so that $\lambda_{D,eff} \approx \lambda_{Di}$, then the DA velocity can be written as $C_{DA} \approx P_H(n_i k_B T_i/m_d n_{d0})^{1/2}$, where $P_H = Z_d n_{d0}/n_{i0} = (n_{i0}-n_{e0})/n_{i0}$ is the Havnes' parameter. As an example: for k_B Te = 2.5 eV = $100T_i$, $n_{i0} = 1\times10^{14}\,m^{-3}$, dust radius a = 0.5 μm, $Z_d = 2000$, k_BTd = 0.025 eV, $m_d = 10^{-15}$ kg, $n_{d0} = 1.0\times10^{10}\,m^{-3}$, C_{DA} = 4 cm/s. For a typical wavelength of 0.5 cm, the DA wave frequency is then 8 Hz.

2.2. *Dust acoustic instability*

DAW excitation was analyzed by Rosenberg (1993, 1996) and Melandsøet al. (1993a) using kinetic theory, and D'Angelo and Merlino (1996) using fluid theory. The general finding was that dust acoustic instability would be excited for ions drifting through the dust with a drift velocity greater than the wave phase velocity. Since the phase velocity is considerably below the ion thermal speed, only a relatively modest ion drift is needed for wave excitation. In typical laboratory discharge plasmas, ion drifts ∼ the ion thermal speed are typically produced by the externally imposed electric fields that sustain the discharge. As a result, self-excited DAWs tend to be ubiquitous in laboratory plasmas with three-dimensional dust suspensions if the neutral pressure is not too high (Merlino 2009). Piel (2011) has argued that in situations in which the ion drift is larger than the ion thermal speed, it is more appropriate to call these waves "dust density waves" (DDW), since in that case, the phase velocity of the unstable DDW deviates from the DAW, since ion shielding is reduced.

A pedagogical approach to DAW excitation is obtained by considering the case of an ion/cold dust plasma (i.e. no free electrons), with ion-neutral and dust-neutral collisions taken into account in the presence of a zero-order electric field which imposes a relative drift between the ion and dust fluids (D'Angelo and Merlino 1996; Merlino and D'Angelo 2005). For a dust drift velocity $\ll$ the wave phase velocity, $\mathrm{v_{ph}}$ the dispersion relation yields a growth rate $\gamma \approx -[\nu_{dn} + (Z_d m_i \nu_{in}/m_d)(1 - u_{io}/\mathrm{v_{ph}})]/2$, and phase velocity (near marginal stability) $\mathrm{v_{ph}} = \omega_r/K \approx (Z_d k_B T_i/m_d)^{1/2}$,where u_{io} is the ion drift velocity, ω_r is the real wave angular frequency, K is the wave number and ν_{in} and ν_{dn} are the ion- and dust-neutral collision frequencies. For instability, u_{io} must exceed the phase velocity by an amount sufficient to overcome the damping due to dust-neutral collisions. Note that the phase velocity coincides with the DA velocity, C_{DA}.

Particle simulations of the ion-dust streaming instability in which the ions and dust were treated as discrete particles and the electrons as a Boltzmann fluid were carried out by Winske et al. (1995). These simulations followed the linear and non-linear evolution of the instability and found that it saturates by trapping some of the plasma ions. Heating of the dust particles by waves not large enough to trap them were also observed. These simulations also showed that the instability was only slightly weaker when a range of dust sizes were included.

2.3. *A new collisionless damping mechanism for the dust acoustic wave*

A defining characteristic of a dusty plasmas is that when the dominant charging mechanism is collection of plasma electrons and ions, the dust charge is not a fixed quantity. The dust charge depends on plasma conditions, and may fluctuate due to fluctuations in the plasma potential produced, for example by electrostatic waves. The effect of grain charge perturbations on dust acoustic waves was first considered by Melandsø et al. (1993b) and Varma et al. (1993). The phase difference between the grain charge variation and the wave potential was found to produce a strong damping effect on the wave. This damping mechanism is a purely collisionless effect.

2.4. *Effects of strong coupling*

Due to the large charge on the dust particles, dusty plasmas often occur in a strongly coupled state, in which the Coulomb coupling parameter $\Gamma = Q_d^2/4\pi\varepsilon_o a k_B T_d$ can be on the order of or considerably greater than 1 ($Q_d = eZ_d$ is the dust charge, and $d = (3/4\pi n_{d0})^{1/3}$ is the interparticle spacing for a dust suspension of density n_{d0}). An important question is: How are the dispersion and excitation properties of the dust waves modified when strong coupling effects are taken into account? This question has been considered by a number of authors and remains a current research topic. A review of work on strong coupling effects was given by Donko et al. (2008).

Three approaches have been used to include the effects of strong coupling on dust acoustic waves. Kaw and Sen (1998) used the generalized hydrodynamic model in which strong coupling effects were included through the use of viscoelastic coefficients. This model holds for values of Γ below the critical value for crystallization. This model showed that strong correlations led to new dispersive effects and a reduction in the frequency and phase velocity. They also showed the possibility of a new transverse mode – a dust shear mode. Wang and Bhattacharjee (1997) also used a hydrodynamic approach known as he generalized thermodynamic model. They showed that in the presence of slow DAWs, the dust grains play a significant role in determining the Debye shielding of the dust particles. Rosenberg and Kalman (1997) used a different approach based on the quasilocalized charge approximation (QLCA). The QLCA relates the small wavenumber dispersion to the total correlation energy of the system. This approach was used to determine when the effects of strong coupling would be more important that collisional effects due to dust-neutral collisions. In a recent extension of this work (Rosenberg et al. 2014) showed that in a dusty plasma in the liquid state, strong coupling effects lead to an enhancement of the growth rate of the DA instability.

3. Experimental observation of the dust acoustic wave

The early 1990s saw rapid development of experiments specifically designed to produce and study dusty plasmas. Most of the experimental work prior to that point was performed in devices used for plasma processing of semiconductors. In these devices, dust particles were an undesired contaminant that were created within the plasma, and the emphasis was on understanding the origin of the particles and developing methods for their removal. Researchers began to invent methods of embedding dust particles within plasmas so that their behavior could be investigated. Since plasma processing devices used RF plasma sources, many of the first generation of dedicated dusty plasma experiments were based on this technique. The GEC device developed in conjunction with the Gaseous Electronics Conference remains one of the most widely used devices for dusty plasma research.

3.1. *Early observations of dust acoustic waves*

The first report of very low frequency fluctuations in a dusty plasma was made by Chu et al. (1994). They used an rf magnetron device in which dust particles were grown in-situ in a $SiH_4/O_2/Ar$ plasma. Fluctuations in the plasma emission and scattered light from the dust were observed at a frequency of 12 Hz and wavelength of 5 mm. The fluctuations in the plasma emission and scattered light from the dust were out of phase. It was also noted that the fluctuations disappeared if the neutral pressure was increased above a critical value, and a Coulomb solid was formed. D'Angelo (1995) interpreted these fluctuations as DAWs.

Basic dusty plasma experiments at the University of Iowa were carried out by two groups – one in the D'Angelo/Merlino lab, and the other in John Goree's lab. Our approach (D/M) was to utilize the Q machine as the basic plasma source and to figure out a way to introduce dust into the plasma. The Q machine was modified by adding a rotating dust dispenser surrounding the plasma column that introduced a gently rain of dust that fell through the plasma column (Xu et al. 1992). Since the dust was not confined in the plasma, this approach could only be used to study dust effects on plasma wave modes, such as ion-acoustic waves and electrostatic ion cyclotron waves (Merlino et al. 1998). To confine the dust, the Q machine was further modified by terminating the plasma column on an anode plate and introducing neutral gas to form an anode double layer (anodic plasma) embedded within the plasma column (Barkan and Merlino 1995). The motivation here was the fact that anodic plasmas in magnetized plasmas contain strong radial electric fields (the anodic plasma has a positive potential relative to the main plasma) that could provide confinement of the dust grains. These expectations were borne out, although the confinement of dust in the anodic plasma was not fully understood until much later (Trottenberg et al. 2006). The dust that was trapped in the anode double layer was well illuminated by light emitted from the Q machine hot plate, and could be observed with the naked eye. For neutral gas pressures (N_2) in the range of 60 – 80 mTorr and anode potential 200 V, very low frequency waves (15 Hz) were observed to propagate at about 9 cm/s

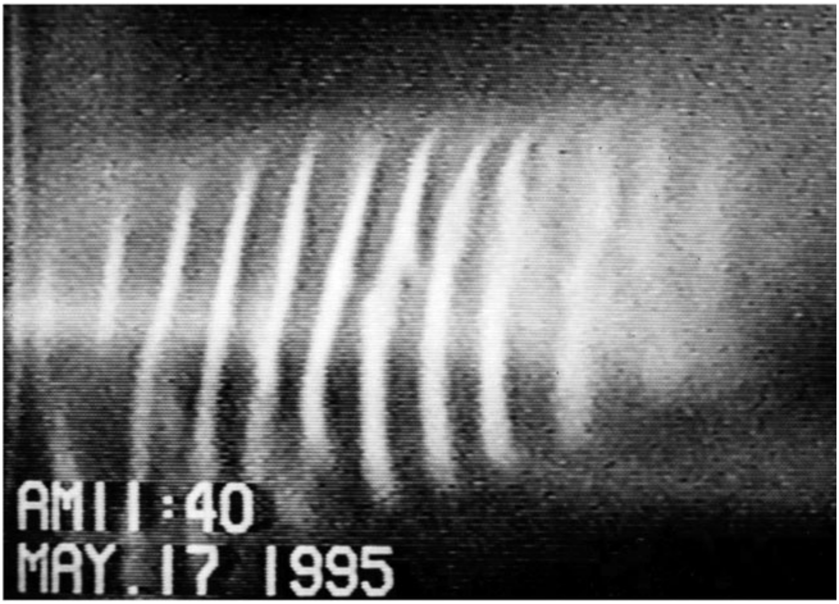

FIGURE 1. Single frame image of a self-excited dust acoustic wave in a DC glow discharge dusty plasma. The bright vertical structures are the wave crests. The wave propagates from right to left.

away from the anode plate. From single frame images of the waves, the wavelength (measured with a ruler) was found to be about 0.6 cm (Barkan et al. 1995). A photo of a DAW observed in this device is shown in Fig. 1. The measured wave properties were in general agreement with linear theory of the DAW, and the excitation was attributed to the ion-dust streaming instability driven by the ion current directed away from the anode.

Dust acoustic waves were observed in a hot cathode (filament) argon (P 1 mTorr) plasma by Prabhakara and Tanna (1996). Alumina powder (0.3 μm average diameter) spread on a plate at the bottom of the plasma chamber was attracted into the plasma and trapped there. The DAW fluctuations were self-excited and could be seen with the naked eye. Fluctuations in the scattered light from the dust and plasma emissions were 180° out of phase, as expected for the DAW.

3.2. *Measurement of the DAW dispersion relation*

Self-excited DAWs provide only one point on a dispersion curve. To measure the dispersion relation the wave frequency must be varied. The measurement of the DAW dispersion relation was performed in a dc glow discharge dusty plasma (Thompson et al. 1997). A glow discharge in argon (P$\sim$70 – 100 mTorr) was formed on a 3 cm diameter anode disk located in a large grounded vacuum vessel. A magnetic field of sufficient strength (9 mT) to magnetize the electrons was used to produce axially elongated anode glows, or *firerods* (An et al. 1994). Dust particles located on a tray beneath the anode were spontaneously incorporated into the plasma during startup of the discharge. DAWs spontaneously appeared in this device when a sufficiently robust dust cloud was formed. The dispersion relation was obtained by applying a sinusoidal voltage modulation to the anode (in series with the DC bias) in the range or 5 – 50 Hz. If the amplitude of the modulation was large enough, DAWs were synchronized to the driving frequency, so by varying the frequency and measuring the wavelength,

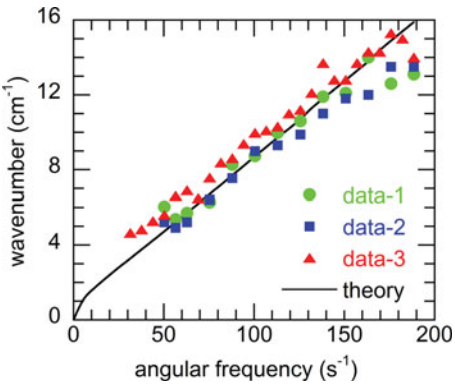

FIGURE 2. (Colour online) Measured DAW dispersion relation, wavenumber vs. angular frequency. Symbols represent different data sets. The solid line is the theoretical dispersion relation obtained from fluid theory.

the dispersion relation was obtained, as shown in Fig. 2. Three different data sets obtained at nominally the same conditions are plotted to indicate the reproducibility and spread in the data. The solid line is a theoretical dispersion relation, also taking into account dust-neutral collisions (for further details see Merlino et al. 1998).

Measurements of the power spectrum and the dispersion relation for self-excited DAWs were performed by Nosenko et al. (2009). At low wave numbers, the wave frequency did not tend to zero, but reached a cutoff frequency. This cutoff was attributed to particle confinement effects.

3.3. *Dust acoustic waves in the strong-coupling regime*

Laboratory dusty plasmas tend to be in the strongly coupled liquid state (not gas-like or crystallized). Thus, DAW studies could potentially provide insight into strong coupling effects. Pieper and Goree (1996) performed measurements of the DAW dispersion relation on a modified parallel plate rf driven plasma in which three layers of 9 μm spherical dust particles were levitated in the sheath above the powered electrode. Longitudinal dust waves were not self-excited, but were driven by a sinusoidal signal applied to a wire stretched across the electrode. The real and imaginary parts of the complex wave number were measured for driving frequencies in the range of 1 – 10 Hz, and at gas pressures of 55, 100, 220, and 300 mTorr. The measured dispersion curves obeyed the wave dispersion relation obtained from the simple fluid theory, including the effect of dust-neutral collisions, but with no strong coupling effects included.

Experimental evidence of strong coupling effects on DAWs produced in an AC modulated DC discharge were reported by Bandyopadhyay et al. (2007). The effect of dust-neutral collisions was a complicating factor in these measurements, and a clear signature of strong coupling effects predicted by Kaw and Sen (1998) was only observed at low pressures.

4. Further experimental developments on dust (density) acoustic waves

Technological advances in solid state lasers, fast megapixel video cameras, gigabyte computer memory, and image analysis software have been exploited over the last 20 years permitting detailed measurements of the behavior of dust acoustic (or dust density) waves. Real time recording using fast (∼1000 frames/s) digital video cameras has replaced the use of analog cameras operating at 30 frames/s, and frame grabber boards to obtain single frame images. By contrast, the DAW in Fig. 1 was taken 20 years ago using a commercial analog video camera and recorded on VHS tape. The tape was played back on a VCR and TV, and the paused image on the TV screen was photographed.

In this section, I highlight some of the experimental developments in dust acoustic wave physics that have occurred over the last 20 years. Since 1990, about 50 papers/yr have been published on various aspects of DAWs and although the majority of these papers were theoretical, there has been a large increase in the number of dusty plasma experiments.

4.1. *Dust acoustic waves in positive column discharges*

Lipaev et al. (1997) discovered that dust particles could be trapped in the standing striations of a DC positive column discharge operated at a pressures from 0.1 to 2 Torr. Dust acoustic waves were observed in this device (Molotkov et al. 1999), and were attributed to the ion/dust streaming instability. The authors point out that in rf discharges the dust particles are levitated near the bottom electrode where the ion drift velocity is $\gg$ the ion thermal speed. Under these conditions, Landau damping would significantly reduce the instability growth rate. In subsequent theoretical and experimental work using the same type of positive column device, it was shown that in the presence of external charge-dependent forces, dust charge variations together with an ion drift caused the instability. This was identified this as a new type of instability that has no analog in ordinary (non-dusty) plasmas (Fortov et al. 2000).

4.2. *Dust acoustic waves under microgravity conditions*

Dust (density) acoustic waves have also been studied under microgravity conditions on dusty plasmas on parabolic flights and onboard the International Space Station (ISS). The first study of low-frequency dust waves performed with the PKE-Nefedov device on the ISS was reported by Khrapak et al. (2003). Grains of two radii (1.7 and 3.4 μm) were injected into the rf produced plasma at a pressure of 24 Pa in argon gas. The smaller grains accumulated closer to the central axis and the larger grains near the top of the cloud. The dust waves were excited by applying a low frequency modulation to the rf electrode. Compressional dust waves were observed only in the small grain cloud. By varying the modulation frequency, the wave dispersion relation was measured. In a later campaign, the experiment was repeated but at a pressure of 12 Pa (Yaroshenko et al. 2004). Dust density waves were observed in both the small and large grain clouds, and a specific waveguide appeared in the dusty plasma that extended from the edge of the void to the edge of the cloud. The measured dispersion relation for these "guided" DAWs was reported by Annibaldi et al. (2007). Dust density wave experiments were also performed on the PK-3 Plus device on ISS. Both self-excited nonlinear waves and modulation-excited waves were observed (Schwabe et al. 2008). Detailed measurements of the particle dynamics in the wave were also performed.

Obliquely propagating dust density waves moving away from the dust void in an rf produced dusty plasma at 15 Pa were observed during a parabolic flight campaign operated by the German Aerospace Center (Piel et al. 2006). A novel observation was that dust density waves propagated at an oblique angle with respect to the ion flow direction. A theoretical model taking into account arbitrary propagation angles was applied to explain the results.

4.3. *Dust acoustic waves in anodic discharges, wave synchronization*

A number of detailed investigations of dust (density) acoustic waves have been carried out by the group in Kiel, Germany under the direction of Alexander Piel. These experiments were carried out in a weakly magnetized, rf powered linear plasma device in argon at 2 Pa. A 3 cm disk located on the axis of the device was used to produce a secondary anodic plasma in which dust particles were trapped. In addition to the wave observations, a detailed study of the dust confinement in the anodic plasma was performed (Trottenberg, 2009). This study showed that the dust cloud was confined by the combination of electric and ion drag forces. DAWs were spontaneously excited and propagated away from the anode. The wave properties were determined using singular value decomposition (SVD). A modulation voltage applied to the anode was use to synchronize the wave frequency. Real wave frequency and growth rates were obtained and compared to both fluid and kinetic theory of DAWs. In a follow-on study the mechanism of the frequency synchronization was investigated (Pilch, et al. 2009). Although frequency synchronization had been successfully used in a number of experiments, this was the first attempt to understand how the synchronization worked. Synchronization of self-excited dust density waves observed in an rf parallel plate dusty plasma in which a dust cloud was confined horizontally in a glass box was also studied by Ruhunusiri and Goree (2012). They discussed the observed synchronization in terms of the commonly used van der Pol oscillator, but found that some aspects of their observations differed from this model.

4.4. *Vertically propagating DAWs, PIV studies, finite dust temperature effects, and frequency clustering*

The application of particle image velocimetry (PIV) to the study of dusty plasmas was pioneered by Ed Thomas (1999). This technique provides measurement of time resolved 2D dust velocity profiles. PIV was successfully applied to obtain 2D mappings of the velocity of dust particles undergoing oscillations in dust acoustic waves (Thomas, Jr. and Merlino 2001). A stereoscopic addition to this method was used to study the spatial growth of DAWs over several wavelengths as the wave grew to the saturation level (Thomas, Jr. 2006). A measurement of the dispersion relation for vertically propagating DAWs was reported by Williams et al. (2008).

The effect of finite dust temperatures on the DAW dispersion relation has been a major focus of research (Thomas, Jr., et al. 2007, Rosenberg et al. 2008, Avinash et al. 2011). Williams and Snipes (2010) using the WUDUPE device measured dust temperatures in a dusty plasma with DAWs present and found that the dust temperature was significantly higher than the other plasma components. In the same device Williams and Duff (2010) confirmed that driven DAWs occur at the same frequency as the current modulation.

Menzel et al. (2010) using an rf discharge on a parabolic flight discovered the phenomenon of “frequency clustering.” Using a Hilbert transform technique to determine the wave amplitude and phase, they observed partial synchronization of the wave frequency within multiple domains. Williams (2014) applied the same technique to study the spatiotemporal evolution of self-excited DAWs in a DC discharge device (WUDUPE), and showed that frequency clustering occurred over a broad range of neutral pressures with the spatial distribution of the clusters varying with pressure.

4.5. *Measurements of the growth of dust (density) acoustic waves*

Various researchers have reported measurements of the growth rate of spontaneously excited DAWs and compared the results with a linear theory of the DA instability.

Zobnin et al. (2002) used an inductively coupled positive column discharge to trap dust and measure the spatial growth rate of DAWs. Their results were compared with an analytic fluid model that included the effects of a DC electric field, gravity, thermophoretic, and ion drag forces, as well as collisions with neutrals and dust charge variations. They concluded that the wave excited by the DA instability is indeed a DAW driven primarily by the DC electric field but also facilitated by the variable charge on the dust.

Flanagan and Goree (2010) observed the spatial growth of DDWs in an rf plasma, with dust confined in a glass box. For the particular conditions of their experiment, they found that the DDWs were only present for argon pressures below 426 mTorr. Growth rate measurements were made just below the threshold pressure so that relatively small amplitude waves (in the linear regime) would be excited. They used a lock-in amplifier, so that both the wave phase and amplitude could be measured. They were able to measure the linear growth rate of the waves as a function of neutral pressure, and compare their measurements with a fluid model.

Heinrich et al. (2011) measured the growth rate of self-excited DAWs in a DC anode glow discharge. A mesh electrode was used to trap a secondary *quiescent* (no DAWs present) dust cloud (the primary cloud was formed near the anode) which, when released would flow toward the primary cloud. As the secondary cloud drifted, DAWs grew spontaneously out of the noise, permitting a determination of the linear growth rate in a system that was not previously affected by the presence of dust waves. In contrast to previous observations of self-excited DAWs, the waveforms were sinusoidal in the linear growth phase. The measured growth rate compared well with a kinetic model of the DA instability including the effects of ion-, electron- and dust-neutral collisions (Rosenberg et al. 2008).

4.6. *Nonlinear dust acoustic waves, wave-particle interactions, turbulence, and shocks*

One of the common observations in DAW experiments is that the wave amplitude is quite large, so that the waves are in the nonlinear state. Self-excited (by drifting ions) nonlinear and highly resolved DDWs were observed in the ground-based PK-3 Plus device (Schwabe et al. 2007). Individual particles could be followed interacting with the waves allowing observation of their resonant Landau acceleration. Liao et al. (2008) investigated particle-wave microdynamics of dust in large amplitude DAWs. The waves induce dust particle oscillations which, with increasing amplitude, leads to disordered particle motion, trapping and heating of the dust. Teng et al. (2009) observed wave breaking of self-excited large amplitude DAWs. Flanigan and Goree (2011) observed the transition to nonlinear DDWs as the gas pressure was reduced. The onset of nonlinearity was indicated by the presence of harmonics with high amplitudes, with doubling and tripling of the growth rates of the second and third harmonics compared to that of the fundamental. In a DC anode glow discharge, Merlino et al. (2012) observed non-sinusoidal DA waveforms, which compared well to a second order theory of DAWs. In a related work, Heinrich et al. (2012) observed large dust particle oscillations, displacements, and trapping of dust particles in large amplitude DAWs. Secondary DAWs were excited in the wave troughs of the nonlinear DAWs which were attributed to a dust-dust streaming instability.

Pramanik et al. (2003) studied the transition to a turbulent DAW spectrum in a DC glow discharge. As the gas pressure was lowered, the DAW oscillations changed from a coherent to a turbulent state through the excitation of higher harmonics. Tsai et al. (2012) observed self-excited intermittent DAW turbulence in a low pressure rf dusty plasma. A broad spectrum of dust density fluctuations was observed with spectral power scaling with frequency as $S(f) \sim f^{-2.6}$.

DA shocks were produced using the PKE-Nefedov laboratory on board the ISS by Samsonov et al. (2003). The shocks were initiated by a suddenly applied gas pulse that created a travelling perturbation in the dust cloud that speeded up and steepened into a DA shock. Fortov et al. (2005) used a vertically stratified DC glow discharge in which injected dust particles levitated in a striation. The cylindrical discharge vessel was surrounded by a circular coil which when suddenly energized by a HV capacitor bank, created a magnetic pulse that excited a perturbation in the dust cloud that steepened into a shock as it propagated. Shock compression ratios up to 15 were observed. Heinrich et al. (2009) reported observations of self-excited DA shocks. Nonlinear DAWs were observed to steepen as they travelled and developed into saw-tooth like structures with a sharp front having a thickness on the order of the interparticle spacing. The evolution of the DA shocks was in good agreement numerical calculations based on the fully nonlinear DA fluid equations (Eliasson and Shukla 2004; Merlino et al. 2012; Shukla and Eliasson 2012).

5. Importance of dust (density) acoustic waves

The study of DAWs is motivated by their potential impact on a broad range of phenomena:

• *Basic plasma physics.*—DA/DDWs, shocks, and solitons can be studied at the single-particle level. Thus dusty plasmas with DAWs provide a unique platform for the investigation of wave-particle interactions that is not possible in ordinary plasmas.

• *Natural phenomena.*—Dusty plasmas occur in many space and astrophysical systems, and DAWs (DDWs) have been discussed as a possible mechanism for fluctuations observed in these systems. Examples include: (a) the earth's mesosphere, (b) planetary rings, (c) comet tails, and (d) the Moon.

• *Dust agglomeration.*—DAWs and shocks may accelerate dust to sufficient velocities to enable like-charged dust grains to stick together even in the presence of Coulomb repulsion.

There are presently several satellite missions investigating the moon, probing its dust environment in hopes of understanding how the lunar regolith particles might be lofted above the surface. Theoretical studies have indicated the possibility that DAWs might be excited in the vicinity of the lunar terminator (Popel et al. 2013). In November of 2014 the Rosetta spacecraft will rendezvous with comet 67P/Churyumov-Gerasimenko and escort it around the sun. This will be the first time that observations of the full range of cometary dusty plasma phenomena will be studied from the bare nucleus to its fully developed tail. Mendis and Horányi (2013) point out that the high resolution cameras on Rosetta might be able to capture small scale structures associated with DAWs. Excitation of DAWs due to interactions by solar wind ions streaming through the tail has been predicted (Arshad et al. 2014). Theoretical studies have investigated the possibility that nonlinear DA solitary waves might be excited by the relative drift between ions and dust in Saturn's E, F, and G rings (Ghosh et al. 2001).

Two experiments have demonstrated agglomeration of micron-sized particles in dusty plasmas under the action of large amplitude DA/DDWs. Dust particles can be grown in chemically active plasmas, and proceed through various phases of agglomeration reaching sizes vv100 nm. However, agglomeration beyond this level is inhibited by the Coulomb repulsion of like-charged dust. (Smaller particles $<$ 100 nm, may be either positively or negatively charged due to charge fluctuations.) Du et al. (2010) presented evidence that agglomeration of negatively charged dust particles was caused by strong DAWs in a dusty plasma. Dust particles accelerated by DAWs, reached velocities sufficiently high to overcome their mutual Coulomb repulsion and stick together, resulting in the formation of clusters of two, three or more particles. Dap et al. (2012) observed at least two dust collision events resulting in agglomeration (sticking) of carbonaceous dust, linked directly to particle motion in self-excited DDWs. They point out, as suggested previously in connection with DA shocks (Heinrich et al. 2009), that the agglomeration process is facilitated by the natural tendency of the dust particle charge to decrease when the dust is compressed to within less than one Debye shielding length.

6. Summary and outlook

This article has attempted to review the genesis of the DAW and to highlight some of the theoretical and experimental developments that have occurred over the last 25 years. The sustained interest in DAWs (and DDWs in general) is due in part to the fact that the waves and constituent particles can be observed both on the fluid and particle levels, allowing for an unprecedented look into the basic plasma physics problem of wave-particle interactions.

The DA/DDW is a defining phenomenon in dusty plasma physics. What delineates dusty plasmas from multicomponent (e.g. negative ion) plasmas is the fact that: (a) dust grains (particularly naturally occurring ones) have a distribution of sizes and shapes, leading to a distribution in mass and charge; (b) the charge on a dust grain is not constant; and (c) the dust is altered by and alters its plasma medium in profound ways.

Research on DA/DDWs continues to be a vigorous activity. What are some of the unresolved problems that might vmotivate future work? Although attempts have been made to include the effects of the dust size distribution, a self-consistent and rigorous formulation of the problem at the kinetic level is still in progress.

One issue that produced considerable lively discussion at the 7$^{\text{th}}$ International Conference on the Physics of Dusty Plasmas in New Delhi, 2014, was the effect of strong coupling on DAWs. It has become increasingly clear that dusty plasmas tend to be in the liquid (moderately coupled) state. To address this issue, a number of theoretical models have been proposed to include strong coupling effects into the basic equations of dusty plasmas. Experiments have been performed under conditions in which strong coupling effects were expected to play a role. However, it is not yet clear if experiments have been performed at a sufficient level of detail and precision to delineate these effects.

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REFERENCES

An, T., Merlino, R. L. and D'Angelo, N. 1994 Cylindrical anode double layers ('firerods') produced in a uniform magnetic field. *J. Phys. D: Appl. Phys.* **27**, 1906.

Annibaldi, S. V., Ivlev, A. V., Konopka, U., Ratynskaia, S., Thomas, H. M., Morfill, G. E., Lipaev A. M., Molotkov, V. I., Petrov, O. F. and Fortov, V. E. 2007 Dust acoustic dispersion relation in three-dimensional complex plasmas under microgravity. *New J. Phys.* **9**, 327.

Arshad, K., Ehsan, Z., Khan, S. A. and Mahmood, S. 2014 Solar wind driven dust acoustic instability with Lorentzian kappa distribution. *Phys. Plasmas* **21**, 023704.

Avinash, K., Merlino, R. L. and Shukla, P. K. 2011 Anomalous dust temperature in dusty plasma experiments. *Phys. Lett. A* **375**, 2854.

Bandyopadhyay, P., Prasad, G., Sen. A. and Kaw, P. K. 2007 Experimental observation of strong coupling effects on the dispersion of dust acoustic waves in a plasma. *Phys. Lett. A* **368**, 491.

Barkan, A. and Merlino. R. L. 1995 Confinement of dust particles in a double layer. *Phys. Plasmas* **2**, 3261.

Barkan, A., Merlino, R. L. and D'Angelo, N. 1995 Laboratory observation of the dust-acoustic wave mode. *Phys. Plasmas* **2**, 3563.

Chu, J. H., Du, J. B. and I, L. 1994 Coulomb solids and low-frequency fluctuations in RF dusty plasmas. *J. Phys. D: Appl. Phys.* **27**, 296

D'Angelo, N. 1995 Comment on Coulomb solids and low-frequency fluctuations in RF dusty plasmas. *J. Phys. D: Appl. Phys.* **28**, 1009.

D'Angelo, N. and Merlino, R. L. 1996 Current-driven dust acoustic instability in a collisional plasma. *Planet. Space Sci.* **44**, 1593.

Dap, S., Lacroix D., Hugon, R., de Poucques, L., Briancon, J. L. and Bougdira, J. 2012 Cluster agglomeration induced by dust-density waves in complex plasmas. *Phys. Rev. Lett.* **109**, 245002.

de Angelis, U., Formisano, V. and Giordano, M. 1988 Ion plasma waves in dusty plasmas: Halley's comet. *J. Plasma Phys.* **40**, 399.

Donko, Z., Kalman, G. J. and Hartmann, P. 2008 Dynamical correlations and collective excitations of Yukawa liquids. *J. Phys.: Condens. Matter* **20**, 413101.

Du, C. R., Thomas, H. M., Ivlev, A. V., Konopka, U. and Morfill, G. E. 2010 Agglomeration of microparticles in complex plasmas. *Phys. Plasmas* **17**, 113710.

Eliasson, B. and Shukla, P. K. 2004 Dust acoustic shock waves. *Phys. Rev.* E **69**, 067401.

Flanagan, T. M. and Goree, J. 2010 Observation of the spatial growth of self-excited dust-density waves. *Phys. Plasmas* **17**, 123702.

Flanagan, T. M. and Goree, J. 2011 Development of nonlinearity in a growing self-excited dust density wave. *Phys. Plasmas* **18**, 013705.

Fortov, V. E., Khrapak, A. G., Khrapak, S. A., Molotkov, V. I., Nefedov, A. P., Petrov, O. G. and Torchinsky, V. M. 2000 Mechanism of dust-acoustic instability in a direct current discharge plasma. *Phys. Plasmas* **7**, 1374.

Fortov, W. E., Petrov, O. F., Molotkov, V. I., Poustylnik, M. Y., Torchinsky, V. M., Naumkin, V. N. and Khrapak, A. G. 2005 Shock wave formation in a dc glow discharge dusty plasmas. *Phys. Rev. E* **71**, 036413.

Ghosh, S., Chadhruri, T. K., Sarkar, S., Khan, M. and Gupta, M. R. 2001 Small amplitude nonlinear dust acoustic wave propagation in Saturn's F, G, and E rings. *Astrophys. Space Sci.* **278,** 463

Heinrich, J. R., Kim, S. H. and Merlino, R. L. 2009 Laboratory observation of self-excited dust acoustic shocks. *Phys. Rev. Lett.* **103**, 115002.

Heinrich, J. R., Kim, S. H., Meyer, J. K. and Merlino, R. L. 2011 Experimental quiescent drifting dusty plasmas and temporal dust acoustic wave growth. *Phys. Plasmas* **18**, 113706.

Heinrich, J. R., Kim, S. H., Meyer, J. K., Merlino, R. L. and Rosenberg, M. 2012 Secondary dust density waves excited by nonlinear dust acoustic waves. *Phys. Plasmas* **19**, 083702.

Kaw, P. K. and Sen, A. 1998 Low frequency modes in strongly coupled dusty plasmas. *Phys. Plasmas* **5**, 3552.

Khrapak, S., Samsonov, D., Morfill, G., Thomas, H., Yaroshenko, V. Rothermel, H., Hagl, T., Fortov, V., Nefedov, A., Molotkov, V., et al. 2003 Compressional waves in complex (dusty) plasmas under microgravity conditions. *Phys. Plasmas* **10**, 1.

Liao, C. T., Teng, L. W., Tsai, C. Y., Io, C. W. and I, L. 2008 Lagrangian-eulerian micromotion and wave heating in nonlinear self-excited dust-acoustic waves. *Phys. Rev. Lett.* **100**, 185004.

Lipaev, A. M., Molotkov, V. I., Nefedov, A. P., Petrov, O. F., Torchinskii, V. M., Fortov, V. E., Khrapak, A. G. and Khrapak, S. A. 1997 Ordered structures in a nonideal dusty glow-discharge plasma. *JETP* **85**, 1110.

Melandsø, F., Aslaksen, T. K. and Havnes, O. 1993a A kinetic model for dust acoustic waves applied to planetary rings. *J. Geophys. Res.* **98**, 13,315.

Melandsø, F., Aslaksen, T. and Havnes, O. 1993b A new damping effect for the dust-acoustic wave. *Planet. Space Sci.* **41**, 321.

Mendis, D. A. and Horányi, M. 2013 Dusty plasma effects in comets: expectations for Rosetta. *Rev. Geophys.* **51**, 53.

Menzel, K. O., Arp, O. and Piel, A. 2010 Spatial frequency clustering in nonlinear dust-density waves. *Phys. Rev. Lett.* **104**, 235002.

Merlino, R. L. 2009 Dust-acoustic waves driven by an ion-dust streaming instability in laboratory discharge dusty plasma experiments. *Phys. Plasmas* **16**, 124501.

Merlino, R. L., Barkan, A., Thompson, C. and D'Angelo, N. 1998 Laboratory studies of waves and instabilities in dusty plasmas. *Phys. Plasmas* **5**, 1607.

Merlino, R. L. and D'Angelo, N. 2005 Electron and ion inertia effects on current-driven collisional dust acoustic, dust ion acoustic, and ion acoustic instabilities. *Phys. Plasmas* **12**, 054504.

Merlino, R. L., Heinrich, J. R., Kim, S. H. and Meyer, J. K. 2012 Nonlinear dust acoustic waves and shocks. *Phys. Plasmas* **19**, 057301.

Merlino, R. L., Heinrich, J. R., Kim, S. H. and Meyer, J. K. 2012 Dusty plasmas: experiments on nonlinear dust acoustic waves, shocks, and structures. *Plasma Phys. Control. Fusion* **54**, 124014.

Molotkov, V. I., Nefedov, A. P., Torchinskii, V. M., Fortov, V. E. and Khrapak, A. G. 1999 Dust acoustic waves in a dc glow-discharge plasma. *JETP* **89**, 477.

Nosenko, V., Zhdanov, S. K., Kim, S. H., Heinrich, J. R., Merlino, R. L. and Morfill, G. E. 2009 Measurement of the power spectrum and dispersion relation of self-excited dust acoustic waves. *EPL* **88**, 65001.

Piel, A. 2011 Some thoughts about dust density waves. In: *Dusty/Complex Plasmas: Basic and Interdisciplinary Research.* New York, AIP Publishing, AIP Conf. Proc. 1307, pp. 50–55.

Piel, A., Klindworth, M., Arp, O., Melzer, A. and Wolter, M. 2006 Obliquely propagating dust-density waves in the presence of an ion beam. *Phys. Rev. Lett.* **97**, 205009.

Pieper, J. B. and Goree, J. 1996 Dispersion pf dust acoustic waves in the strong coupling regime. *Phys. Rev. Lett.* **77**, 3137.

Pilch, I., Reichstein, T. and Piel, A. 2009 Synchronization of dust density waves in anodic plasmas. *Phys. Plasmas* **16**, 123709.

Popel, S. I., Morfill, G. E., Shukla, P. K. and Thomas, H. 2013 Waves in a dusty plasma over the illuminated part of the Moon. *J. Plasma Phys.* **79**, 1071.

Prabhakara, H. R. and Tanna, V. L. 1996 Trapping of dust and dust acoustic waves in laboratory plasmas. *Phys. Plasmas* **3**, 3176.

Pramanik, J., Veeresha, B. M., Prasad, G., Sen, A. and Kaw, P. K. 2003 Experimental observation of dust-acoustic wave turbulence. *Phys. Lett. A* **312**, 84.

Rao, N. N., Shukla, P. K. and Yu, M. Y. 1990 Dust-acoustic waves in dusty plasmas. *Planet. Space Sci.* **38**, 543.

Rosenberg, M. 1993 Ion-and dust-acoustic instabilities in dusty plasmas. *Planet. Space Sci.* **41**, 229.

Rosenberg, M. 1996 Ion-dust streaming instability in processing plasmas. *J. Vac. Sci. Technol. A* **14**, 631.

Rosenberg, M. and Kalman, G. 1997 Dust acoustic waves in strongly coupled dusty plasmas. *Phys. Rev. E* **56**, 7166.

Rosenberg, M., Kalman, G. L., Hartmann, P. and Goree, J. 2014 Effects of strong coupling on the dust acoustic instability. *Phys. Rev. E* **89**, 013103

Rosenberg, M., Thomas, Jr., E. and Merlino, R. L. 2008 A note on dust wave excitation in a plasma with warm dust: Comparison with experiment. *Phys. Plasmas* **15**, 073701.

Ruhunusiri, W. D. S. and Goree, J. 2012 Synchronization mechanism and Arnold tongues for dust density waves. *Phys. Rev. E* **85**, 046401.

Samsonov, D., Morfill, G., Thomas, H., Hagl, T.,Rothermel, H., Fortov, V., Lipaev, A., Molotkov, V., Nefedov, A., Petrov, O., Ivanov, A. and Krikalev, S. 2003 Kinetic measurements of shock wave propagation in a three-dimensional complex (dusty) plasma. *Phys. Rev. E* **67**, 036404.

Schwabe, M., Rubin-Zuzic, M., Zhdabov, S., Thomas, H. M. and Morfill, G. E. 2007 Highly resolved self-excited density waves in a complex plasma. *Phys. Rev. Lett.* **99**, 095992.

Schwabe, M., Zhdanov, S. K., Thomas, H. M., Ivlev, A. V., Rubin-Zuzic, R., Morfill, G. E., Molotkov, V. I., Lipaev, A. M., Fortov, V. E. and Reiter, T. 2008 Nonlinear waves externally excited in a complex plasma under microgravity conditions. *New J. Phys.* **10**, 033037.

Shukla, P. K. and Eliasson, B. 2012 Nonlinear dynamics of large-amplitude dust acoustic shocks and solitary pulses in dusty plasmas. *Phys. Rev. E* **86**, 046402.

Teng, L. W., Chang, M. C., Tseng, Y. P. and I, L. 2009 Wave-particle dynamics of wave breaking in the self-excited dust acoustic wave. *Phys. Rev. Lett.* **103**, 245005.

Thompson, C. Barkan, A., D'Angelo, N. and Merlino, R. L. 1997 Dust acoustic waves in a direct current glow discharge. *Phys. Plasmas* **4**, 2331.

Thomas, Jr., E. 1999 Direct measurements of two-dimensional velocity profiles in direct current glow discharge plasmas. *Phys. Plasmas* **6**, 2672.

Thomas, Jr., E. 2006 Measurements of spatially growing dust acoustic waves in a dc glow discharge plasma. *Phys. Plasmas* **13**, 042107.

Thomas, Jr., E., Fisher, R. and Merlino, R. L. 2007 Observation of dust acoustic waves driven at high frequencies: Finite dust temperature effects and wave interference. *Phys. Plasmas* **14**, 123701.

Thomas, Jr., E. and Merlino, R. L. 2001 Dust particle motion in the vicinity of dust acoustic waves. *IEEE Trans. Plasma Sci.* **29**, 152.

Trottenberg, T., Block, D. and Piel, A. 2006 Dust confinement and dust acoustic waves in weakly magnetized anodic plasmas. *Phys. Plasmas* **13**, 042105.

Tsai, Y. Y., Chang, M. C. and I, L. 2012 Observation of multifractal intermittent dust-acoustic wave turbulence. *Phys. Rev. E* **86**, 045402.

Varma, R. K., Shukla, P. K. and Krishan, V. 1993 Electrostatic oscillations in the presence of grain-charge perturbations in dusty plasmas. *Phys. Rev. E* **47**, 3612.

Wang, X. and Bhattacharjee, A. 1997 Hydrodynamic waves and correlation functions in dusty plasmas. *Phys. Plasmas* **4**, 3759.

Williams, J. D. 2014 Evolution of frequency clusters in the naturally occurring dust acoustic wave. *Phys. Rev. E* **89**, 023105.

Williams, J. D. and Duff, J. 2010 Observation of the coupling of the driven dust acoustic wave. *Phys. Plasmas* **17**, 033702.

Williams, J. D. and Snipes, E. K. 2010 Measurement of the dust temperature in the dispersion relation of the dust acoustic wave. *IEEE Trans. Plasma Sci.* **38**, 847.

Williams, J. D., Thomas, Jr., E. and Marcus, L. 2008 Observation of vertically propagating driven dust acoustic wave: Finite temperature effects. *Phys. Plasmas* **15**, 043704.

Winske, D., Gary, S. P., Jones, M. E., Rosenberg, M., Chow, V. W. and Mendis, D. A. 1995 Ion heating in a dusty plasma due to the dust/ion acoustic instability. *Geophys. Res. Lett.* **22**, 2069.

Xu, W., Song, B., Merlino, R. L. and D'Angelo, N. 1992 A dusty plasma device for producing extended, steady state, magnetized dusty plasma columns. *Rev. Sci. Instrum.* **63**, 5266.

Yaroshenko, V. V., Annaratone, B. M., Khrapak, S, A., Thomas, H. M., Morfill, G. E., Fortov, V. E., Lipaev, A. M., Molotkov, V. I., Petrov, O. F., Ivanov, A. I., et al. 2004 Electrostatic modes in collisional complex plasmas under microgravity conditions. *Phys. Rev. E* **69**, 066401.

Zobnin, A. V., Usachev, A. D., Petrov, O. F. and Fortov, V. E. 2002 Dust-acoustic instability in an inductive gas-discharge plasma. *JETP* **95**, 429.