Pergamon

Planet. Space Sci., Vol. 44, No. 3, pp. 239–242, 1996

0032–0633/96 $15.00+0.00

0032–0633(95)00109–3

Experiments on ion-acoustic waves in dusty plasmas

A. Barkan, N. D'Angelo and R. L. Merlino

Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242-1479, U.S.A.

Received 8 May 1995; revised 11 August 1995; accepted 11 August 1995

Abstract. An experiment is described on ion-acoustic (IA) waves in dusty plasmas, which was performed in the dusty plasma device (DPD) of Xu *et al.* (*Rev. Sci. Instrum.* **63,** 5266, 1992). It is found that, as expected, the presence of negatively charged dust grains increases the phase velocity of the waves and, at the same time, also reduces the strength of the collisionless (Landau) damping to which the waves are subjected.

1. Introduction

In the last ten years or so a considerable amount of *theoretical* work has been published on the subject of waves in dusty plasmas, beginning with the study by Bliokh and Yarashenko (1985) of electrostatic waves in Saturn's rings. More recent contributions are those of, e.g. Rao *et al.* (1990), D'Angelo (1990), D'Angelo and Song (1990), Shukla (1992), Shukla and Silin (1992), Bharuthram and Shukla (1992), Melandsø *et al.* (1993), Rosenberg (1993), Chow and Rosenberg (1995), D'Angelo (1994), and Li *et al.* (1994). Little, on the other hand, has been reported so far on experimental work, namely: (a) the study by Barkan *et al.* (1995) of electrostatic ion-cyclotron (EIC) waves, and (b) the observation by Chu *et al.* (1994) of very low frequency ($f \sim 12$ Hz) fluctuations, later interpreted by D'Angelo (1995) as dust-acoustic waves.

In the present paper we describe our recent study of grid-launched ion-acoustic waves (of tens of kHz frequency) propagating through a dusty plasma column of the type described by Xu *et al.* (1992). We find that, as expected, the presence of negatively charged dust grains increases the phase velocity of the waves and, as a consequence, also reduces the strength of the collisionless (Landau) damping to which the waves are subjected. These results are in line with those reported by Song *et al.* (1991) on the propagation and damping of ion-acoustic waves in a plasma with negative ions. In their experiment the phase velocity of the ion-acoustic "fast" mode increased with an increasing concentration, ε, of the negative ions, while the wave damping decreased with increasing ε. This effect in a negative ion plasma was predicted by D'Angelo *et al.* (1966) while the similar result for a plasma with negatively charged dust grains was pointed out explicitly by Shukla and Silin (1992).

In Section 2 of this paper we describe the experimental setup and the general plasma and dust conditions under which the measurements were made. Section 3 presents the experimental results, which are then compared with theory. Section 4 contains the conclusions.

2. Experimental setup

The experiment utilizes as the plasma source a Q-machine (Motley, 1975) in which a fully ionized, magnetized ($B \lesssim 0.4$ T) potassium plasma column of ~ 4 cm diameter and ~ 80 cm long is produced by surface ionization of potassium atoms from an atomic beam oven on a hot (~ 2500 K) tantalum plate. The constituents of the plasma are K^+ ions and electrons with approximately equal temperatures $T_i \approx T_e \approx 0.2$ eV, and densities in the range 10^5–10^{10} cm^{-3}.

To dispense dust particles into the plasma, the plasma column is surrounded over the end portion of its length (~ 30 cm) by the device shown schematically in Fig. 1. This dust dispenser consists of a rotating metal cylinder ("drum") and a stationary screen. Dust particles, initially loaded into the bottom of the cylinder, are carried by the rotating cylinder up to the top and fall onto the screen. A series of stiff metal bristles attached to the inside of the cylinder scrapes across the outer surface of the screen as the cylinder is rotated. This continuous scraping vibrates the screen allowing the dust to fall evenly through the plasma column. The fallen dust which collects at the bottom of the cylinder is then recycled. The dust we used was hydrated aluminum silicate (kaolin) of various sizes and shapes. The screen limits the dispensed grain sizes to < 100 μm. Samples of dust grains were collected from within the

Correspondence to: R. L. Merlino

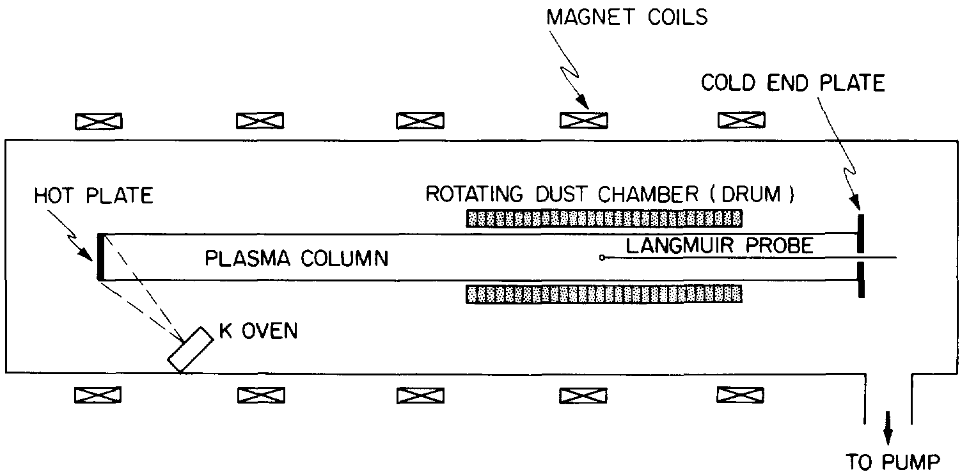

Fig. 1. Schematic diagram of the dusty plasma device (DPD)

vacuum chamber and an analysis was made of photographs taken with an electron microscope to determine their size distribution. These photographs showed that 90% of the grains had sizes in the 1–15 μm range with an average size $a \sim 5$ μm.

The plasma diagnostics are performed by means of a Langmuir probe that also enables us to determine how the negative charge in the plasma is divided between free electrons and negatively charged dust grains. Figure 2 shows Langmuir characteristics obtained under identical conditions except for the absence (upper curve) or the presence (lower curve) of dust, with the electron portion of the characteristics shown as positive current. When the dust is present, the electron saturation current $I_{e,dust}$ to a positively biased probe is smaller than the current $I_{e,no\ dust}$ measured without dust. This is due to the fact that electrons which attach to dust grains of extremely low mobility are not collected by the probe. Careful checks were made to ensure that the probe functions properly in the dusty plasma environment, as evidenced in Fig. 2 by the return of the electron saturation current to the "no dust" level when the dust is abruptly turned off. For further details on the characteristics of the dusty plasma and the charging of the dust grains see Xu *et al.* (1992, 1993) and Barkan *et al.* (1994).

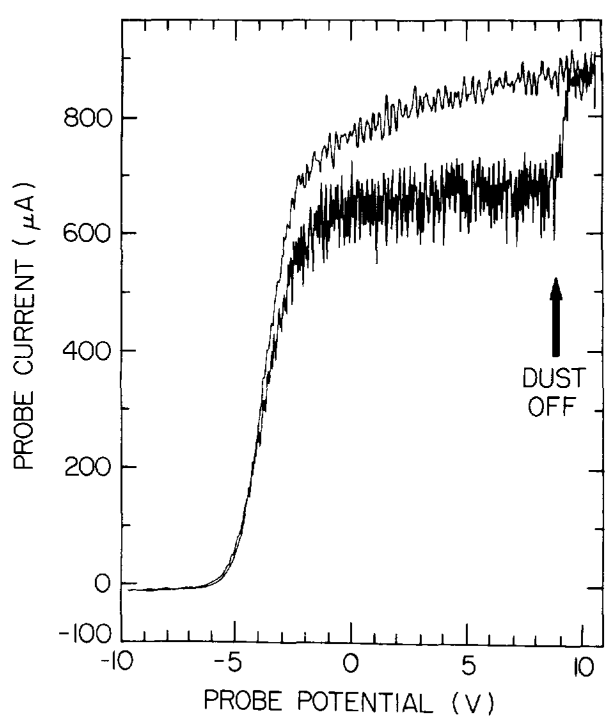

Fig. 2. Langmuir probe characteristics obtained under identical conditions except for the absence (upper curve) or the presence (lower curve) of dust

From the Langmuir probe characteristics, the ratio

$$\eta = \frac{(I_{e,dust}/I_{e,no\ dust})}{(I_{i,dust}/I_{i,no\ dust})}$$

is readily obtained. Since the saturation currents are proportional to the respective densities and $n_{e,no\ dust} = n_{i,no\ dust}$, it is also $\eta = n_{e,dust}/n_{i,dust}$. Thus, the quantity η measures the fraction of negative charge present as free electrons. An $\eta = 1$ refers to the case of no negatively charged dust grains, while an $\eta < 1$ corresponds to a plasma in which some of the negative charge is on dust grains. As explained in detail in Xu *et al.* (1993), at a fixed dust density the parameter η can be changed simply by varying the plasma density $n_{e,no\ dust}$, smaller values of η being obtained at the lower values of $n_{e,no\ dust}$.

The ion-acoustic waves were excited in the present experiment in the manner used previously by Wong *et al.* (1964), i.e. by means of a grid inserted into the plasma column, perpendicular to the magnetic field (see Fig. 3)

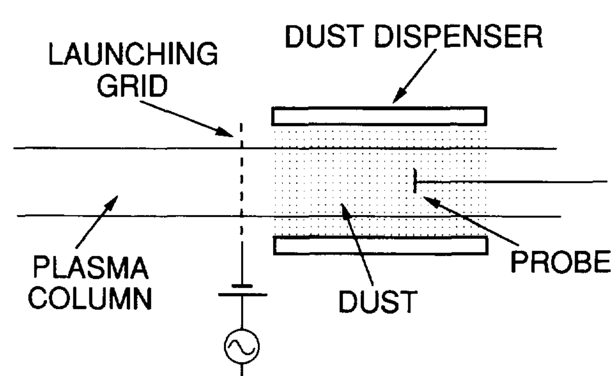

Fig. 3. Experimental setup for the IA waves studies

and located approximately 3 cm upstream from the dust dispenser. The grid was biased at several volts negative with respect to the space potential and a tone-burst sinusoidal voltage signal, of frequency $f \simeq 20$–80 kHz and amplitude 4–5 V peak-to-peak, was applied to it. This produced near the grid a density perturbation which then traveled down the column, into the region of the dust dispenser, as an ion-acoustic wave. By means of the axially movable Langmuir probe (disk 1 cm in diameter) phase and amplitude measurements could be performed at various axial locations and the wave phase velocity, v_{ph}, wavelength, λ, and attenuation length, δ, determined. In the present experiments, in order to observe substantial effects of the dust on the wave properties, it was necessary to operate at values of η as low as ~ 0.2. This, in turn, for the fixed dust density provided by the dust dispenser, meant that we had to work with plasma densities as low as $\sim 10^6$ cm^{-3}. At these densities and with the electron temperature $T_e \simeq 0.2$ eV, the Debye length is ≈ 0.3 cm. Thus, the launcher grid had to have the rather unusual feature of an interwire spacing of ~ 0.5 cm, in order to obtain appreciable density modulation by the applied sinusoidal voltage. In addition, the further condition that the ion gyroradius be comparable to or larger than the grid wire spacing, required that the magnetic field be not much above 1000 gauss (at 1000 gauss the gyroradius of 0.2 eV K^+ ions is ~ 0.3 cm).

3. Experimental results

The effect of negatively charged dust on the propagation and damping properties of the ion-acoustic waves was demonstrated as follows.

With the dust dispenser turned off ($\eta = 1$), at any given plasma density $n_{i,\text{no dust}}$ the phase velocity $v_{ph} = f \cdot \lambda$ of the wave and its attenuation length, δ, were obtained by using the same method employed previously by Wong *et al.* (1964), i.e. from the measured curves of time of arrival (or amplitude, $\Delta n/n$) vs. the axial position of the detecting Langmuir probe. Next, with the dust dispenser turned on, some new η was obtained, in the range $0.2 \lesssim \eta < 1$, its actual value depending only on the initial plasma density $n_{i,\text{no dust}}$, since the dust density was kept fixed throughout. At this η, the wave phase velocity and the attenuation length were measured by the same method as in the absence of dust. The two quantities $v_{ph}(\eta)/v_{ph}(1)$ and $(\delta/\lambda)_\eta/(\delta/\lambda)_1$, plotted as functions of η in Figs 4 and 5, respectively, clearly show the influence of the negatively charged dust on the wave phase velocity and damping. As the value of η decreases and the percentage of the negative charge per unit volume which resides on the dust grains becomes larger, the wave phase velocity also increases, while the damping becomes less severe (larger values of δ/λ).

In Fig. 4 the full lines were obtained from fluid theory calculations (D'Angelo, 1990), for three different values of the plasma zero-order drift along **B**, while the full line of Fig. 5 was derived from previous Vlasov theory calculations (e.g. D'Angelo *et al.*, 1979) of δ/λ vs. v_{ph}, combined with the Fig. 4 curve of v_{ph} for $v_{drift} = 0$. There appears to be substantial agreement between theory and experiment. This indicates, in particular, that the main effect of the negative dust on damping is a reduction of the Landau damping, most pronouncedly at the lowest values of η.

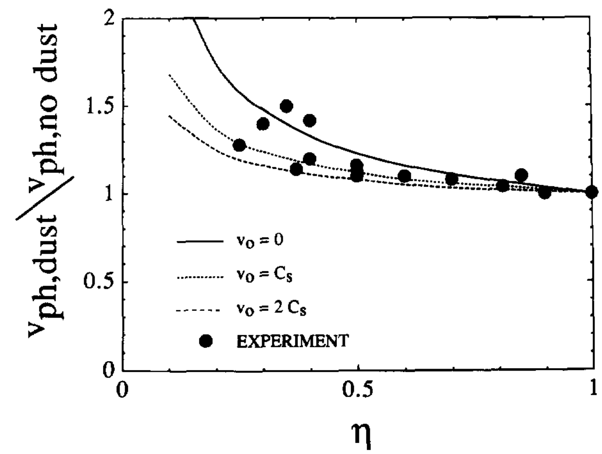

Fig. 4. The ratio $v_{ph}(\eta)/v_{ph}(1)$ vs. η. The full lines are from fluid theory calculations for three different values of the plasma zero-order drift velocity along **B**, i.e. $v_{drift} = 0$, C_s and $2C_s$, where C_s is the ion-acoustic speed

Finally, the same data of Figs 4 and 5 were combined in Fig. 6, in a plot of $(\delta/\lambda)_\eta/(\delta/\lambda)_1$ vs. $v_{ph}(\eta)/v_{ph}(1)$, to illustrate in a perhaps clearer fashion how the reduction of the damping is brought about by the increase of the wave phase velocity, as the value of η is reduced.

4. Conclusions

Until now, only two types of electrostatic waves appear to have received some attention from experimentalists: the electrostatic ion-cyclotron (EIC) waves (Barkan *et al.*, 1995) and the dust-acoustic waves (Chu *et al.*, 1994).

With the present experiments, the ion-acoustic (IA) waves can now be added to the still short list.

The present experiments were performed in the dusty-plasma device (DPD) of the type described by Xu *et al.* (1992) and provided the following results:

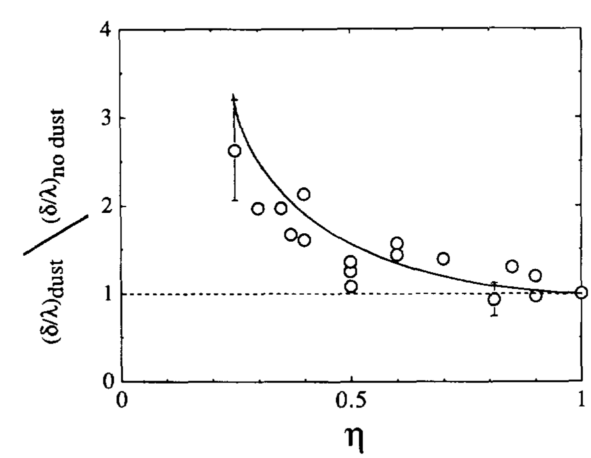

Fig. 5. The ratio $(\delta/\lambda)_\eta/(\delta/\lambda)_1$ vs. η. The full line is obtained from Vlasov theory calculations of δ/λ vs. v_{ph} and the Fig. 4 curve of v_{ph} vs. η for $v_{drift} = 0$

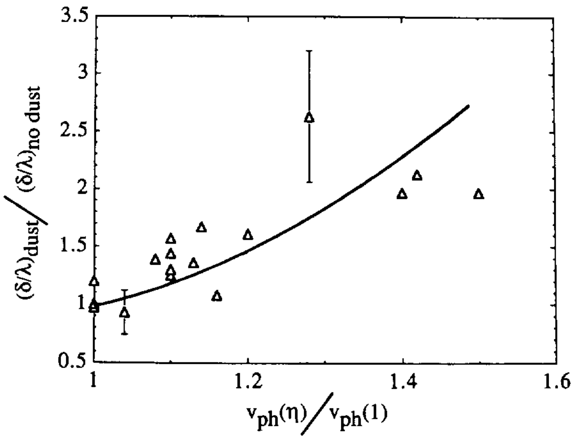

Fig. 6. A plot of $(\delta/\lambda)_\eta/(\delta/\lambda)_1$ vs. $v_{ph}(\eta)/v_{ph}(1)$

(a) ion-acoustic waves are indeed a possible plasma wave mode in dusty plasmas,

(b) the phase velocity of the wave increases when negatively charged dust is present, and

(c) as a consequence of the phase velocity increase, the wave (Landau) damping becomes less severe.

All these results are in general agreement with available theories and, in addition, are in line with the conclusions of Song *et al.* (1991) on the propagation and damping of ion-acoustic waves in plasmas containing appreciable fractions of negative ions.

Acknowledgments. Work supported by ONR.

References

Barkan, A., D'Angelo, N. and Merlino, R. L., Charging of dust grains in a plasma. *Phys. Rev. Lett.* **73,** 3093, 1994.

Barkan, A., D'Angelo, N. and Merlino, R. L., Laboratory experiments on electro-static ion cyclotron waves in a dusty plasma. *Planet. Space Sci.*, **43,** 905, 1995.

Bharuthram, R. and Shukla, P. K., Vortices in non-uniform dusty plasmas. *Planet. Space Sci.* **40,** 647, 1992.

Bliokh, P. V. and Yarashenko, V. V., Electrostatic waves in Saturn's rings. *Sov. Astron., Engl. Transl.* **29,** 330, 1985.

Chow, V. and Rosenberg, M., Electrostatic ion cyclotron instability in dusty plasmas. *Planet. Space Sci.*, **43,** 613, 1995.

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

D'Angelo, N., Low-frequency electrostatic waves in dusty plasmas. *Planet. Space Sci.* **38,** 1143, 1990.

D'Angelo, N., Ion-acoustic waves in dusty plasmas. *Planet. Space Sci.* **42,** 507, 1994.

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

D'Angelo, N. and Song, B., The Kelvin–Helmholtz instability in dusty plasmas. *Planet. Space Sci.* **38,** 1577, 1990.

D'Angelo, N., von Goeler, S. and Ohe, T., Propagation and damping of ion waves in a plasma with negative ions. *Phys. Fluids* **9,** 271, 1966.

D'Angelo, N., Joyce, G. and Pesses, M. E., Landau damping effects on solar wind fast streams. *Astrophys. J.* **229,** 1138, 1979.

Li, F., Havnes, O. and Melandsø, F., Longitudinal waves in a dusty plasma. *Planet. Space Sci.* **42,** 401, 1994.

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

Motley, R. W., *Q Machines*. Academic Press, New York, 1975.

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

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

Shukla, P. K., Low-frequency modes in dusty plasmas. *Phys. Scr.* **45,** 504, 1992.

Shukla, P. K. and Silin, V. P., Dust ion-acoustic wave. *Phys. Scr.* **45,** 508, 1992.

Song, B., D'Angelo, N. and Merlino, R. L., Ion-acoustic waves in a plasma with negative ions. *Phys. Fluids* **B3,** 284, 1991.

Wong, Y. A., Motley, R. W. and D'Angelo, N., Landau damping of ion acoustic waves in highly ionized plasmas. *Phys. Rev.* **133,** A436, 1964.

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

Xu, W., D'Angelo, N. and Merlino, R. L., Dusty plasmas: the effect of closely packed grains. *J. geophys. Res.* **98,** 7843, 1993.