Laboratory Observations of Self-Excited Dust Acoustic Shocks

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Repeated, self-excited dust acoustic shock waves (DASWs) have been observed in a dc glow discharge dusty plasma using high-speed video imaging. Two major observations are reported: (1) The self-steepening of a nonlinear dust acoustic wave (DAW) into a saw-tooth wave with sharp gradient in dust density, very similar to those found in numerical solutions of the fully nonlinear fluid equations for a nondispersive DAW [B. Eliasson and P. K. Shukla, Phys. Rev. E **69**, 067401 (2004)], and (2) the collision and confluence of two DASWs.

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Introduction.—Laboratory plasmas are intrinsically non-equilibrium systems in which a state of ionization is maintained by an external energy source. Systems, such as plasmas, which are open and nonlinear tend to exhibit self-organization leading to spatial pattern formation. Pattern formation is common in nature [1] and occurs, e.g., in Rayleigh-Bénard convection [2], chemically active systems [3], granular materials [4], microfluidic crystals [5], and wave patterns in cardiac muscle [6]. A simple pattern that arises from an instability that is periodic in space and oscillatory in time is the travelling wave. If a controlling parameter of the system exceeds an instability threshold and pushes the system far outside of equilibrium, nonlinear waves, sustained by the balance between the drive, nonlinearity, dispersion, and dissipation, may be excited. Nonlinear waves (also known as autowaves [7]) have characteristics that are quite different from linear waves, e.g., when two nonlinear wave trains collide, one or the other may be consumed or a shock may form [1,8].

The dust acoustic wave (DAW) is a low frequency compressional dust mode in a dusty plasma. The dispersion relation for this mode was first derived by Rao, Shukla, and Yu [9] by treating the dusty plasma as a multicomponent system in which the negatively charged dust was modeled as a fluid obeying the continuity and momentum equations. Both the electrons and ions were taken to be in Boltzmann equilibrium, and, for the long wavelength acousticlike mode, the densities were related by the quasineutrality condition, $n_i = n_e + Z_d n_d$, where $n_{(i,e,d)}$ are the (ion, electron, dust) densities, respectively, and Z_d is the dust charge number. The phase velocity for the DAW is $C_{\mathrm{DA}} = \sqrt{(kT_d + \sigma kT_i)/m_d}$, where $\sigma = \alpha Z_d^2/[1 + \tau(1 - \alpha Z_d)]$, $\alpha = n_{do}/n_{io}$, $\tau = T_i/T_e$, $T_{(e,i,d)}$ is the (electron, ion, dust temperature), m_d is the mass of the dust particles, and $n_{(d,i)o}$ is the equilibrium (dust, ion) density. Montgomery pointed out that, for the case of ion-acoustic waves in a plasma with $\tau \ll 1$, these equations are just the Euler equations for an inviscid fluid [10], for which it is well known that a compressive pulse will steepen as it propagates [8]. The evolution of a plasma pulse into an ion-acoustic shock, as predicted by Montgomery [10], was first observed by Andersen *et al.* [11]. The dust acoustic shock waves (DASWs), described below, also have properties similar to shock waves in gases.

Historically, shock waves were the purview of fluid dynamics, but in recent years they have been observed in such diverse systems as granular materials [12], avalanching snow [13], and coagulating "blood" plasma [14]. Nonlinear dust waves and shocks have been investigated in dusty plasmas using externally applied dust density disturbances [15]. Large amplitude, self-excited dust density waves have been studied in anodic plasmas [16], and in an rf discharge plasma [17]. Extensive theoretical work has been done on dust acoustic (DA) solitary waves and shocks [18], e.g., the work of: (i) Melandsø and Shukla [19], in which the Riemann invariants for both the high and low frequency DAWs were obtained; (ii) Gupta *et al.*, [20], who showed that dissipation due to nonadiabatic dust charge variation can generate DASWs; (iii) Mamun and Cairns [21], who showed that shocks may be formed due to dissipation connected with the strong coupling between dust grains; and (iv) Eliasson and Shukla [22], who obtained DASWs as nonstationary solutions of the fully nonlinear, nondispersive hydrodynamic DAW equations.

We report here high-speed video observations of self-excited, repeated DASWs formed in a dc glow discharge dusty plasma, with relevance to space physics, astrophysics, and acoustics: (i) The excitation of nonlinear dust waves may provide an explanation for some of the unusual features observed in Saturn's rings [23]. (ii) The propagation of strong, compressional DASWs through dust molecular clouds may initiate and sustain the condensation of small grains into larger grains due to the grain charge reduction associated with the increase in dust density [20]. (iii) Since dusty plasmas can be observed visually and diagnosed using standard video image processing methods, they can be used to study acoustic wave scattering and diffraction [24] and nonlinear phenomena such as solitons and shock waves.

Experimental setup.—The experiments were performed in the device shown schematically in Fig. 1. A glow discharge plasma was formed in argon gas at a pressure $\sim$100 mtorr (13 Pa) by applying a $\sim$300 V dc bias to a 4 cm diameter anode disk located on the axis of a large, grounded vacuum chamber. A weak magnetic field $\sim$0.01 T provides confinement for the electrons which results in a cylindrical anode glow discharge which extends axially from the anode. Typical values of, respectively, the ion density, and electron and ion temperatures were: $n_i \sim 10^{14}$–10^{15} m^{-3}, $T_e \sim 2$–3 eV, and $T_i \sim 0.03$ eV. Dust particles are incorporated into the plasma from a tray located below the anode onto which was spread a few millimeters of kaolin powder. The average size of the dust particles that are confined within the anode glow plasma was $\sim$1 μm. For an average dust radius $a = 0.5$ μm, the mass and charge of the dust particles is estimated to be $m_d \sim 10^{-15}$ kg, and $Z_d = Q_d/e \sim -2000$. The dust density, n_{do} is $\sim 10^{10}$–10^{11} m^{-3}. The particle cloud was illuminated by 532 nm light from an Nd:YAG diode laser which was expanded into a vertical sheet about 1 mm thick using a cylindrical lens. Light scattered by the particles was viewed at a right angle by a 1 Mpixel video camera (Photron Fastcam-1024 PCI) at 500 fps. The intensity of the scattered light is proportional to the dust density. DAW amplitudes, $\Delta n_d/n_{do}$ were determined from the measured pixel intensities I, as $\Delta I/I_{\rm avg}$, where ΔI is the deviation of the pixel intensity from the average pixel intensity, $I_{\rm avg}$, as described in [25]. $I_{\rm avg}$ is obtained by averaging the pixel intensities of all images in a 1 s video sequence. Further experimental details can be found elsewhere [24].

Results and discussion.—DAWs appeared spontaneously in the dusty plasma [24], excited most likely by an ion-dust streaming instability [26–28]. A single frame video image of a DAW with an wavelength of ≈ 4 mm and frequency of 54 Hz is shown in Fig. 2(a). The bright vertical features are the wave crests which propagate away from the anode at an average speed of $\sim$20 cm/s. Although the wave amplitudes were high, the waves did not steepen into shocks. The formation of shocks was observed when a slit (Fig. 1) was inserted in front of the anode. The slit was formed by two aluminum strips coated with a nonconducting black paint and separated vertically by 1 cm. The length of the slit was much larger than the diameter of the anode. The effect of introducing the slit on the morphology of the DAWs is shown in Figs. 2(b) and 2(c). The slit plates were electrically floating at a negative potential, and the resulting electrostatic potential structure around the slit confined the negatively charged dust (in the y direction) to an elongated (in the x direction) 2D duct. The anode-slit configuration is similar to a gasdynamic shock tube used to channel sound waves along the tube allowing shock waves to form and propagate.

In Fig. 2(b), when the slit was 11.5 mm from the anode, the dusty plasma formed near the slit entrance where the DAWs were excited, eventually expanding outward as cylindrical waves from a line source. Figure 3 shows profiles of the scattered light intensity in 8 ms time steps for the two bracketed wave fronts in Fig. 2(b). The profiles refer to a horizontal (z) strip across the image about 1 mm wide (in y). The time-space paths and the amplitudes of these colliding pulses are shown in Fig. 4. The higher amplitude trailing pulse travelling at $\sim$100 mm/s catches up with the lower amplitude forerunner travelling at 65 mm/s. The trailing wave overtakes and *consumes* the forerunner at about 50 ms, and a new pulse is formed which

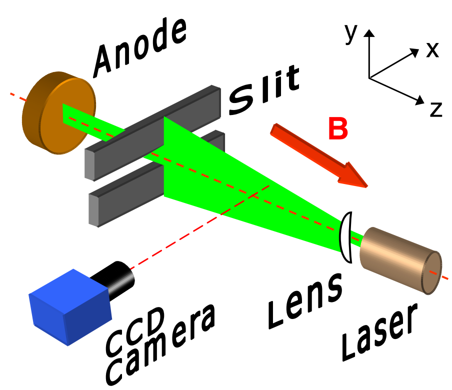

FIG. 1 (color online). Schematic of the experimental setup.

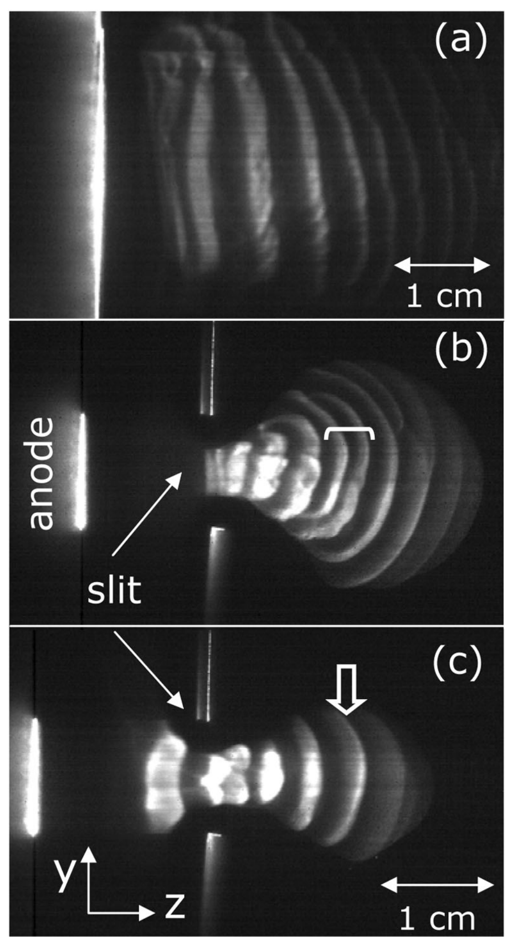

FIG. 2. Single frame video images of (a) DAW with no slit, and with slit (b) 11.5 mm and (c) 15.0 mm from the anode.

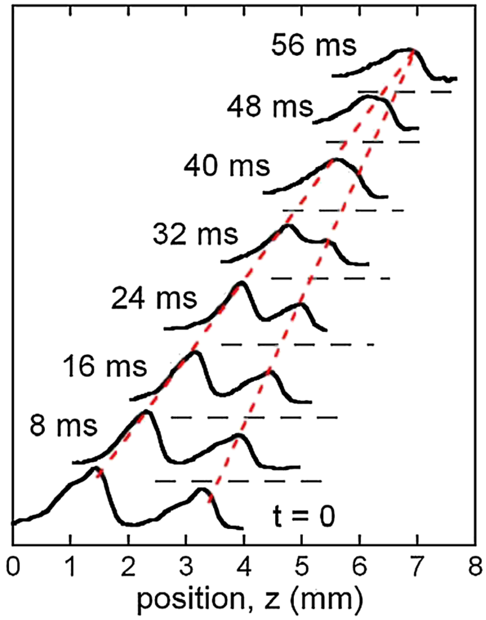

FIG. 3 (color online). Profiles of scattered light intensity of two colliding DASWs at 8 ms intervals.

travels at a speed that is less than the speed of the original leading pulse. The confluence of pulses, as observed in Figs. 3 and 4, is characteristic of shock waves [8].

The formation of a DASW was studied in detail using the setup in Fig. 2(c) in which the distance between the anode and slit was increased to 15 mm. DAW pulses were excited at a point roughly midway between the anode and slit. The pulses grew in amplitude and width as they propagated toward the slit and appeared to be "focused" (note the inward curvature of the front) to vertically compressed structures as they passed through the slit. Subsequently the waves expanded and steepened into shocks. The evolution of a DASW is shown in Fig. 5 with scattered light intensity profiles shown in 10 ms time steps. The intensity profiles in Fig. 5 were obtained from single frame images of the type shown in Fig. 2(c), recorded at 500 fps, and starting at the position indicated by the arrow. The formation of a sawtooth-like shock structure is evident, and is very similar to shocks obtained in numerical solutions of the fully nonlinear fluid equations for nondispersive DAWs (cf. Fig. 1 of Ref. [22]). The shock wave in Fig. 5 propagates at a constant speed, $V_s \approx 74$ mm/s. An estimate for the dust acoustic speed puts it in the range $C_{\mathrm{da}} \sim 60$–85 mm/s depending on T_d (see further comments below). An approximate value of the shock speed provided in [20] was $V_s \approx C_{\mathrm{DA}}(N_{d,L} + N_{d,R})/2$, where $N_{d,(L,R)}$ are the values of the dust density (behind, in front of) the shock relative to the average dust density. The relative dust densities, $N_{d,L}$ and $N_{d,R}$, can be obtained from Fig. 5. With $N_{d,L} \sim 2.4$, $N_{d,R} = 1$, $Z_d \sim 2000$, $m_d \sim 10^{-15}$ kg, $n_{do}/n_{io} \sim 10^{-4}$, and $T_e = 2.5$ eV, we find, $V_s \approx 69$ mm/s, which compares well to the measured value.

A plot showing the shock thickness, δ (defined in the insert to Fig. 5), and amplitude, $\Delta n_d/n_{do} \sim \Delta I/I_{\mathrm{avg}}$, is shown in Fig. 6. The shock amplitude followed a roughly linear decay as indicated by the solid line (linear correlation coefficient $R = 0.987$). In the absence of dissipation, a compressive cylindrical pulse would fall off as $1/\sqrt{r}$ from the axis. The steeper amplitude fall off is a possible indication of dissipation within the shock, similar to that observed in gasdynamic shocks and attributed to the effects of viscosity. The measurements of the shock thickness vs position shows that the shock steepened as it traveled, and stabilized at a minimum thickness $\delta \sim 0.3$–0.4 mm. The thickness of gasdynamic shocks is usually approximately the mean free path for atom-atom collisions. For the dusty plasma, the mean free path is determined by dust-neutral collisions, with the collision frequency, ν_{dn}, given by the Epstein formula. For a gas pressure of 100 mtorr and dust radius $a = 0.5$ μm, $\nu_{\mathrm{dn}} \sim 50$ s^{-1}, the mean free path $\lambda_{\mathrm{dn}} = V_{T,d}/\nu_{\mathrm{dn}}$, where $V_{T,d}$ is the dust thermal speed. If the dust were cold ($T_d = 0.025$ eV) $\lambda_{\mathrm{dn}} \sim 0.05$ mm, while

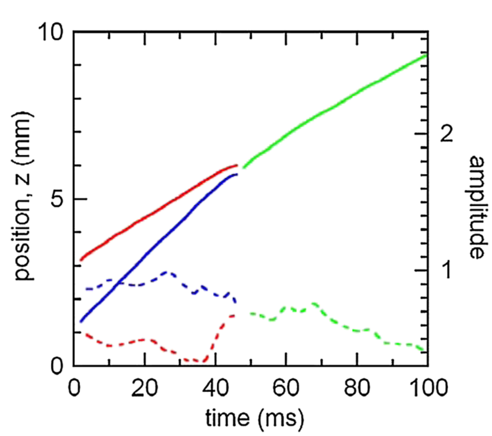

FIG. 4 (color online). Space-time paths (solid lines) of the colliding DASW shown in Fig. 3. Amplitudes of the colliding shocks are shown as dashed lines.

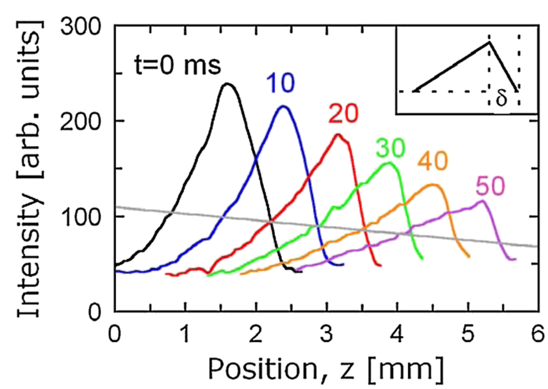

FIG. 5 (color online). Scattered light intensity profiles obtained from single frame video images as in Fig. 2(c) showing self-steepening of a DASW. Average scattered light intensity, I_{avg} shown as the downward sloping solid line. Inset shows definition of the shock width, δ.

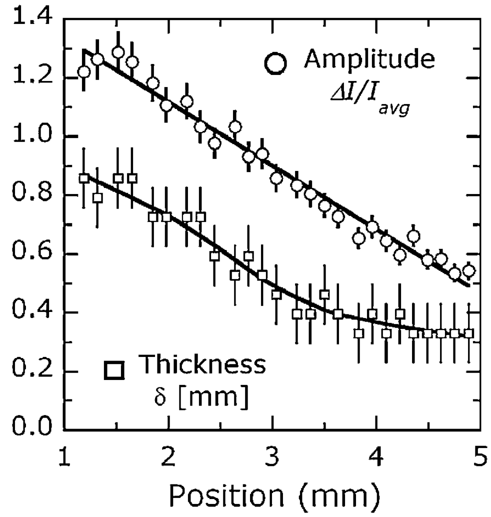

FIG. 6. Shock amplitude and thickness vs position, for the DASW in Fig. 5.

for dust at $T_d \sim 10$–25 eV, $\lambda_{\rm dn} \sim 1$–1.5 mm. It is unlikely that the dust was cold ($T_d = 0.025$ eV) for two reasons. First, dust acoustic waves have been shown to increase the dust temperature and prevent the formation of Coulomb crystals [27]. Secondly, if the dust were cold, the coupling parameter, $\Gamma = (eZ_d)^2/(4\pi\varepsilon_o dkT_d)$, where $d = (3/4\pi n_{d0})^{1/3}$ is the average interparticle spacing, would be $\sim 10^3$ and the dust would have been in the strongly coupled state. Visual observations show that the dusty plasma was in a more liquidlike state, which is consistent with a $\Gamma \sim 1$, for $T_d \sim$ tens of eV.

Mamun and Cairns [21] have shown that strong correlation effects between the dust particles can provide the necessary dissipation for stable shock formation. They predict a shock width $\delta = \nu_d/V_s$, where ν_d is the kinematic shear viscosity. Kaw and Sen [28] give a normalized viscosity $\eta^* \approx 1.04$ for $\Gamma = 1$, so that $\nu_d \approx 20$ mm^2/s for the parameters relevant to our experiments. With $Vs = 74$ mm/s, we find a $\delta \approx 0.3$ mm, in good agreement with the observed value. We note the possibility that measurements of the shock thickness might be used to determine shear viscosities.

Gupta *et al.* [20] have discussed the possibility that nonadiabatic dust charge variation could provide a *collisionless* dissipation mechanism for DASW formation. This mechanism would be important for small but nonzero values of the parameter, $\omega_{\rm pd}/\nu_{\rm ch}$, where $\omega_{\rm pd}$ is the dust plasmas frequency and $\nu_{\rm ch}$ is the dust charging frequency (inverse of the dust charging time). For our dusty plasmas conditions we estimate that, $\omega_{\rm pd} \sim 300$–1000 s^{-1}, and $\nu_{\rm ch} \sim 10^4$–10^5 s^{-1}, so that $\omega_{\rm pd}/\nu_{\rm ch} < 0.1$. This mechanism may be important in our case, although no predicted shock width was provided in [20] to which the experimental value could be compared. The possible role of nonabiabatic dust charge variation is an important issue in dusty plasma physics, so that this point deserves further attention.

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