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S. Jaiswal; P. Bandyopadhyay; A. Sen

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Excitation of Nonlinear Wave Patterns in Flowing Complex Plasmas

S. Jaiswal[1,2,a)], P. Bandyopadhyay[2] and A. Sen[2]

[1]*Deutsches Zentrum für Luft- und Raumfahrt (DLR), 82234 Weßling, Germany.*
[2]*Institute for Plasma Research, Bhat, Gandhinagar, Gujarat 382428, India.*

[a)]Corresponding author: surabhijaiswal73@gmail.com

Abstract. We describe experimental observations of nonlinear wave structures excited by a supersonic mass flow of dust particles over an electrostatic potential hill in a dusty plasma medium. The experiments have been carried out in a $\Pi-$ shaped experimental (DPEx) device in which micron sized Kaolin particles are embedded in a DC glow discharge Argon plasma. An equilibrium dust cloud is formed by maintaining the pumping speed and gas flow rate and the dust flow is induced either by suddenly reducing the height of a potential hill or by suddenly reducing the gas flow rate. For a supersonic flow of the dust fluid precursor solitons are seen to propagate in the upstream direction while wake structures propagate in the downstream direction. For flow speeds with a Mach number greater than 2 the dust particles flowing over the potential hill give rise to dispersive dust acoustic shock waves. The experimental results compare favorably with model theories based on forced K-dV and K-dV Burger's equations.

INTRODUCTION

Equilibrium plasma flows occur in many natural situations such as in astrophysical jets, solar wind etc. as well as in magnetic and inertial fusion experiments where these plasma flows can influence the equilibrium plasma features of the system as well its collective modes and instabilities. The encounter of such plasma flows with a stationary charged object can give rise to a rich variety of dynamical phenomena involving collective excitations. The study of such an interaction in a laboratory setting can provide much insight into fundamental processes governing linear and nonlinear collective excitations arising from the encounter. A dusty plasma, consisting of micron or submicron sized particles immersed in an electron–ion plasma, provides a unique platform and a convenient tool to explore such phenomena. The massive dust particles which usually get negatively charged due to collection of more electrons than ions can be visually identified by illuminating them with a laser and their dynamics can be captured in video recordings using CCD cameras. Such a non-intrusive diagnostic is a great convenience that makes a dusty plasma a suitable medium for studying flow induced phenomena. In this paper we report on experimental and theoretical investigations of different nonlinear waves and structures due to the interaction of plasma flows with charged stationary objects. In particular, we discuss the nature and conditions for the generation of precursor solitons and dispersive shocks in the upstream region due to dust flowing over a potential hill [1, 2].

EXPERIMENTAL ARRANGEMENT

The experiments have been performed in a newly built Dusty Plasma Experimental (DPEx) device at the Institute for Plasma Research [3]. The vacuum vessel consists of a Π-shaped Pyrex glass tube that has an experimental area of 8 cm inner diameter and 65 cm length in the horizontal section and two service portions of 30 cm length and of same diameter that form the vertical sections. A long cathode tray is placed in the horizontal portion (Z-axis) where all the dusty plasma experiments are performed whereas the vertical portion is utilized for pumping, gas inlets, anode connection, and for other functional access. These experimental arrangements provide a good access for optical diagnostics. The vacuum vessel is evacuated by a rotary pump connected at the vertical portion. The mass flow controller which is connected in the horizontal portion and interfaced with the computer, is the heart of the experimental setup

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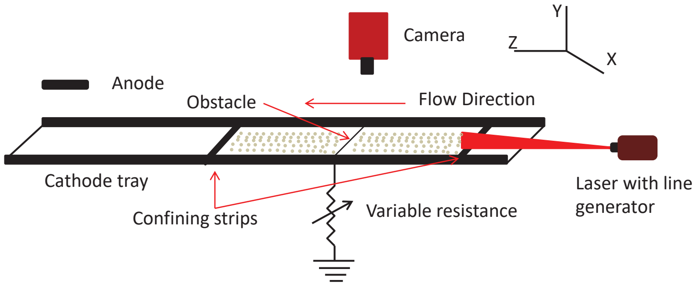

FIGURE 1. Schematic diagram of experimental arrangement for flow induced excitations.

as it is utilized for manipulating the dust cloud by changing the gas flow in a well controlled manner. A DC glow discharge plasma is produced between the disc shaped anode and long grounded cathode tray by applying a high voltage DC in the background of argon gas. Micron sized kaolin particles (with a size dispersion ranging from 2 to 6 μm) are sprinkled on the cathode tray in order to form a dusty plasma. The levitated particles are confined in between two confining potential strips placed on the cathode at 25 cm apart. A copper wire of 1mm diameter is mounted in between the strips at a height of 1 cm from the cathode which can be grounded or switched to a floating or intermediate potentials by drawing a current through a variable resister connected in between the wire and the ground. The particles are illuminated by a laser beam, which is expanded parallel to the surfaces of the electrodes. The reflected laser light is recorded with a CCD-camera. Experiments are conducted at pressures within p = 9–14 Pa and discharge voltage of 320–400 V. Different methods are used for dust flow generation. In one configuration the potential hill over the wire is reduced by switching it to floating potential from grounded potential. In the second configuration, the flow is generated by suddenly reducing the mass flow of the gas. This method is used to generate a highly supersonic dust flow.

RESULTS AND DISCUSSION

The wave pattern formation has been studied in both flow generation method, e.g., lowering the potential hill height and reducing the mass flow of neutral gas [4]. In the first set of experiments, initially the wire is set on the grounded potential so that particles are confined in between the potential hill created by the wire and a right confining strip. The dust flow is generated by reducing the potential hill above the wire and thereby removing the barrier that obstructs the particles to flow. The flow speed of the dust cloud is determined by the amount of initial lowering of the height of the wire potential. Upon release from the potential barrier the flowing dust particles quickly attain a terminal velocity U due to the slowing down effect from the neutral drag force [4]. This velocity is found to remain uniform over a substantial region of the device until the time that the cloud runs out of dust particles. We have measured this velocity for different lowering of hill height by open PIV tool in MATLAB [5]. For subsonic flow of the dust fluid, wake fields are excited in the left side of the wire traveling at the speed of ≈ 2.30 cm/s.

In the case of a supersonic flow a dramatic change in the nature of excitation has been observed. In addition to the wake fields to the left of the wire a large solitary wave is excited to the right of the wire traveling opposite to the direction of flow. In the frame of the fluid where the hill is moving from left to right the wake fields are in the downstream region whereas the soliton propagates in the upstream direction as can be seen from the intensity plot (Fig 2). The actual speed after taking into account of the flow comes out to be 4–5 cm/s. with a Mach number of ≈ 1.5. Thus the speed of the flow decides the generation of these nonlinear structures. It is found that the precursor pulses are emitted in regular time intervals and keep growing in amplitude as they travel to the right till they attain a saturated amplitude value. After attaining the saturation they travel faster than the dust acoustic speed. Furthermore, their speed also depends on the size of their amplitude which shows a property of KdV solitons [6]. In addition to this they show another characteristic — the intersolitonic time intervals (T_s) varies inversely with the 3/2 power of the amplitude, i.e., $T_s \propto A^{-3/2}$ — which is consistent with the theoretical results obtained from a solution of a forced KdV equation for precursor solitons [7].

In the second set of experiments the wire was kept at ground potential and the flow was generated by reducing the mass flow of neutrals. This method was used to generate highly supersonic flows (high Mach number of M > 2) over the wire. Due to the sudden reduction of mass flow of neutrals, the neutrals flow from right to left with very

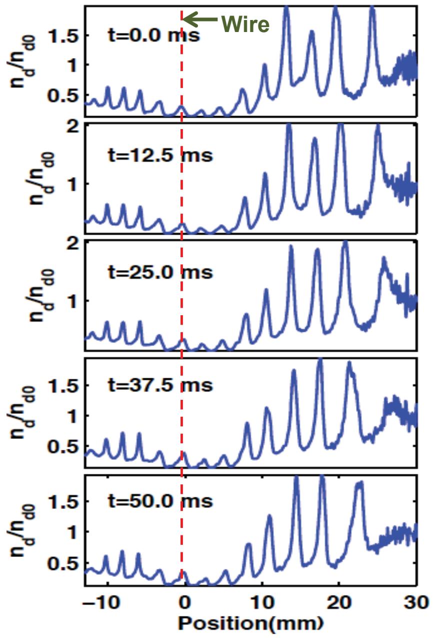

FIGURE 2. Time evolution of precursor solitons. The '0' position corresponds to the position of wire.

high velocity to attain the homogeneous neutral density. During the flow they carry the dust particles along their direction of flow hence dust particles are also found to flow with supersonic velocity. The flowing dust particles get compressed due to strong obstruction created by the potential hill over wire and are subjected to a sudden density jump near the wire which subsequently expands and forms a shock that is found to propagate in the direction of the fluid flow. With the evolution of time it is converted into a dispersive dust acoustic shock wave (DASW) by creation of compression and rarefaction in the dust density near the wire as seen in Fig 3. It is seen that a single crest grows in

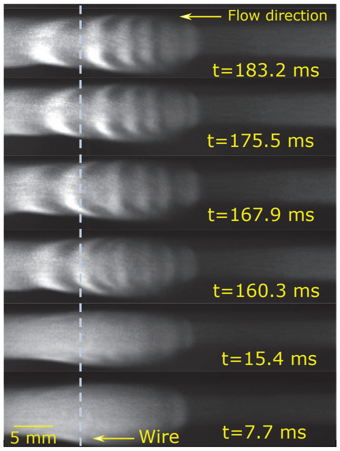

FIGURE 3. Time evolution of dispersive dust acoustic shock fronts. The dashed ('0') position in the picture corresponds to the position of the wire.

amplitude as it propagates towards the wire and after crossing the wire the amplitude of the pulse decreases, whereas the width increases as shown in fig 4. The velocity of the shock waves is calculated as ≈ 10 cm/s ($M > 2$) at a specific discharge condition. The experiments also reveal that there exists a threshold value in the difference of gas flow rate (13.75 ml$_s$/min) and in the height of the potential hill beyond which shock waves get triggered. Also the shocks are not excited whenever the wire is kept on a floating potential as the particles then do not feel the presence of the wire (the

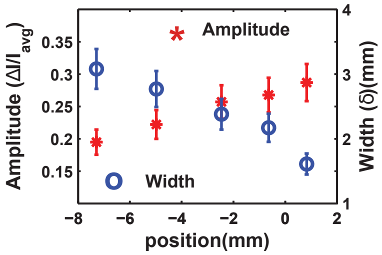

FIGURE 4. Variation of amplitude (⋆) and shock thickness (◯) of a leading pulse with position. The change of flow rate is 19.25 ml/min [1].

surface potential of the dust is always close to the floating potential). The generation of dispersive shock waves and variation of the amplitude and thicknesses of the shock structures are qualitatively similar to the oscillatory solution of the KdV Burgers equation which has been derived by using the generalized hydrodynamic (GH) model for weakly collisional dusty plasmas [8]. However, the model falls short of explaining the exact dissipation mechanism as it does not provide an adequate measure of the shock thickness. Considering the dust neutral collision, shock thickness in such a case can be approximately equal to the dust–neutral collision mean free path and for our experimental parameters the estimated values are quite close to our experimentally measured shock thickness.

In summary, nonlinear wave excitations due to the interaction of a supersonic dusty plasma flow with a charged obstacle have been studied. The experimental findings have established for the first time the existence of precursor solitons in a plasma medium — a phenomenon hitherto observed only in hydrodynamic experiments. The observations are well explained by a theoretical model based on the forced KdV equation. Our experimental studies have also explored the excitation of dispersive shock waves and observed their occurrence when the flow velocity exceeds a Mach number of 2. The propagation characteristics of such shocks have been studied as a function of the flow velocity and other experimental parameters and are found to agree well with theoretical results based on the KdV-Burgers equation.

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