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# Experimental study of shock formation in a dusty plasma

Q.-Z. Luo, N. D'Angelo, and R. L. Merlino[a]
*Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242*

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An experimental investigation of the effect of negatively charged dust on ion acoustic shock formation in a $Q$ machine is described. Ion acoustic compressional pulses were observed to steepen as they traveled through a dusty plasma if the percentage of the negative charge in the plasma on the dust grains was $\gtrsim 75\%$. © *1999 American Institute of Physics.* [S1070-664X(99)03309-1]

## I. INTRODUCTION

If a large amplitude density pulse is launched into a plasma having equal electron and ion temperatures, $T_e = T_i$, Landau damping prevents the formation of a sharp leading edge (''shock'') and the pulse spreads out. If the Landau damping is eliminated, the pulse steepens as it propagates and a shock structure is formed. This has been observed experimentally, for example, by increasing the $T_e/T_i$ ratio by cooling the ions through ion-neutral collisions,[1] or by introducing negative ions into the plasma.[2,3] In the presence of negative ions, ion waves exhibit two modes of propagation: a ''fast'' mode and a ''slow'' mode.[4] As the percentage of negative ions is increased, the phase velocity of the fast mode increases, and as a result the number of ions interacting with the wave decreases and the damping is reduced. In the absence of Landau damping, the fluid equations used to describe ion acoustic-like phenomena in plasmas are mathematically similar to the Euler equations for an ideal fluid. The solutions of these equations have the property that any compressive pulse will steepen as it travels.[5]

The present experiment investigates the propagation characteristics of large amplitude ion acoustic-like compressional pulses in a dusty plasma. The formation of shock waves in a dusty plasma may be important, for example, in processes occuring in interstellar dust-molecular clouds, supernova explosions, cosmic particle acceleration, and cometary plasmas.[6]

The propagation characteristics of small amplitude sinusoidal ion acoustic waves launched into a dusty plasma have already been studied.[7] In those experiments it was found that the presence of negatively charged dust grains increased the phase velocity of the waves and reduced the strength of the (Landau) damping. Theoretically it has been shown that the presence of a negatively charged dust component modifies the dispersion relation for ion acoustic waves.[8] This modified ion acoustic mode, the so-called dust ion acoustic (DIA) mode, has a phase velocity given by

$$V_{\mathrm{DIA}} = \frac{\omega}{K} = \left[\frac{kT_i}{m_i} + \frac{kT_e}{m_i(1-\epsilon Z)}\right]^{1/2}, \tag{1}$$

where $\omega$ and $K$ are the wave angular frequency and wave number, $kT_e$ and $kT_i$ are the electron and ion temperatures in energy units, $m_i$ is the mass of the positive ions, $\epsilon$ is the ratio $n_d/n_i$ of the dust density to the ion density, and $Z$ is the number of negative elementary charges on the dust grains. The quantity $\epsilon Z$ is the fraction of the negative charge in the plasma which resides on the dust grains. We see from (1) that the phase velocity increases with increasing $\epsilon Z$. Since for $\epsilon Z \sim 1$, $V_{\mathrm{DIA}} \gg v_{i,\mathrm{th}}$ (ion thermal velocity), thus the waves are subject to insignificant ion Landau damping.

In the following Sec. II we describe the experimental setup and the measurement techniques. The results are presented and discussed in Sec. III. A summary of our findings and conclusions is given in Sec. IV.

## II. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

The experiments were performed in a $Q$ machine device[9] that was modified to allow the introduction of dust grains into the plasma. A schematic diagram of the setup is shown in Fig. 1(a). Cesium atoms from an atomic beam oven are surface ionized (forming $\mathrm{Cs}^+$ ions) on a 6-cm-diam tantalum hot plate, HP (~2000–2500 K), which also emits electrons thermionically. The background neutral atom pressure was always below $10^{-5}$ Torr. The plasma is confined radially by a uniform longitudinal magnetic field with a strength up to 0.45 T, is approximately 1 m in length, and is terminated at the end opposite the hot plate with an electrically floating end plate (EP). Typically, $Q$ machine plasmas have electron and ion temperatures, $T_e \approx T_i \approx 0.2$ eV. The plasma densities were determined from the ion saturation current, $I_{\mathrm{is}}$, to a 1.8-cm-diam tantalum disk Langmuir probe using the relation $I_{\mathrm{is}} = (nev_{i,\mathrm{th}}/4)\,A_p$, (where $n$ is the plasma density, $v_{i,\mathrm{th}}$ is the ion thermal velocity, $A_p$ is the probe collecting area, and $e$ is the elementary charge) and were in the range $n \sim 10^6 - 10^7\ \mathrm{cm}^{-3}$. At these relatively low plasma densities and neutral atom densities both ion–ion and ion-atom collisions are unimportant.

To introduce dust grains into the plasma, the plasma column is surrounded over a 50 cm portion of its length by the rotating dust dispenser, as shown in Fig. 1(a). The dust dispenser consists of a rotating (up to about 150 rpm) metal cylinder and a stationary fine mesh. Dust particles, initially loaded into the bottom of the cylinder, are carried to the top and deposited on the stationary screen. As the stationary

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[a] Electronic mail: robert-merlino@uiowa.edu

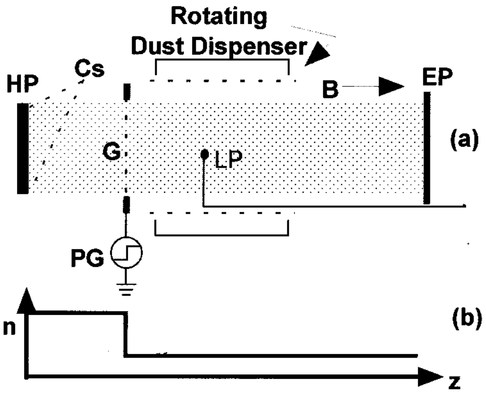


FIG. 1. (a) Schematic of the experimental arrangement. HP: hot plate, EP: floating end plate, G: grid, LP: Langmuir probe, Cs: cesium stomic beam oven, PG: pulse generator. (b) Typical axial plasma density distribution when the grid is closed.

screen is agitated by the vibration of the cylinder, the dust deposited on it is gently sifted through the plasma column. The dust which falls back to the bottom of the cylinder is recirculated continuously through the plasma. The dust is in the form of a fine powder of aluminum silicate (kaolin) with grain sizes ranging up to microns. The concentration of dust within the plasma can be controlled, to some extent, by varying the rotation speed of the cylinder.

When the dust grains enter the plasma they are rapidly charged by the collection of electrons and ions.[10] The charge on a dust grain can be estimated from the relation $Q = 4\pi\epsilon_0$ a $V_s$, where a is the dust grain ''radius'' and $V_s$ is the floating potential of the grain relative to the plasma. For our typical plasma conditions $V_s \approx -4kT_e \approx -1$ V, so that for a dust grain of size 0.1 $\mu$m, we have that $Q \approx 1 \times 10^{-17}$ C $(Z = Q/e \approx 70)$. The charging time is estimated as $\tau_{\text{ch}} \sim Q/I$, where $I \sim I_e \sim e\ n\ v_{e,\text{th}}\ \pi a^2$ is the electron current to the grain ($v_{e,\text{th}}$ is the electron thermal velocity). For a plasma density $n \sim 10^7\ \text{cm}^{-3}$ and $v_{e,\text{th}} \sim 2 \times 10^7$ cm/s, we find that the charging time for 0.1 $\mu$m grains is $\tau_{\text{ch}} \sim 1$ ms.

The presence of negatively charged grains in the plasma modifies the usual charge neutrality condition which now becomes

$$n_i = n_e + Z n_d, \tag{2}$$

where $n_\alpha$ $(\alpha = i,e,d)$ is the density of the ions, electrons, and dust grains, respectively. With $\epsilon = n_d/n_i$, the ratio of the dust to ion density, condition (2) can be expressed as

$$1 - (n_e/n_i) = \epsilon Z. \tag{3}$$

The quantity $\epsilon Z$ can be estimated from measurements of the ion and electron saturation currents to the Langmuir probe.[10,11] The measurement involves obtaining a probe $I-V$ characteristic in the absence of dust and one with the dust present. The ratio of $n_e/n_i$ in Eq. (3) is obtained from $n_e/n_i = (I_e/I_{e0})/(I_i/I_{i0})$, where $I_{e0}$ and $I_{i0}$ are the electron and ion probe saturation currents obtained in the absence of dust and $I_e$ and $I_i$ are the saturation currents measured in the presence of dust.

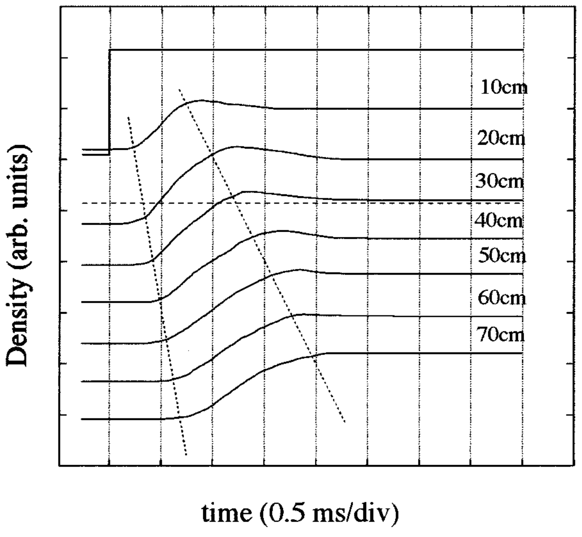
The plasma density pulses are produced by applying an appropriate dc bias and square wave pulse to a grid inserted into the plasma column at about 5 cm in front of the rotating dust dispenser. In order to operate with a dusty plasma in which a significant fraction of the total negative charge is on the dust grains, it is necessary to operate at relatively low plasma densities $< 10^7\ \text{cm}^{-3}$. At these densities, the plasma Debye length is ~0.3 cm. To produce appreciable density perturbations then requires that the spacing of the wires in the grid be ≈0.5 cm. The grid is constructed using fine tungsten wire (5 mil diameter) strung on a stainless steel support ring. The grid is normally biased at ~−6 V with respect to the grounded hot plate and absorbs a large fraction of the ions impinging on it, resulting in an axial density distribution as shown schematically in Fig. 1(b). We refer to this biasing configuration as ''closed'' in the sense that the grid prevents most of the plasma from passing through. By suddenly changing the bias to ~−2 V (~the plasma space potential), the grid ''opens up,'' launching a large amplitude density pulse downstream toward the end plate. In actuality this is accomplished by applying a ''train'' of square wave pulses to the grid of rise time ~0.1 $\mu$s, pulse width ~10 ms, and pulse separation ~30 ms. The pulse rise time is short compared to the inverse ion plasma frequency which is ~10 $\mu$s. The pulse width and separation are chosen to allow time for the plasma to relax back to the ''normal'' state before the next pulse is applied. The typical time for a pulse to travel the length of the experimental region is ~few ms. The density pulses are followed by recording the ion current (proportional to the density, $n$) to a negatively biased movable Langmuir probe at several axial positions downstream of the grid as a function of time from the ''opening'' of the grid.

## III. EXPERIMENTAL RESULT AND DISCUSSION

The evolution of the density pulses was studied for various values of the parameter $\epsilon Z$, the fraction of negative charge on the dust grains, ranging from $\epsilon Z = 0$ (no dust) to $\epsilon Z \sim 0.95$. Figure 2(a) shows the time histories of the density at various axial positions from the grid in the absence of dust $(\epsilon Z = 0)$. In this case there in no tendency for the leading edge of the pulse to ''steepen'' as it propagates, instead the pulse ''spreads out'' as it proceeds away from the grid. However, with the dust on and with an $\epsilon Z > 0.75$, we clearly observe a ''sharpening up'' of the leading edge of the density pulse [Fig. 2(b)] as it proceeds along the column. This steepening effect is illustrated in Fig. 2 by comparing the sets of dashed lines which mark the advancement of the leading and trailing edges of the moving fronts. In Fig. 2(a) the lines diverge due to the spreading out of the pulse, while in Fig. 2(b) the lines converge due to the formation of a sharp leading edge (shock). The development of the pulse front in the two cases (dust and no dust) can also be illustrated by plotting the pulse rise time (shock thickness) versus distance from the grid, as shown in Fig. 3.

The effect of the dust on shock formation was also studied for different values of $\epsilon Z$. With the probe at one fixed axial location (50 cm from the grid), $n$ vs $t$ curves were obtained at various $\epsilon Z$ values. From these curves values of

(a) DUST OFF



(b) DUST ON

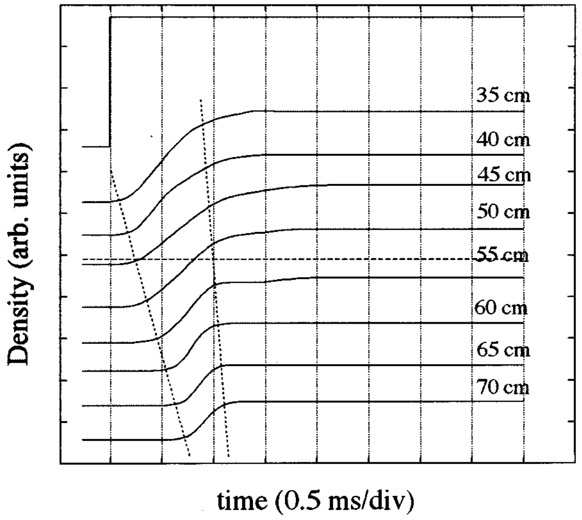


FIG. 2. Density vs time plots at various axial positions from the grid, obtained from measurements of the ion saturation current to a negatively biased Langmuir probe. (a) No dust case. (b) With dust and $\epsilon Z > 0.75$. In both (a) and (b) the horizontal lines are the zero levels corresponding to the uppermost $n$ vs $t$ trace. For clarity, all other traces have been displaced downward by equal amounts. The top square wave is the pulse applied to the grid and is shown for timing purposes. The sets of dashed lines mark the advancement of the leading and trailing edges of the pulses. In (a) the dashed lines diverge indicating a spreading out of the pulses, whereas in (b) the lines converge indicating steepening or shock formation.

the pulse rise time (shock thickness) were measured with the results shown in Fig. 4. The steepening effect becomes most appreciable for $\epsilon Z \gtrsim 0.75$, thus indicating that a substantial amount of negatively charged dust must be present in order to reduce the damping of the ion acoustic wave components in the density pulse. This point is also evident from measurements of the pulse velocity versus $\epsilon Z$, as shown in Fig. 5. We see that for $\epsilon Z \gtrsim 0.8$ there is a rapid increase in the pulse speed. This result is quite similar to the one observed for sinusoidal ion acoustic waves launched into a dusty plasma,[7] and for the case of density pulses in a negative ion plasma.[3]

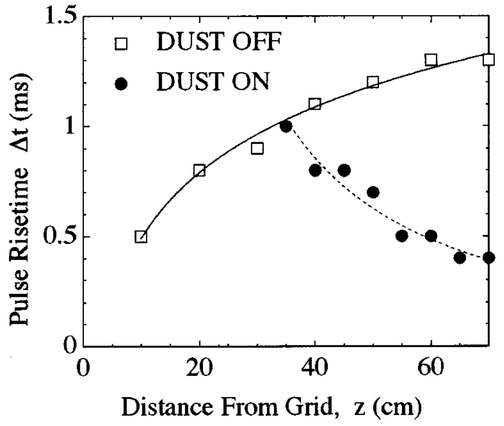


FIG. 3. Measured pulse rise time (width in time of the transition between low and high density) vs distance from the grid, obtained from the data of Fig. 2. With the dust present the pulse rise time (shock thickness) decreases with increasing distance from the grid.

For comparison, the dashed line in Fig. 5 is the normalized phase velocity of the dust ion acoustic wave, computed from Eq. (1). These measurements support the conclusion that at relatively high values of $\epsilon Z$ there is a substantial reduction in the Landau damping that would otherwise prevent the formation of sharp density structures (shocks) in a plasma with $T_e = T_i$, in the absence of negatively charged dust. If one imagines that the density pulse is composed of a combination of ion acoustic Fourier components, it seems reasonable that the sharpening effect observed at high $\epsilon Z$'s may be attributable to a decrease in the damping which accompanies the increase in the phase velocity.

## IV. SUMMARY AND CONCLUSIONS

The evolution of large amplitude density pulses propagating in a dusty plasma has been investigated. In the absence of the negatively charged dust component we have consistently observed a spreading out of the pulse as it propagates down the plasma column. However, in the presence of a substantial component of negatively charged dust

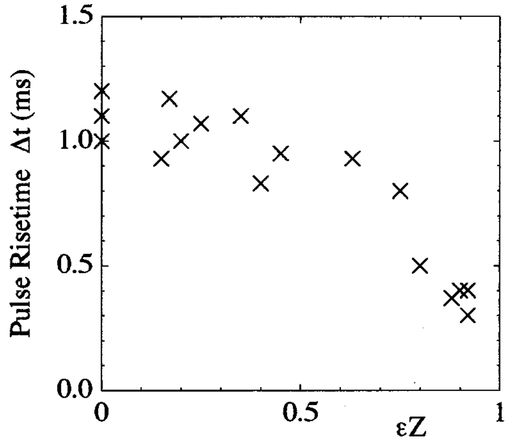


FIG. 4. Pulse rise times vs $\epsilon Z$. These data were obtained by recording $n$ vs $t$ traces at a fixed distance from the grid (50 cm) for various values of $\epsilon Z$.

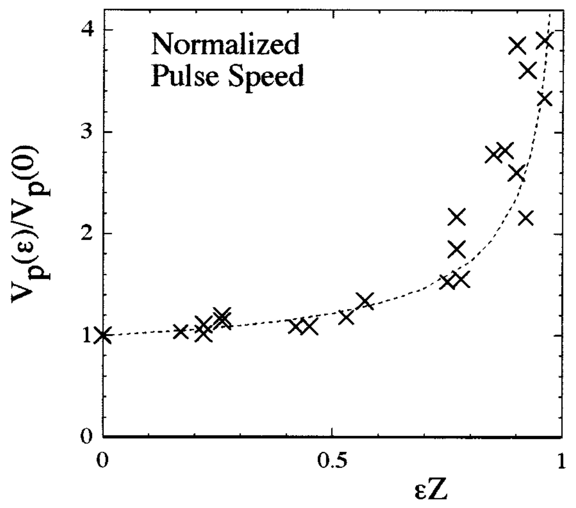


FIG. 5. Pulse speed vs $\epsilon Z$, normalized by the value of the pulse speed with no dust ($\epsilon=0$). These data were obtained from $n$ vs $t$ traces, of the type shown in Fig. 2, for various $\epsilon Z$ values. For each value of $\epsilon Z$ the speed is obtained from a plot of the pulse arrival time vs distance from the grid.

(when the fraction of negative charge on the dust, $\epsilon Z$ is $\gtrsim 0.75$) we have clearly observed a sharpening up of the leading edge of the pulse. This sharpening effect (shock formation) is correlated with an increase in the pulse speed with increasing $\epsilon Z$. Previous experiments have established that the presence of negatively charged dust greatly reduces the strength of the Landau damping of ion acoustic waves, even in a plasma with equal ion and electron temperatures.[7] The results of the present experiment demonstrate that a similar effect occurs for large amplitude plasma density pulses propagating through a dusty plasma containing negatively charged dust grains.

We note in conclusion, that these results may be relevant to the formation of shock waves in astrophysical contexts where large plasma density disturbances may encounter dust clouds.

## ACKNOWLEDGMENTS

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