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Laboratory experiments on electrostatic ion cyclotron waves in a dusty plasma

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Abstract. Current driven electrostatic ion cyclotron (EIC) waves have been observed in a dusty plasma laboratory experiment. The theoretical prediction that a substantial amount of negatively charged dust makes the plasma more unstable to the EIC instability appears to be borne out by the experimental results.

1. Introduction

In nebulas, planetary magnetospheres and comet environments, solid matter in the form of dust particles is often found embedded in an ionized gas. A system of this type is referred to as "dusty plasma". For reviews of dusty plasma phenomena in situations of astrophysical interest or within the Solar System, see Spitzer (1978) or Goertz (1989), respectively.

Waves in dusty plasmas have been studied theoretically for about a decade, beginning with the work of Bliokh and Yarashenko (1985) on electrostatic waves in Saturn's rings. Among the more recent contributions we may mention those of Rao *et al.* (1990), D'Angelo (1990), D'Angelo and Song (1990), Shukla (1992), Bharuthram and Shukla (1992), Melandsø *et al.* (1993), Rosenberg (1993), and Chow and Rosenberg (1995).

To the best of our knowledge, however, no experimental work on waves in dusty plasmas has been reported so far. The present paper describes our recent attempt at observing in a laboratory dusty plasma the current driven electrostatic ion cyclotron (EIC) instability which, for ordinary plasmas, has been studied for about three decades (e.g. D'Angelo and Motley, 1962; Schrittwieser, 1988).

A prediction of some of the theoretical work referred to above (D'Angelo, 1990; Chow and Rosenberg, 1995) is that the presence in a plasma of a substantial amount of negatively charged dust should make the plasma more unstable to the EIC instability, lowering the critical drift of the electrons along the magnetic field lines. This result is not surprising, in view of the observation by Song *et al.* (1989) that in a plasma with a large concentration of negative ions the EIC instability has a lower threshold than in a plasma with no negative ions.

The present observations, in a plasma with negatively charged dust, show general agreement with the theoretical predictions of Chow and Rosenberg (1995) concerning the enhancement of the instability by the dust.

In Section 2 of the paper the experimental set-up is described, while Section 3 deals with the experimental procedure and the results. A discussion of the results is found in Section 4.

2. Experimental set-up

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 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 throughout the plasma

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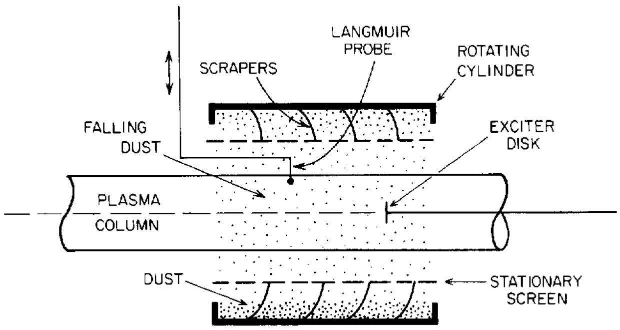

Fig. 1. Schematic diagram of the experimental set-up, showing the dust dispenser and the exciter disk

column. The fallen dust which collects at the bottom of the cylinder is then recycled. The dust we used was hydrated aluminium 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 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 $I_{e,\mathrm{dust}}$ to a positively biased probe is smaller than the current $I_{e,\mathrm{no\,dust}}$

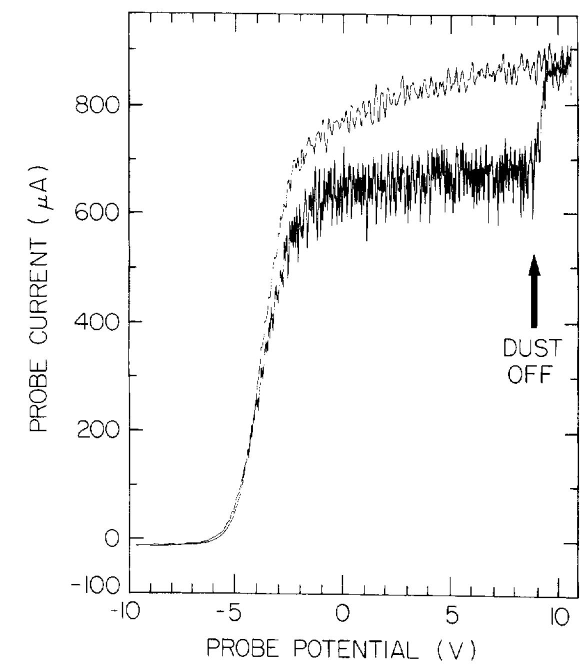

Fig. 2. Langmuir probe characteristics obtained under identical conditions except for the absence (upper curve) or the presence (lower curve) of kaolin dust. The return of the electron saturation current to the "no dust" level when the dust is abruptly turned off is shown in the upper right corner of the figure

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).

From the Langmuir probe characteristic the ratio

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

is readily obtained. Since the saturation currents are proportional to the respective densities and $n_{e,\mathrm{no\,dust}} = n_{i,\mathrm{no\,dust}}$, it is also $\eta = n_{e,\mathrm{dust}}/n_{i,\mathrm{dust}}$. 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 $n_{e,\mathrm{no\,dust}}$, smaller values of η being obtained at the lower values of $n_{e,\mathrm{no\,dust}}$.

The EIC waves were excited in the present experiment in the same manner used previously (see, e.g. Schrittwieser, 1988) in ordinary plasmas without dust, namely by drawing an electron current, along the magnetic field lines, to an "exciter" disk located on the axis of the plasma column near its end. The disk had a diameter of 0.5 cm, large enough to avoid the so-called "filamental quenching" (e.g. Cartier *et al.*, 1985). The propagation of the EIC waves excited by the current to the disk could be studied by means of the radially moveable Langmuir probe (Fig. 1).

3. Experimental procedure and results

The effect of negatively charged dust on the excitation of EIC waves was demonstrated experimentally as follows. For any given plasma conditions in the absence of dust, EIC waves were excited by drawing an electron current to the exciter disk, which was biased at a voltage anywhere from ~ 0.5 to ~ 5 V above the space potential. The amplitude of the wave, $A_{\mathrm{no\,dust}}$, was recorded and, without introducing any other changes in the plasma conditions, the dust dispenser was turned on producing a dusty plasma whose parameter η could be determined as indicated in Section 2. A new EIC wave amplitude, A_{dust}, was then measured. The ratio $R = A_{\mathrm{dust}}/A_{\mathrm{no\,dust}} \gtrsim 1$ could be taken as an indicator of the enhancement of the instability produced by the dust.

The measured R vs. η values are shown in Fig. 3. For $\eta \gtrsim 0.7$, the ratio R is near unity, indicating that for these conditions the dust has hardly any effect on the wave amplitude. However, as η decreases from ~ 0.7 down to ~ 0.25 (and the percentage of the negative charge per unit volume which resides on the dust grains increases), the amplitude ratio R is seen to increase to as much as ~ 2. Thus, from the data of Fig. 3, one infers an enhancement

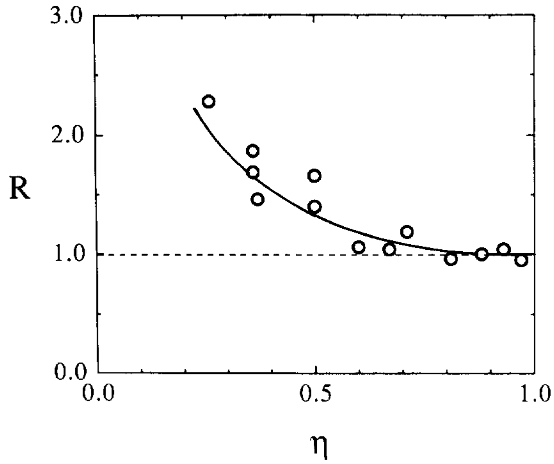

Fig. 3. The ratio $R = A_{dust}/A_{no\,dust}$ of the EIC wave amplitudes with and without dust is shown as a function of the parameter $\eta = n_{e,dust}/n_{i,dust}$. As η decreases, the percentage of the total negative charge which is on dust grains increases. The measurements are typically performed with plasma densities in the $\sim 10^6$ to $\sim 10^9$ cm^{-3} range, dust densities of $\sim 5\times10^4$ cm^{-3} and an average grain size ~ 5 μm

of the wave amplitude at the lower values of η, in line with the theoretical predictions of Chow and Rosenberg (1995).

A more striking demonstration of the above effect was obtained by first biasing the exciter disk at a voltage somewhat below the minimum required for wave excitation in the absence of dust, and then generating the EIC waves simply by turning on the dust dispenser.

Additional measurements on these waves in the presence of dust provided (a) the wave frequency, f, as a function of the magnetic field, B, and (b) the propagation properties of the waves. As in the early EIC wave observations (D'Angelo and Motley, 1962; Motley and D'Angelo, 1963), also when dust was present we observed a wave frequency some 10–20% larger than the ion gyrofrequency, while the wave propagation was also primarily radially outward. The perpendicular (to **B**) wavelength was measured in the same manner as in the early work and turned out to be ~ 2.5 cm, while the parallel wavelength was much larger than this.

4. Discussion

In the last decade a large amount of theoretical work has been performed on waves and instabilities in dusty plasmas. However, until now, no experimental work on the subject has been reported. In this paper we have described an investigation of electrostatic ion cyclotron (EIC) waves performed in a Q-machine, modified by the addition of a suitable dust dispenser. Two predictions of the theory (e.g. D'Angelo, 1990; Chow and Rosenberg, 1995) have been verified, namely: (a) EIC waves are indeed a possible plasma wave mode in dusty plasmas, and (b) the presence of negatively charged dust enhances the instability growth rate. Although (b) is inferred from the observed large-amplitude (non-linear) behavior of the waves, it seems reasonable enough to assume that an observed larger wave amplitude is an indicator of an enhanced linear growth rate.

In the experiments, the quantity η was varied from 1 down to ~ 0.25. The corresponding variation of the parameter δ ($=1/\eta$) of Chow and Rosenberg (1995), is from 1 to ~ 4. Figure 2 of Chow and Rosenberg (1995) indicates an increase of the maximum growth rate by about a factor 2, as δ changes from 1 to 3. The work of Chow and Rosenberg (1995) also provides a simple expression for the critical electron drift for excitation of the current driven EIC instability, namely

$$v_{crit} = C_i\left(12\eta\frac{T_i}{T_e}+6\right)$$

where C_i is the ion thermal speed.

Finally, as noted earlier, the present experimental results in plasmas with negatively charged dust, are quite similar to those obtained by Song *et al.* (1989) in an experiment in which the presence of negative ions enhanced the growth rate of the EIC instability.

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