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Dusty Plasmas: The Effect of Closely Packed Grains

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A dusty plasma device recently described in the literature has been utilized to study experimentally the charging of dust grains by the surrounding plasma. By varying the ratio d/λ_D between the intergrain distance and the plasma Debye length, the effects predicted by Goertz and Ip (1984), and subsequently reanalyzed in a more general fashion by Whipple et al. (1985), when "isolated" dust grains become "closely packed" grains have been demonstrated experimentally.

1. INTRODUCTION

Much of the solid matter in the universe exists in the form of dust particles often embedded in an ionized gas. Such a multicomponent system is usually referred to as "dusty plasma."

Dusty plasmas occur in several situations of astrophysical interest [e.g., *Spitzer*, 1978], such as nebulas, planetary magnetospheres, and comet environments. Dust-plasma interactions are now thought to be responsible for some of the fine structure of Saturn's rings, as observed by the Voyager spacecraft. Phenomena related to the presence of electrically charged dust grains in the Earth's summer mesopause have been discussed by *Havnes et al.* [1990]. The dust particles connected with the formation of noctilucent clouds may become charged substantially positive, and this could explain the enhanced radar backscatter often observed from the mesopause region. Also, the presence of dust surrounding any large, man-made Earth-orbiting structure, such as a space station, is expected to affect the properties and behavior of the surrounding ionospheric plasma.

Reviews of recent work on dusty plasmas have been published by *Goertz* [1989], with particular emphasis on phenomena in the solar system, and also by *de Angelis* [1992] and *Northrop* [1992].

Until recently, most studies of dusty plasmas have been theoretical. However, as the potential importance of dusty plasmas became more apparent, it seemed desirable to undertake laboratory studies in parallel with the theoretical efforts. Dust particles as contamination particles in RF-produced plasmas have been investigated by *Carlile et al.* [1991] and *Bouchoule et al.* [1991]. A device for the dispersal of micron- and submicron-sized particles in a vacuum has been described by *Sheehan et al.* [1990] and used by them in conjunction with the alkali plasma of a Q machine [e.g., *Motley*, 1975]. We have described [*Xu et al.*, 1992] a rotating-drum dust dispersal device, which we have used, also in conjunction with a Q machine, to produce extended, steady state, magnetized dusty plasma columns. This device is capable of generating dusty plasmas in which more than 90% of the negative charge is attached to dust grains. For a detailed description of the device the reader is referred to *Xu et al.* [1992]. In the present paper we consider in greater detail the question of the charging of dust grains by a surrounding plasma, with particular emphasis on the effects to be expected when dust grains are placed close to each other, i.e., when the average distance of a grain from its nearest neighbor, d, becomes comparable to or smaller than the plasma Debye length λ_D. These effects have been analyzed by *Goertz* [1989], who considered the situation of a plasma with a series of 10 equally spaced infinite plane sheets of dust grains embedded in it. This "one-dimensional" configuration, while unrealistic, serves to illustrate the effects of placing dust grains close to one another, $d \lesssim \lambda_D$. One of these effects is that the average charge on each grain is reduced relative to the situation in which the grains are well separated, $d \gg \lambda_D$.

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This paper is organized as follows. Section 2 presents a brief discussion of the charging mechanisms of dust grains and of the effects expected [*Goertz and Ip*, 1984; *Whipple et al.*, 1985; *Goertz*, 1989] when the dust density is large ($d \lesssim \lambda_D$). Section 3 contains a description of the dusty plasma device (DPD) of *Xu et al.* [1992] and of the diagnostics which were used. Section 4 describes the experimental results, with emphasis on the situation prevailing when $d \lesssim \lambda_D$. Section 5 presents the conclusions.

2. CHARGING OF DUST GRAINS

Charging of dust grains may be due to the collection of ions and electrons from the surrounding plasma, photoelectron emission by UV radiation, ion sputtering, emission of secondary electrons, etc.

When collection of ions and electrons is the dominant charging mechanism, the situation of a dust grain is similar to that of an electrically floating Langmuir probe in a laboratory plasma. The charge Q on the dust grain changes according to

$$\frac{dQ}{dt} = I_i - I_e \tag{1}$$

where I_i and I_e are the ion and electron currents, respectively, to the grain. The charge Q is related to the surface potential V_s by

$$Q = CV_s \tag{2}$$

where C is the capacitance of the dust grain, which, for an assumed spherical grain of radius a, is given by

$$C = 4\pi\varepsilon_0 a. \tag{3}$$

The latter expression for the capacitance is valid when the grain radius a is much smaller than the Debye length λ_D of the ambient plasma. A spherical shape, of course, is not the

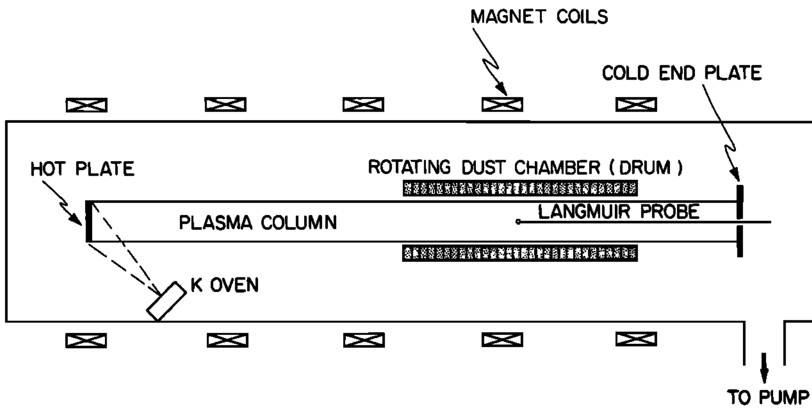

Fig. 1. Schematic diagram of the dusty plasma device.

most common shape for most types of dust, but (3) still provides a reasonable estimate for irregular grains of linear dimension a.

The surface potential V_s of a grain is determined by the condition that the grain be electrically floating, i.e.,

$$\left(\frac{dQ}{dt}\right)_{V=V_s} = (I_i - I_e)_{V=V_s} = 0. \tag{4}$$

The balance of ion and electron currents determines V_s as

$$V_s = -\alpha \frac{\kappa T_e}{e} \tag{5}$$

where T_e is the electron temperature; κ and e are Boltzmann's constant and the electronic charge, respectively; and α is a constant which depends on the ratio of the ion to electron mass [*Spitzer*, 1978]. For an electron-proton plasma, $\alpha \approx 2.5$, whereas for an electron-K^+ plasma, $\alpha \approx 4$.

Equations (2), (3), and (5) allow an estimate of the charge Q. For example, if $a = 0.1\ \mu$m and $\kappa T_e = 1$ eV, we obtain, for the case of a hydrogen plasma, $Q \simeq 2.8 \times 10^{-17}$ C $\simeq 174$ elementary charges.

This simple analysis applies to the case of "isolated" dust grains in a plasma. If the number density of the grains is sufficiently large, the distance d between neighboring grains may become of the order of or even less than the Debye length. In such a case the difference $U = V_s - V_p$ between the surface potential V_s on the grains and the plasma potential V_p has a smaller magnitude than in the case of $d \gg \lambda_D$. Consequently, the average charge on the grains, $Q = CU$, is smaller than that for isolated grains [*Goertz and Ip*, 1984]. *Havnes et al.* [1987] have shown that the charge Q and the potential U depend only on the parameter $P = aNT/n_0$, where T is the plasma temperature in electron volts, a is the grain radius in meters, and N and n_0 are the dust and plasma densities, respectively. Figure 5 of the review paper by *Goertz* [1989] shows that when P is small, U approaches the isolated grain value of $-2.5(\kappa T_e/e)$ for an electron-proton plasma. If P is increased by either increasing the dust density N or decreasing the plasma density n_0, the magnitude of the average charge on the grains ($\sim U$) is reduced by collective electrostatic effects. It will become apparent in section 4 that this expected variation of Q as one moves from the regime of isolated grains to that of "close neighbors" is borne out by our experimental results.

The analysis of *Goertz and Ip* [1984] made some approximations that are valid only if the collective effects of the dust grains on their charging are small. A subsequent paper by *Whipple et al.* [1985] showed how to carry out the analysis without these approximations. For example, instead of the vacuum capacitance $4\pi\varepsilon_0 a$, Whipple et al. use the capacitance of a grain immersed in the plasma and modified by the proximity of neighboring grains [*Whipple et al.*, 1985, equation (24)]. Also, for the potential difference between grain surface and plasma, instead of the $-4(\kappa T_e/e)$ that would exist for an isolated grain, they use the actual value, whatever it turns out to be [*Whipple et al.*, 1985, equation (38), Figure 5].

At the present state of our experiments it will make little difference in the conclusions which theory is adopted, but one may look forward to the time when experiments are such

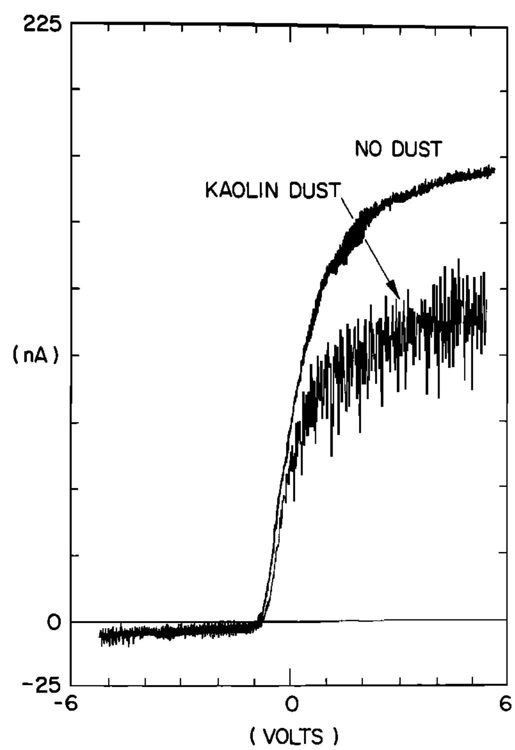

Fig. 2. Langmuir probe characteristics obtained under the same conditions, except for the absence/presence of kaolin dust.

that the choice might matter. It is worth pointing out that some complications may arise in any case from the facts that (1) the dust grains have generally a broad size distribution and (2) most dust grains have a shape that is far from the spherical shape generally assumed in the theoretical works.

3. Dusty Plasma Device and Diagnostics

A schematic diagram of the dusty plasma device (DPD) is shown in Figure 1. A magnetically confined, ~4-cm-diameter and ~80-cm-long plasma column is produced in a Q machine [e.g., *Motley*, 1975] by ionization of potassium atoms (from an atomic beam oven) on a hot (~2500 K) tantalum surface. The plasma column is surrounded over a length of 30 cm by a metallic cylinder ("drum") coaxial with the plasma. On the inside the drum is provided with "slots" into which dust is poured before the vacuum vessel of the Q machine is pumped out. An external motor can rotate the drum around its own axis with a rotation rate that is continuously variable up to 180 rpm. The rotation of the drum provides a continuous "rain" of dust through the plasma column, the amount of dust in the plasma depending, for a given initial loading of the slots, on the rate of rotation.

We have used three different types of dust, namely, aluminum oxide (Al_2O_3) with nominal grain sizes of 0.01 μm and 0.3 μm and kaolin (hydrated aluminum silicate, $Al_2Si_2O_7n(H_2O)$) with sizes greater than or equivalent to several microns. These dust sizes, incidentally, each fall within one of the three main groups of atmospheric nucleation centers (Aitken nuclei, large nuclei, and giant nuclei) discussed, for example, by *Mason* [1975]. The main diagnostic tool of the dusty plasma consists of a Langmuir probe movable along the axis of the plasma column (see Figure 1) and made of a tantalum disk 0.5 cm in diameter, oriented normally to the magnetic field. By using the Langmuir probe in essentially the same manner as done previously [*Song et al.*, 1989] in plasmas with appreciable fractions of negative ions, it is possible 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 the same conditions except for the absence/presence of kaolin dust. When the dust is present, the negative saturation current J_- (dust) to a positively biased probe is smaller than the current measured without dust, J_- (no dust). This is a consequence of the fact that electrons which attach to dust grains of extremely low mobility are not collected by the probe.

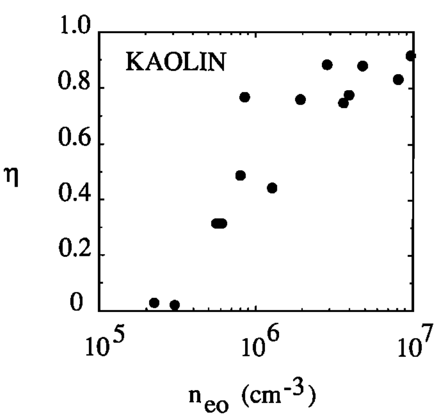

Fig. 3*a*. The percentage of negative charge on free electrons, η, versus the plasma density n_{e0}. The (kaolin) dust density is kept constant.

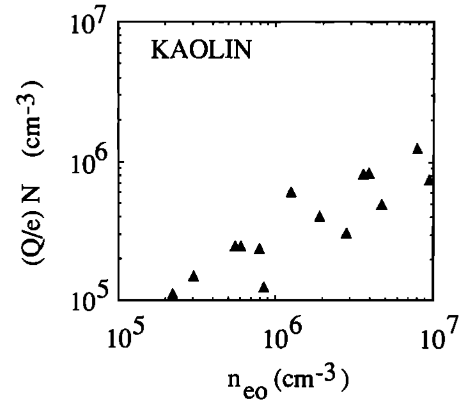

Fig. 3*b*. The quantity $(Q/e)N$ versus n_{e0} obtained from the data in Figure 3*a*.

Let $n_{+0} = n_{e0}$ be the plasma density when no dust is present and n_+ and n_e the positive ion and (free) electron densities, respectively, in the presence of dust. If N is the number of dust grains per unit volume and Q the average charge on the grains, the condition of charge neutrality reads

$$en_+ = en_e + QN. \tag{6}$$

If we define the quantity

$$\eta = \left(\frac{n_e}{n_{e0}}\right)\left(\frac{n_+}{n_{+0}}\right)^{-1} = \frac{n_e}{n_+} \tag{7}$$

we can write

$$\eta = \frac{en_e}{en_+} = \frac{en_+ - QN}{en_+} = 1 - \frac{QN}{en_+} \tag{8}$$

or

$$\frac{QN}{e} = n_+(1 - \eta). \tag{9}$$

Also,

$$\frac{QN}{e} = \beta n_{e0}(1 - \eta) \tag{10}$$

if $n_+ = \beta n_{+0} = \beta n_{e0}$.

Equation (10) states that the number of negative elementary charges per unit volume that one finds on dust grains can be expressed in simple fashion in terms of the positive ion density βn_{+0} and the parameter η. Equation (7) indicates that the parameter η can be obtained directly from the Langmuir probe characteristics, with and without dust, as

$$\eta = \frac{J_- \text{ (dust)}}{J_- \text{ (no dust)}} \frac{J_+ \text{ (no dust)}}{J_+ \text{ (dust)}}. \tag{11}$$

For the case in which J_+ (dust) $= J_+$ (no dust), i.e., when the positive ion density is essentially unaffected by the dust,

$$\eta = \frac{J_- \text{ (dust)}}{J_- \text{ (no dust)}}. \tag{12}$$

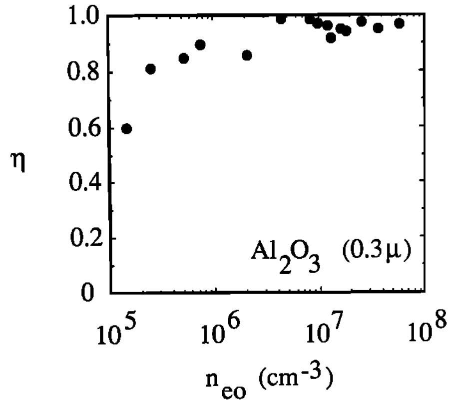

Fig. 4*a*. Same as Figure 3*a*, except for 0.3-μm dust of Al_2O_3.

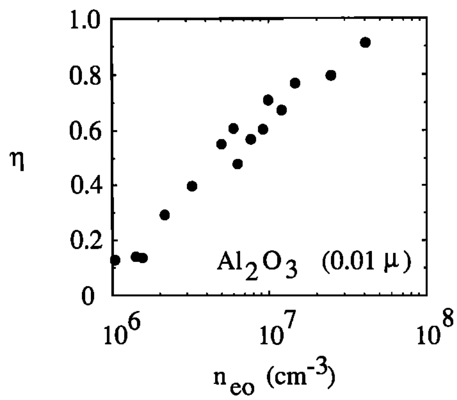

Fig. 5*a*. Same as Figure 3*a*, except for 0.01-μm dust of Al_2O_3.

The variation of η with the rotation rate of the drum, r, for a fixed dust loading of the slots and a given plasma density (at $r = 0$) has been presented by *Xu et al.* [1992, Figures 6 and 8]. As r is increased from $r = 0$, the amount of dust in the plasma initially increases, and η correspondingly decreases. However, for $r \gtrsim 0.7$, η begins to return to near unity, an indication that at those rotation rates the centrifugal force on the dust grains at the inner surface of the drum balances the force of gravity, i.e., $m_d\omega^2R = m_dg$, where m_d is the mass of a dust grain, ω the angular speed of the dust chamber, R its inner radius, and g the acceleration of gravity.

A more interesting type of result is the variation of η with the plasma density n_{e0}. This was briefly discussed by *Xu et al.* [1992] and is presented in more detail in the next section.

4. Experimental Results

In this section we show the measured variation of η, the fraction of negative charge per unit volume which resides on free electrons, with the plasma density n_{e0}. The η versus n_{e0} curves in Figures 3*a*, 4*a*, and 5*a* were taken by varying n_{e0} at constant dust density in the plasma, i.e., at fixed rotation rate r of the drum for a given initial dust loading of the slots. They allow us to construct, using (10), curves of QN/e versus n_{e0}, indicating how the average charge on the dust grains varies with plasma density.

Curves of η versus n_{e0} and QN/e versus n_{e0} obtained with kaolin dust are shown in Figures 3*a* and 3*b*, respectively. The corresponding data for an aluminum oxide (Al_2O_3) dust of nominal size 0.3 μm are given in Figures 4*a* and 4*b*, while those for an aluminum oxide dust of nominal size 0.01 μm are presented in Figures 5*a* and 5*b*.

Evidently, for all three types of dust, as the plasma density decreases while the amount of dust is kept constant, the parameter η falls from values near unity to much lower values (well below 0.1 in the case of a kaolin dust). This result seems quite reasonable, since as n_{e0} is decreased, a fixed amount of dust absorbs a number of electrons from the plasma which represents a larger and larger fraction of those present in the absence of dust. However, as Figures 3*b*, 4*b*, and 5*b* indicate, the average charge on the dust grains does not remain constant (at $Q \simeq C[4(\kappa T_e/e)]$, as discussed in section 2) but decreases steadily with decreasing n_{e0}. This appears to be due to the effect discussed, for example, by *Goertz and Ip* [1984], *Whipple et al.* [1985], and *Goertz* [1989] (see section 2) and which arises when the intergrain distance d becomes comparable to or smaller than the plasma Debye length λ_D. In our experimental procedure, d is kept constant during one run (fixed amount of dust), while λ_D is varied by varying the plasma density.

We may analyze the situation a little more in detail by referring, for example, to Figures 3*a* and 3*b* (kaolin dust). The effect under discussion begins to appear at $n_{e0} \approx 10^7$ cm^{-3} and becomes more and more prominent at lower densities. At $n_{e0} \approx 10^7$ cm^{-3} and with $\kappa T_e \simeq 0.2$ eV the plasma Debye length is $\lambda_D \approx 0.1$ cm. The value of d can be inferred from the observation that (see Figure 3*a*) at n_{e0} =

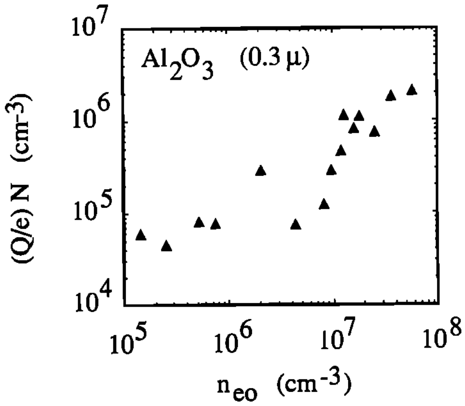

Fig. 4*b*. Same as Figure 3*b*, except for 0.3-μm dust of Al_2O_3.

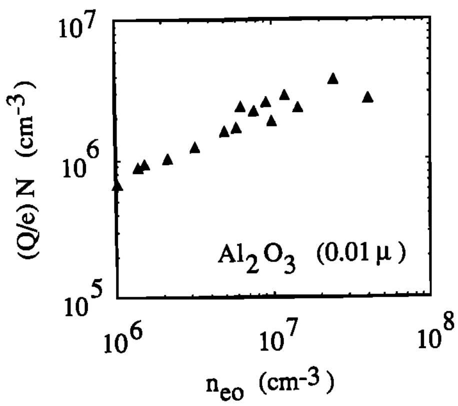

Fig. 5*b*. Same as Figure 3*b*, except for 0.01-μm dust of Al_2O_3.

10^6 cm^{-3}, $\eta \simeq 0.5$. Since, generally, n_+ differs from n_{e0} by no more than a factor of 2 ($0.5 \lesssim \beta \lesssim 1$), equation (10) indicates that for the situation of Figure 3a, $(QN/e) \approx 0.5 \times 10^6$ cm^{-3}. The quantity Q/e for the average dust grain can, in turn, be estimated from the size distribution of the grains [see *Xu et al.*, 1992, Figure 4]. With an average size of $a \simeq 10$ μm one finds (equations (2), (3), and (5)) that $Q/e \approx 5500$. Then $N \approx 10^2$ cm^{-3} and $d \approx (1/N^{1/3}) \approx 0.2$ cm. Thus at $n_{e0} = 10^7$ cm^{-3}, $\lambda_D = 0.1$ cm is only half as large as $d \simeq 0.2$ cm. At $n_{e0} = 10^6$ cm^{-3}, while d is still 0.2 cm, λ_D has increased to ~0.3 cm. These simple estimates do indicate that the close neighbors effect is likely to be responsible for the variation of QN/e versus n_{e0} observed in Figure 3b. Examination of Figures 4 and 5 affords similar conclusions. It is interesting also to estimate the parameter $P = NaT/n_{e0}$ discussed by *Goertz* [1989]. With $N \approx 10^2$ cm^{-3}, $a \approx 10^{-5}$ m, $T \approx 0.1$ eV, and $n_{e0} \approx 10^6$ cm^{-3} we find $P \approx 2 \times 10^{-10}$. This is within the range of P for which [see *Goertz*, 1989, Figure 5] the collective effect (Debye screening) is expected to be most pronounced. If the data in Figure 3a are analyzed in terms of the *Whipple et al.* [1985] theory, one finds (T. Northrop, private communication, 1992) that $Q \simeq -685e$ while $N \simeq 730$ cm^{-3}, that is, more dust grains but fewer charges per grain.

5. CONCLUSIONS

A dusty plasma device (DPD) has been put into operation and utilized to study the charging of dust grains by the surrounding plasma. The DPD was realized by adding a rotating dust dispenser to the usual alkali plasma column of a Q machine.

Three types of dust were employed, namely kaolin with grain sizes between ~1 μm and ~50 μm [see *Xu et al.*, 1992] and aluminum oxide dusts with nominal sizes 0.3 μm and 0.01 μm.

The fraction of negative charge in the plasma which is in the form of free electrons has been determined as a function of the plasma density n_{e0}. These measurements indicate how the average negative charge on dust grains changes as the ratio d/λ_D between the intergrain distance and the plasma Debye length is varied from above to below unity. The observed effect appears to be the same as that described by *Goertz and Ip* [1984], *Whipple et al.* [1985], and *Goertz* [1989].

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