Charging of Dust Grains in a Plasma

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(Received 2 May 1994)

Charging of micron-sized dust grains in a plasma has been investigated experimentally. Dust grains were dispersed into a fully ionized, steady-state, magnetized plasma column consisting of electrons and K^+ ions, both at a temperature of ≈ 0.2 eV. Langmuir probe measurements were used to determine how the negative charge in the plasma is divided between free electrons and dust grains. By varying the ratio d/λ_D between the intergrain spacing and the plasma Debye length, the predicted reduction in the grain charge for the case of "closely packed" grains ($d/\lambda_D < 1$) has been demonstrated experimentally.

PACS numbers: 52.25.Vy, 94.10.Nh, 98.58.Ca

There is currently considerable interest in understanding the properties of plasmas containing dust particles [1]. This recent interest in "dusty plasmas" has been driven, in large part, by the discovery of the fine structure of Saturn's rings, as observed by the Voyager spacecraft [2], and, on the technological side, by the realization that dust particles, actually grown in plasmas [3], present a serious contamination problem in the plasma-aided manufacturing of semiconductor devices [4]. Of course, astrophysicists have long recognized the role of dust in, e.g., nebulas, interstellar clouds, planetary magnetospheres, and cometary environments [5]. Some examples of recent theoretical and numerical work on dusty plasmas has focused on the charging of dust grains in plasmas [6–8], waves in dusty plasmas [9], and the transport of dust in plasmas [10]. Examples of experimental work in this area include studies of particle generation in plasmas [11], observations of "Coulomb solids" [12], and the construction of devices for the dispersal of dust in plasmas [13,14] for basic laboratory studies.

In this Letter we describe the results of a laboratory experiment on the charging of dust grains in a low-temperature plasma. Specifically, we investigated the effects to be expected [15] at relatively high dust particle densities when the average distance between dust grains becomes comparable to the Debye length, $\lambda_D = [\epsilon_0 kT/e^2 n_0]^{1/2}$ (k is Boltzmann's constant, T is the plasma temperature, and n_0 is the plasma density), the characteristic measure of the shielding distance in a plasma. We first summarize some of the relevant theoretical results concerning the charging of dust grains in a plasma [15,16].

Dust grains become charged due to the collection of ions and electrons from the plasma, photoelectron emission by UV radiation, ion sputtering, secondary electron emission, etc. In low-temperature laboratory plasmas, the collection of ions and electrons is the dominant charging process. For the case of isolated grains in the plasma, the charge on the dust is easily calculated for spherical grains of radius a. Since a grain is electrically floating, it collects electrons and ions subject to the condition $(I_i - I_e)_{V=V_s} = 0$, where I_i and I_e are the magnitudes of the ion and electron currents to the grain and V_s is its surface potential. The balance of electron and ion currents occurs at a surface potential V_s, which satisfies $\exp(eV_s/kT) = (m_e/m_i)^{1/2}(1 - eV_s/kT)$, where T is the plasma temperature and m_e and m_i are the electron and ion masses. For a hydrogen plasma, we find $V_s = -2.5kT/e$, while for a singly charged potassium plasma $V_s = -4.0kT/e$. The grain charge Q is related to its surface potential by $Q = CV_s$, where C is the capacitance of a dust grain, which for spherical grains of radius a is given by $C = 4\pi\epsilon_0 a$ (assuming that the dust grain radius is much smaller than the Debye length λ_D of the ambient plasma).

For the case of densely packed dust grains where the spacing between grains d is comparable to or less than λ_D, the difference $U = V_s - V_p$ between the surface potential V_s and the plasma potential V_p has a smaller magnitude than in the case with $d \gg \lambda_D$, and consequently the average charge on a dust grain $Q = CU$ is smaller than that for isolated grains. This effect of placing grains close to each other has been analyzed by Goertz [15] for the one-dimensional situation of a plasma with a series of ten equally spaced infinite plane dust "sheets" and by Young *et al.* [7] for the case of a two-dimensional array of infinitely long dust "rods" in a plasma. The average charge Q (<0) on a dust grain can also be calculated [16] by requiring overall charge neutrality

$$en_i = en_e - QN, \tag{1}$$

where n_i and n_e are the electron and ion densities, respectively, and N is the density of dust grains in the plasma. Because the ions are much heavier than the electrons, initially the ion current to a grain is much smaller than the electron current, and the grain becomes negatively charged. This increases the ion current and decreases the electron current until the currents are equalized, $I_i = I_e$. When the ions and electrons have Maxwellian distributions with temperatures T_i and T_e, respectively, these currents, for U (and Q) < 0 are given by

$$I_e = e n_e \sqrt{\frac{kT_e}{m_e}}\, \exp\left(\frac{eU}{kT_e}\right)\pi a^2, \qquad \text{(2a)}$$

$$I_i = e n_i \sqrt{\frac{kT_i}{m_i}}\left(1 - \frac{eU}{kT_i}\right)\pi a^2. \qquad \text{(2b)}$$

In Eq. (2a) the exponential factor is due to the repulsion of electrons by the negatively charged grain, whereas the factor $1 - eU/kT_i$ in Eq. (2b) is due to orbital motion effects. Using Eq. (1), the equality of I_i and I_e, together with the relation $Q = 4\pi\epsilon_0 aU$, the following equation for QU/kT can be obtained:

$$\sqrt{\frac{m_i}{m_e}}\left(1 + \frac{4\pi\epsilon_0}{e}P\frac{eU}{kT}\right)\exp\left(\frac{eU}{kT}\right) + \frac{eU}{kT} - 1 = 0, \qquad \text{(3)}$$

where $P = NakT/en_0$ (in units of mV) is the parameter introduced by Havnes *et al.* [16] and $T = T_i = T_e$ and $n_i = n_0$ has been used. Equation (3) gives the variation of the (grain minus plasma) potential U (or average charge $Q \propto U$) with the parameter P. A set of eU/kT vs P "universal" curves is obtained from Eq. (3), each curve corresponding to a given ion mass. The solution for a K^+ plasma is shown as the dashed curve in Fig. 1. If one imagines holding kT and n_0 fixed, this curve shows the effect of varying the dust density. For relatively low values of N (small P values), the potential U approaches the isolated grain value of $-4kT/e$. As N (and therefore P) is increased, the intergrain spacing decreases (relative to the fixed Debye length), and the average grain charge is also reduced. We next describe an experiment in which this effect was investigated.

The experiment utilizes as the basic plasma source, a Q machine [17] 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 the surface ionization of potassium atoms from an atomic beam oven on a hot (~2500 K) tantalum plate. The basic constituents of the ambient plasma are K^+ ions and electrons with approximately equal temperatures $T_i \approx T_e \approx 0.2$ eV and densities in the range of $\sim 10^5 - 10^{10}$ cm^{-3}. To dispense dust particles into the plasma, the plasma column is surrounded over a portion of its length by the device shown schematically in Fig. 2. 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 agitates the screen allowing the dust particles to dispense evenly throughout the plasma column. The fallen dust which collects at the bottom of the cylinder is then recycled. The dust grains were 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 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 grain size $a \sim 5$ μm. The dust density N was inferred using two methods. First, we measured the mass of a sample of dust collected over a small time interval with an elongated "spoon" inserted into the device. From this measurement of the dust flux (g/s cm^2), the density can be determined from the known dust velocity (due to gravity) and dust size distribution. For an average dust size $a \cong 5$ μm we obtained $N \approx 6 \times 10^4$ cm^{-3}. From this measurement, we could also confirm that the dust density was uniform over the length of the dispersal unit. As a second method, the ion density was measured as a function of distance within the dust cloud. An exponential decay was observed with a mean free path for ion-dust collisions $\lambda \approx 25$ cm. Taking $\lambda \simeq (N\pi a^2)^{-1}$ and using $a \simeq 5$ μm, we obtain an $N \simeq 5 \times 10^4$ cm^{-3}. The values of N obtained are also consistent with measurements of the attenuation of the light from the tantalum hot plate after passing through the dust cloud.

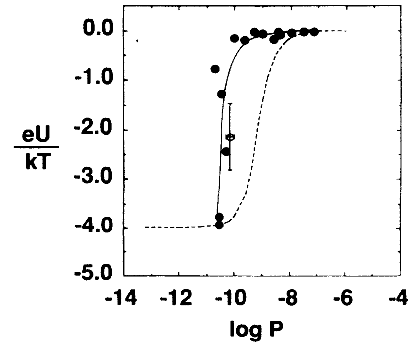

FIG. 1. The variation of the (grain-plasma) potential (proportional to the grain charge) in terms of kT/e, as a function of $P = NakT/en_0$ (units of mV), for $N = 5 \times 10^4$ cm^{-3}, $a = 5$ μm, and $kT = 0.2$ eV. The dashed curve is the theoretical result obtained from Eq. (3).

The main diagnostic tool of the dusty plasma was a Langmuir probe, movable along the axis of the plasma

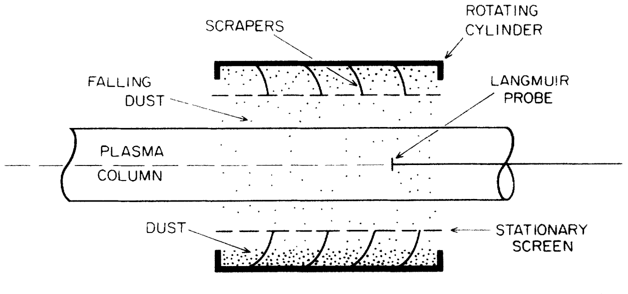

FIG. 2. Schematic diagram of the device used to disperse dust into the plasma column.

column (see Fig. 2) and consisting of a tantalum disk ~5 mm in diameter, oriented normally to the magnetic field. The Langmuir probe enables us to determine how the negative charge in the plasma is divided between free electrons and negatively charged dust grains. Figure 3 shows Langmuir characteristics obtained under identical conditions except for the absence (upper curve) or presence (lower curve) of dust, with the electron portion of the characteristic shown as positive current. When the dust is present, the electron saturation current I_e to a positively biased probe is smaller than the current I_{e0} 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. The ratio $\eta \equiv (I_e/I_{e0})/(I_i/I_{i0})$ is then a measure of the fraction of negative charge present as free electrons in the dusty plasma, i.e., $\eta = n_{e,\text{dust}}/n_{i,\text{dust}}$, where the ratio I_i/I_{i0} of probe ion current, with and without dust, takes into account the attenuation of the plasma by the dust cloud. Careful checks were made to ensure that the probe functions properly in the dusty plasma environment, as evidenced in Fig. 3, by the return of the electron saturation current to the "no-dust" level when the dust is abruptly turned off. The plasma density $n_0 = n_{e0}$ was computed using the relation $I_{e0} = en_{e0}v_{e,\text{th}}A$, where $v_{e,\text{th}}$ is the electron thermal velocity and A is the collecting area of the probe. From the measurements of η and the plasma density n_i we can obtain the quantity $QN/e = n_i(1 - \eta)$ by invoking the condition of charge neutrality $en_i = en_e - QN$. The experimental procedure then consists of measuring η as a function of plasma density n_0, while holding N, a, and kT fixed. The variation of QN/e (i.e., of Q for fixed N) with n_0 is shown in Fig. 4. Evidently, as the plasma density decreases while N is held fixed, the average charge on a dust grain does not remain constant but decreases with decreasing n_0 (increasing λ_D). This is presumably due to the effect discussed by Goertz [15] and Whipple *et al.* [6], which arises when the intergrain spacing d ($\sim N^{-1/3}$) becomes comparable to or smaller than the plasma Debye length λ_D. Quantitatively, using $N \approx 5 \times 10^4$ cm^{-3}, $a = 5$ μm, and $kT = 0.2$ eV, we find that Q/e approaches the isolated grain value $Q/e \simeq (4\pi\epsilon_0/e)a(4kT/e) \simeq 3000$, when the ratio $\kappa = N^{-1/3}/\lambda_D$ of the intergrain spacing to the Debye length is ≈ 5, and decreases to $Q/e \approx 30$ for $\kappa \approx 0.5$.

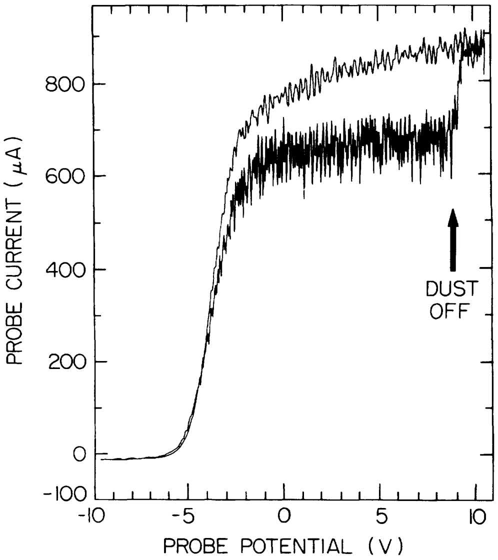

FIG. 3. Langmuir probe characteristics obtained under identical conditions, except for the absence (upper plot) or presence (lower plot) of kaolin dust. In the lower characteristic, the dust dispenser is abruptly turned off near the end of the trace to check that the electron current returns to the no-dust value.

The result shown in Fig. 4 can be recast into a form for comparison with Eq. (3) by expressing $U = Q/4\pi\epsilon_0 a$ into the form

$$\frac{eU}{kT} = \frac{e}{4\pi\epsilon_0}\frac{1}{Na(kT/e)}\frac{QN}{e}.$$

The resulting values for eU/kT vs $\log P$ obtained from the data of Fig. 4 are shown in Fig. 1. The error bars reflect the uncertainty in the determination of the product Na. The experimental data show the same general trend as predicted by the simple model. As P increases (experimentally by decreasing the plasma density), a transition is observed from the isolated grain conditions (low P) to the condition of densely packed grains (high P), where the collective interaction of the charged dust grains is important (U and $Q \rightarrow 0$). We stress that it is not reasonable to expect a close quantitative agreement between the experimental data and the simple theory illustrated in the dashed line in Fig. 1. For example, Havnes *et al.* [16] have shown that if the plasma is not fully thermalized, as assumed in the model of Eq. (3), the eU/kT vs $\log P$ curve will be shifted significantly to the left. Furthermore, several other assumptions in the model are not met in the actual experimental conditions, making a quantitative agreement unlikely. For example,

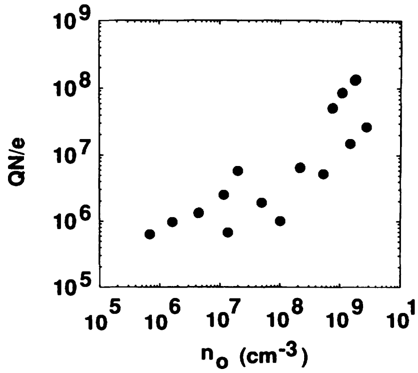

FIG. 4. The number of negative elementary charges per unit volume on dust grains, QN/e in units of cm^{-3}, vs the ambient plasma density.

the model assumes single-size spherical grains to which electrons and ions attach with sticking coefficients of unity. (The effects of the grain size distribution has only recently received some theoretical attention [18].) In spite of the apparent general agreement of our laboratory results with current theories and ideas of dust grain charging, certain aspects of the problem are still not clarified and require further experimental work.

In conclusion, we have experimentally investigated the charging of dust grains in a plasma with sufficient dust to alter the plasma characteristics. As predicted theoretically, the charge on a dust grain in a dense dust cloud can be substantially reduced compared to the charge on an isolated grain.

This work was supported by the Office of Naval Research.

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