CHARGING OF DUST IN A NEGATIVE ION PLASMA

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Abstract.—We investigate experimentally the charging of dust particles in a plasma consisting of positive ions, negative ions and electrons. In typical laboratory plasmas containing electrons and positive ions, dust grains acquire a negative charge. In negative ion plasmas, charging due to the negative ions, in addition to positive ions and electrons, must be taken into account. Calculations show that if a significant fraction of the electrons are attached to negative ions, the magnitude of the charge on the dust particles is reduced. If the ratio $\varepsilon = n_e/n_+$ of the electron density to positive ion density is sufficiently small and the positive ions are lighter than the negative ions, then the dust charge can be positive. This possibility is investigated in Q machine plasma operating with potassium ions, and in which the highly electronegative gas SF_6 is added which attaches low energy electrons to produce the SF_6^- negative ion. The relatively cold electrons in the Q machine plasma (T_e = 0.2 eV) enhances the attachment probability allowing values of $\varepsilon < 10^{-3}$ to be attained.

1. Introduction.—Dust grains immersed in a typical electron/positive ion plasma will acquire a negative charge due to the preferential attachment of the more mobile electrons [1, 2]. The dust grain charges to a negative potential relative to the plasma so that electrons are repelled and positive ions are attracted to the particles. The floating potential of the dust grain is determined by the balance of electron and ion currents that are collected. If energetic electrons are present in the plasma, the effects of secondary emission may also have to be taken into account [3]. Photoelectric emission from dust in the presence of UV light can result in dust acquiring a positive charge [4]. Charging of dust in space and astrophysical environments is typically dominated by this photoelectron emission. A detailed discussion of dust charging mechanisms, including references to primary sources, is presented in Chapter 2 of the monograph of Shukla and Mamun [5].

In this paper we investigate the charging of dust in a plasma consisting of positive ions, electrons and negative ions (for simplicity we refer to this as a negative ion plasma). Mamun and Shukla [6] considered the charging of dust grains in a plasma with negative ions and showed that the negative ions significantly decrease the magnitude of the dust grain charge. D'Angelo [7] discussed theoretically the excitation of ion-acoustic and dust acoustic waves in a plasma with positive dust grains produced in a negative ion plasma. Annaratone and Allen computed the floating potential of a dust particle in an electronegative plasma using orbital motion limited theory [8]. They showed also that under certain conditions, positively charged dust could be obtained.

In Sec. 2 we compute the charge on a dust grain in a negative ion plasma and show that a positive charge is possible if the positive ions are lighter than the negative ions and the relative concentration of free electrons is sufficiently small. In Sec. 3 the device for studying the charging of dust in a negative ion plasma, and the method of producing a negative ion plasma is described. The experimental method used to infer the sign of the dust charge in the negative ion plasma is discussed in Sec. 4. Experimental evidence of the production of positively charged dust based on this measurement is presented in Sec. 5. A final summary is given in Sec. 6.

2. The charge on a dust particle in a negative ion plasma.— Consider an *isolated* spherical dust grain of radius a introduced into a plasma consisting of electrons of density n_e, singly charged positive ions of density n_+, and singly charged negative ions of density n_-. Define

$$\varepsilon \equiv \frac{n_-}{n_+} \qquad [1]$$

as the fraction of negative ions relative to positive ions. Using the charge neutrality condition

$$n_+ = n_e + n_- \qquad [2]$$

we have that

$$\frac{n_e}{n_+} = 1 - \varepsilon \qquad [3]$$

The temperatures of the positive ions, electrons and negative ions are T_+, T_e and T_-, respectively.

a. Currents to a dust grain in a negative ion plasma.—The electron, negative ion and positive ion currents to the dust grain of radius a are given by :

$$I_e = I_{eo} \times \begin{cases} 1 + eV_s/kT_e & V_s > 0 \\ e^{eV_s/kT_e} & V_s < 0 \end{cases} \qquad [4]$$

$$I_- = I_{-o} \times \begin{cases} 1 + eV_s/kT_- & V_s > 0 \\ e^{eV_s/kT_-} & V_s < 0 \end{cases} \qquad [5]$$

$$I_+ = I_{+o} \times \begin{cases} e^{-eV_s/kT_+} & V_s > 0 \\ 1 - eV_s/kT_+ & V_s < 0 \end{cases} \qquad [6]$$

where

$$I_{jo} = q_j n_j \left(\frac{kT_j}{m_j}\right)^{1/2} 4\pi a^2 . \qquad [7]$$

V_S is the potential of the dust grain relative to the plasma. The grain surface potential is then obtained by requiring

$$I_+ + I_e + I_- = 0 \qquad [8]$$

We give an example to show under what conditions one could obtain positively charged grains in such a plasma. For simplicity, consider the case where all species are at the same temperatures = T, and define the normalized surface potential

$$\psi_S = eV_S / kT \qquad [9]$$

Combining Eq. [1] – Eq. [9] we obtain

$$(1-\varepsilon)\sqrt{\frac{m_+}{m_e}} + \varepsilon\sqrt{\frac{m_+}{m_-}} = \begin{cases} \dfrac{e^{-\psi_s}}{1+\psi_S} & \psi_S > 0 \\ \dfrac{1-\psi_S}{e^{\psi_s}} & \psi_S < 0 \end{cases} \qquad [10]$$

This equation can be solved numerically for ψ_{S}.

A plot of ψ_S vs. the parameter n_e/n_+ for the case in which the positive ion is potassium K^+ (mass = 39) and the negative ion is SF_6^- (mass = 146) is shown in Fig. 1. Notice that the positive ion is the *lighter* species. Thus in the presence of a heavy (compared to the + ion) negative ion, the charge on the dust is reduced, and for $n_e/n_+ < 2 \times 10^{-3}$ the dust surface potential (and charge) can be *positive***.**

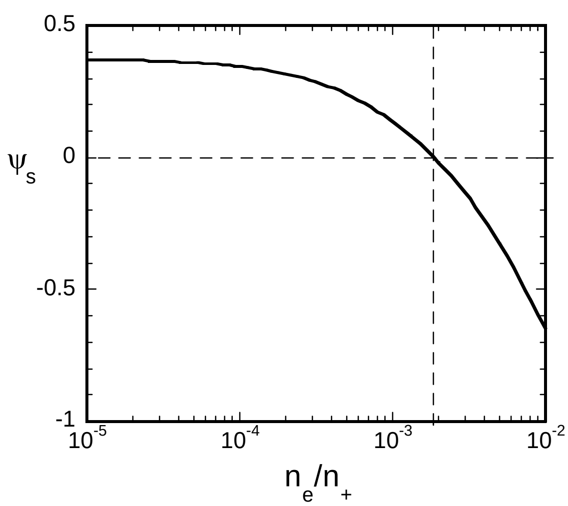

Fig. 1.—The normalized dust surface potential vs. the fractional concentration of electrons in the plasma. $T_+ = T_e = T$.

Once the dust surface potential is determined, the charge on the dust is computed using

$$Q = 4\pi\varepsilon_o a V_S \qquad [11]$$

where a is the radius of the dust particle.

b. Effect of the temperature ratios.—Fig. 2 shows a plot similar to Fig. 1 but for two values of the negative ion temperature, $T_- = 0.025$ eV and 0.2 eV. As expected, the transition to positively charged dust occurs at a higher value of n_e/n_+ for $T_- = 0.025$ eV.

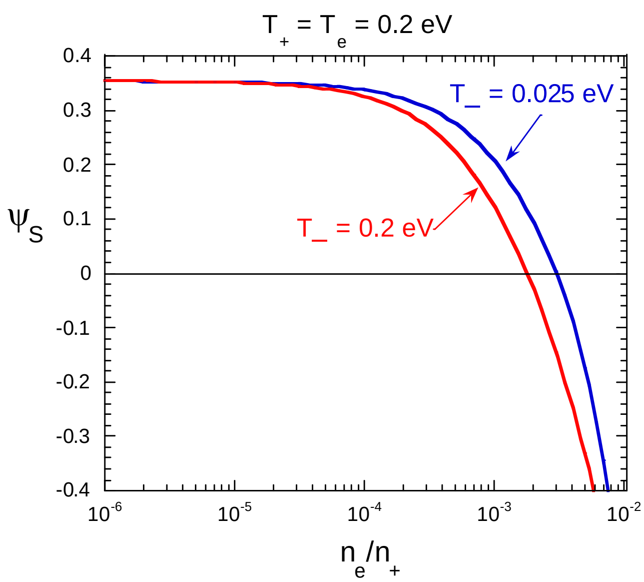

Fig. 2.—The normalized dust surface potential vs. the fractional electron concentration, for two values of the negative ion temperature.

c. Effect of positive ion mass.—Fig. 3 shows a plot of the normalized dust potential, ψ_S, for singly charged argon, helium and xenon ions. The effect of various positive ion masses is summarized in Fig. 4 which shows a plot of the quantity $\varepsilon(0)$, the value of $\varepsilon = n_e/n_+$ for which $\psi_S = 0$, versus the positive ion mass number. With the negative ion $(SF_6)^-$, positive dust is more easily achieved with a lighter ion mass.

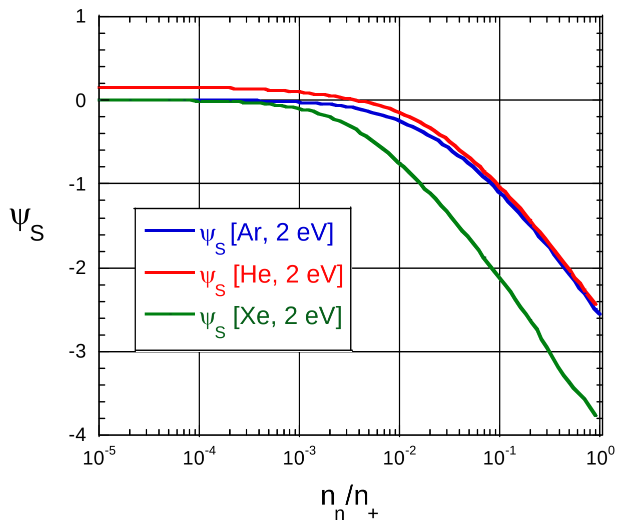

Fig. 3.—The normalized dust surface potential vs. the fractional electron concentration for argon, helium and xenon positive ions.

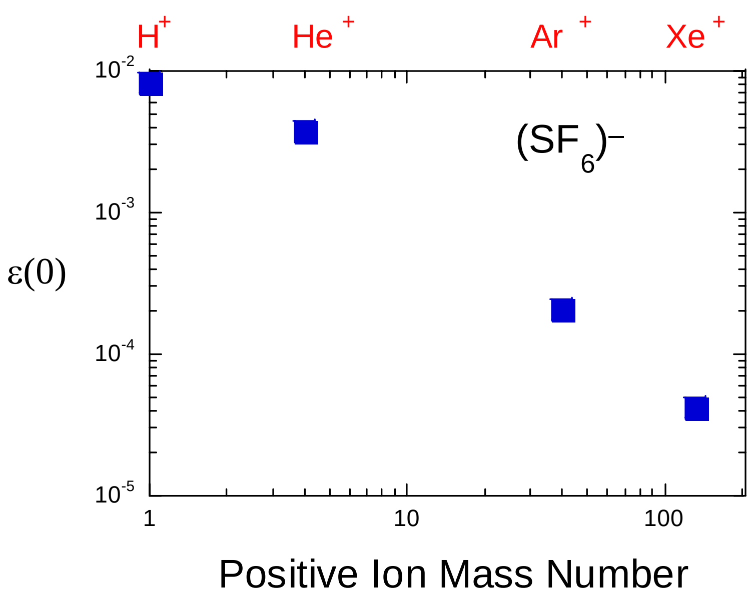

Fig. 4.—The quantity ε(0), the value of the fractional electron concentration for which the dust surface potential = 0, vs. the positive ion mass number.

3. Experimental device and methods.—In this section we describe the device used to produce a dusty plasma (dusty Q machine) and the method of obtaining a negative ion plasma.

a. The dusty plasma device.—A schematic of the experimental device used to produce a dusty plasma is shown in Fig. 5.The basic plasma source is a Q machine which produces a fully ionized K^+ / e^- plasma of approximately 6 cm diameter and ~1 m length by the surface ionization of potassium atoms from an atomic beam oven on a hot (~2500 K) tantalum plate. The ions and electrons have approximately equal temperatures $T_+ \approx T_e \approx 0.2$ eV and densities up to ~ 10^{10} cm^{-3}. The plasma is confined radially by a uniform axial magnetic field of 0.3 T. The method of dispersing dust into the plasma is essentially the same as that used in our previous experiments and described in Xu et al. [9] The dispenser consists of a rotating cylinder which surrounds the plasma column of a length of 30 cm. The inner surface of the cylinder is lined with aluminum wool which is embedded with fine dust particles that are initially loaded into the bottom of the cylinder. As the cylinder rotates the dust particles gently fall through the plasma where they become charged by electron and ion collection. As described in our earlier work,

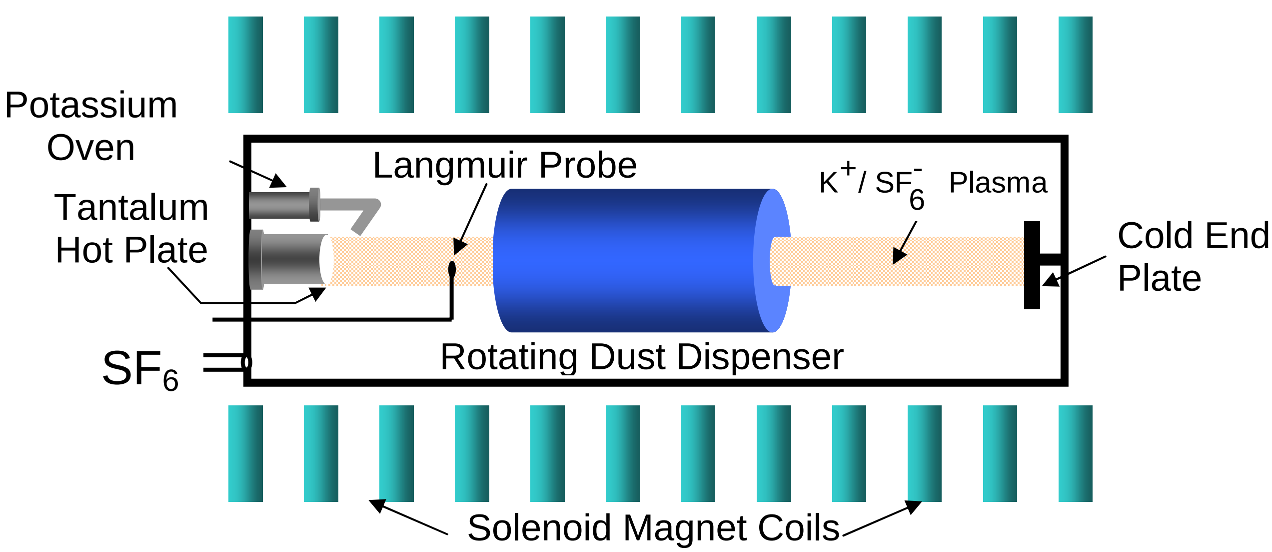

Fig. 5.—Schematic of the dusty plasma device.

the dust in this case acquires a negative charge. The dust particles were hollow glass microspheres that had a large size distribution ranging from a few microns uo to about 100 microns, with the majority of particles (50%) approximately 35 microns in diameter.

b. Production of negative ion plasmas.—A negative ion plasma is formed by attachment of electrons on the highly electronegative sulfur hexafluoride SF_6 molecule by the reaction

$$e^- + SF_6 \rightarrow SF_6^-$$

The sulfur hexafluoride gas is admitted into the vacuum chamber through a variable leak valve. The attachment efficiency depends on the electron energy and is most pronounced for electrons with energies in the range of a few tenths of an eV, which coincides quite well with the electrons in the Q machine plasma. At higher electron energies, dissociation of the SF_6 molecule becomes increasingly likely, leading to the formation of additional negative ion species such as SF_5^- and F^- [10]. For this reason the Q machine is an ideal device in which to form negative ion plasmas. In fact it is possible to produce a negative ion plasma in which the electron concentration relative to the positive ions, n_e/n_+, is so small that we have essentially a positive ion/negative ion plasma.

The effect of negative ion production can be observed using a Langmuir probe. Fig. 6 shows a series of Langmuir probe current vs voltage characteristics as the partial pressure of SF_6 is increased. Positive current in these plots corresponds to the collection of negative particles (electron and SF_6^-). The uppermost plot corresponds to the case in which no SF_6 gas has been added. As the SF_6 pressure is increased, more electrons become attached to form SF_6^- ions and there is a corresponding reduction in the negative current due to the fact that the SF_6^- ions are considerably less mobile than the electrons. The effectiveness of electron

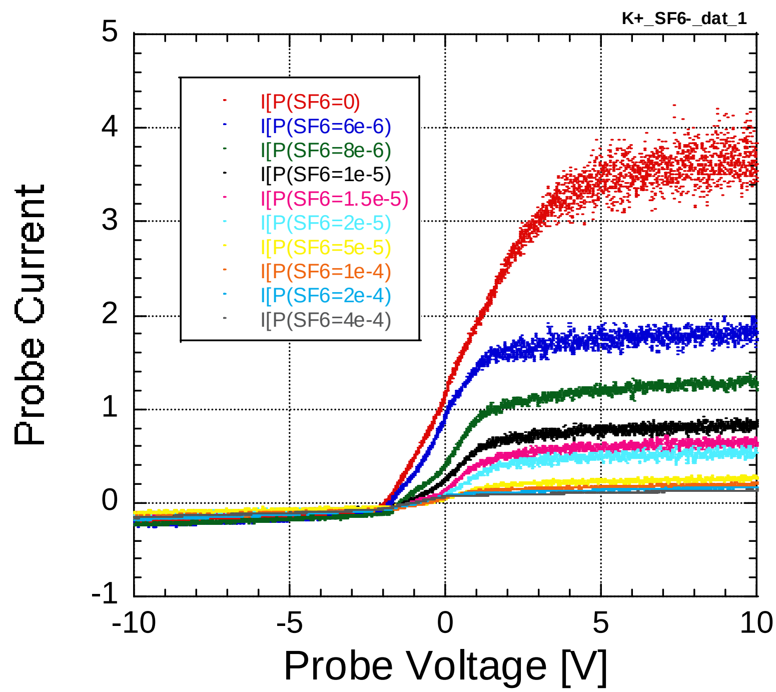

Fig. 6.—Langmuir probe characteristics for various values of the SF_6 partial pressure. Positive currents correspond to the collection of electrons and negative ions.

attachment is evident from the fact that at an SF_6 partial pressure of only 6×10^{-6} Torr, the negative probe current is reduced by about a factor of 2.

The Langmuir probe characteristic corresponding to the highest SF_6 partial pressure is shown on an expanded scale in Fig. 7. This nearly symmetric probe characteristic (comparable positive and negative currents) is an indication that a nearly electron-free plasma have been formed. An estimate for the quantity $\varepsilon = n_e/n_+$, the fraction of free electrons remaining in the plasma can be made from the measurement of the ratio of negative probe saturation current to positive probe saturation current. Taking the positive saturation current as $I_+ = en_+v_{+,th}A$ and the negative saturation current as $I_- = en_ev_{e,th}A + en_-v_{-,th}A$, where $v_{j,th} = (kT_j/m_j)^{1/2}$ is the

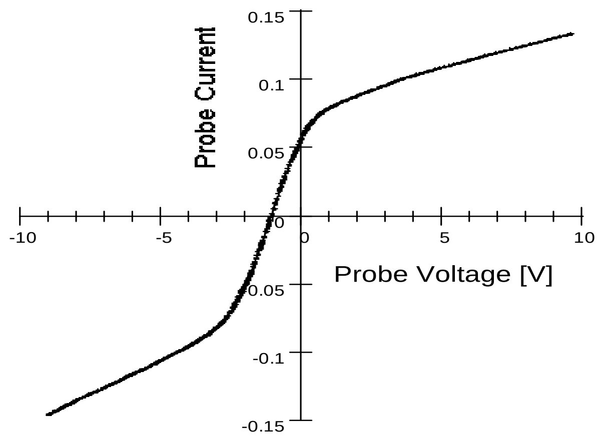

Fig. 7.—Replot of the Langmuir probe characteristic in Fig. 6 for the SF_6 partial pressure of 4×10^{-4} Torr.

thermal speed of species j, and A is the probe area, and using $n_+ = n_e + n_-$, the quantity $\varepsilon = R\sqrt{m_e/m_+}\sqrt{T_+/T_e} - \sqrt{m_e/m_-}\sqrt{T_-/T_e}$, where $R = I_-/I_+$. For the characteristic shown in Fig. 7 with $R \approx 1$ we find that $\varepsilon \sim 10^{-3}$ for a plasma with K^+ positive ions SF_6^- negative ions and electrons, with $T_+ \cong T_e \simeq 2T_-$.

The probe measurement provides an order of magnitude estimate of ε. A more accurate determination can be made using the results of work of Sato [11] and Ishikawa et al [12], who showed that ε can be determined by measurements of the propagation characteristics of various electrostatic plasma waves in a negative ion plasma. A plot of ε vs the SF_6 partial pressure obtained under essentially identical conditions to our setup (a single ended Q machine operating with potassium at about the same magnetic field strength) is shown in Fig. 8. The higher SF_6 pressures used in our experiment correspond to an $\varepsilon \sim 10^{-3} - 10^{-4}$. Thus we see that by operating at sufficiently high SF_6 pressures, it is possible to produce a plasma in which the electrons are removed to about one part in 10,000. We show in the next section how this plasma can be used to produce a dusty plasma having positively charged dust.

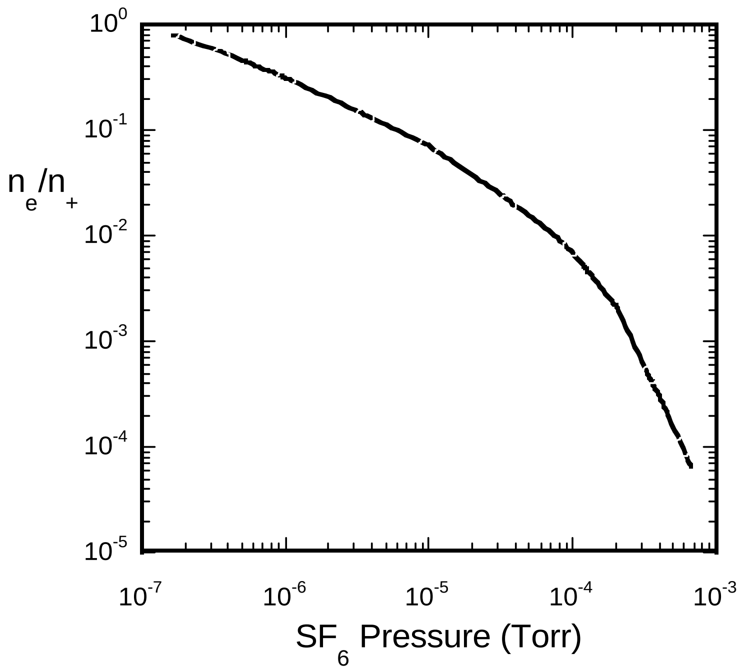

Fig. 8.—The fractional electron concentration in a Q machine negative ion plasma with K^+ positive ions vs. the SF_6 partial pressure, From ref. [11].

4. Experimental evidence for a dusty plasma with positively charged dust.—

The experimental procedure consists of first introducing SF_6 into the plasma to produce the negative ions and then dispersing dust into this plasma. The main diagnostic tool of the dusty plasma was the Langmuir probe. In our earlier work [1] on the charging of dust grains in an ordinary electron/positive ion plasma, the Langmuir probe was used to determine how the negative charge in the plasma was divided between free electrons and negatively charged dust grains. Langmuir probe characteristics were obtained under identical conditions except for the ansence or presence of dust. When the dust was present, the electron saturation current to the positively biased probe was reduced compared to the current measured without dust. This was due to the fact that electrons which attach to the dust grains of extremely low mobility are not collected by the probe. A typical Langmuir probe characteristic illustrating this is shown in Fig. 9. From the reduction in electron saturation current and applying the condition for charge neutrality, the quantity Qn_d/e, the number of negative elementary charged per unit volume on dust grains could be inferred.

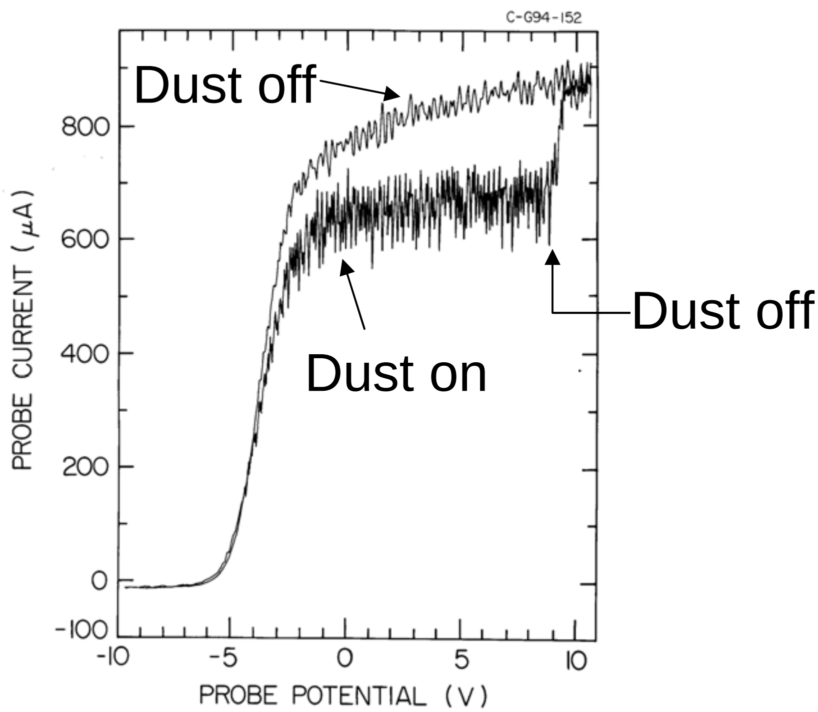

Fig. 9.—Langmuir probe characteristic taken in an electron/K^+ plasma, taken from ref. [1], showing the reduction in the electron current when dust particles are dispersed into the plasma.

A very similar method was applied in the present work to infer the charge (sign) of the dust introduced into the negative ion plasma. For sufficiently low values of $\varepsilon = n_e/n_+$ we assume that electron collection by the dust is small compared to collection of negative ions. This is justified if $n_e v_{e,th} << n_- v_{-,th}$. This condition can be expressed as $\varepsilon << \sqrt{kT_-/m_-}\Big/\sqrt{kT_e/m_e}$. For $T_- \approx (0.5\text{-}1)T_e$ this corresponds to an $\varepsilon << (1.4 - 1.9) \times 10^{-3}$. Now at an SF_6 pressure ~ 1 × 10^{-3} T, we have that $\varepsilon \sim 10^{-4}$, justifying this assumption. In such a positive ion negative ion plasma, in the presence of charged dust, the condition of charge neutrality reads $n_+ + (Q/e)n_d = n_-$. Before the dust is added, the probe saturation currents (per m^2) can be written as $I_{+o} = en_{+o}v_{+,th}$ and $I_{-o} = en_{-o}v_{-,th}$, where $n_{-o} \approx n_{+o} = n_o$. When the dust is present, the probe currents are $I_+ = en_+v_{+,th}$ and $I_- = en_-v_{-,th}$. We assume, as in our previous work that there the contribution to the probe current from charged dust is negligible. Combining the equation of charge neutrality with the probe currents we have

$$\left(\frac{Q}{e}\right)n_d = Zn_d = n_o\left(\frac{I_-}{I_{-o}} - \frac{I_+}{I_{+o}}\right) \qquad [11]$$

Thus, measurements of the relative changes in saturation currents can be used to determine the *sign* of Z. Thus a Z > 0 (positive dust) is indicated by the condition $I_-/I_{-o} > I_+/I_{+o}$, or the fractional reduction in the positive current must be greater than the fractional reduction in negative current.

The Langmuir probe characteristics taken with dust introduced into the positive ion/negative ion plasma is shown in Fig. 10. The blue curve is one taken before dust was added and the red on was taken with the dust present. The yellow curves are portions of a trace taken immediately after the dust was turned off to ensure that dust contamination of the probe was not significant. Measurements of the saturation currents from Fig. 10 indicates that $I_-/I_{-o} \cong 0.7$, while $I_+/I_{+o} \cong 0.6$, or that Z > 0. According to the dust charging theory of Sec. 2, at $\varepsilon \sim 10^{-4}$, the normalized dust surface potential should be in this case $eV_s/kT_+ \sim +0.3$. Although one example has been shown, we have observed repeatedly, that when a sufficient number of negative ions is present in the plasma, the probe characteristic measurements indicate the presence of positively charged dust.

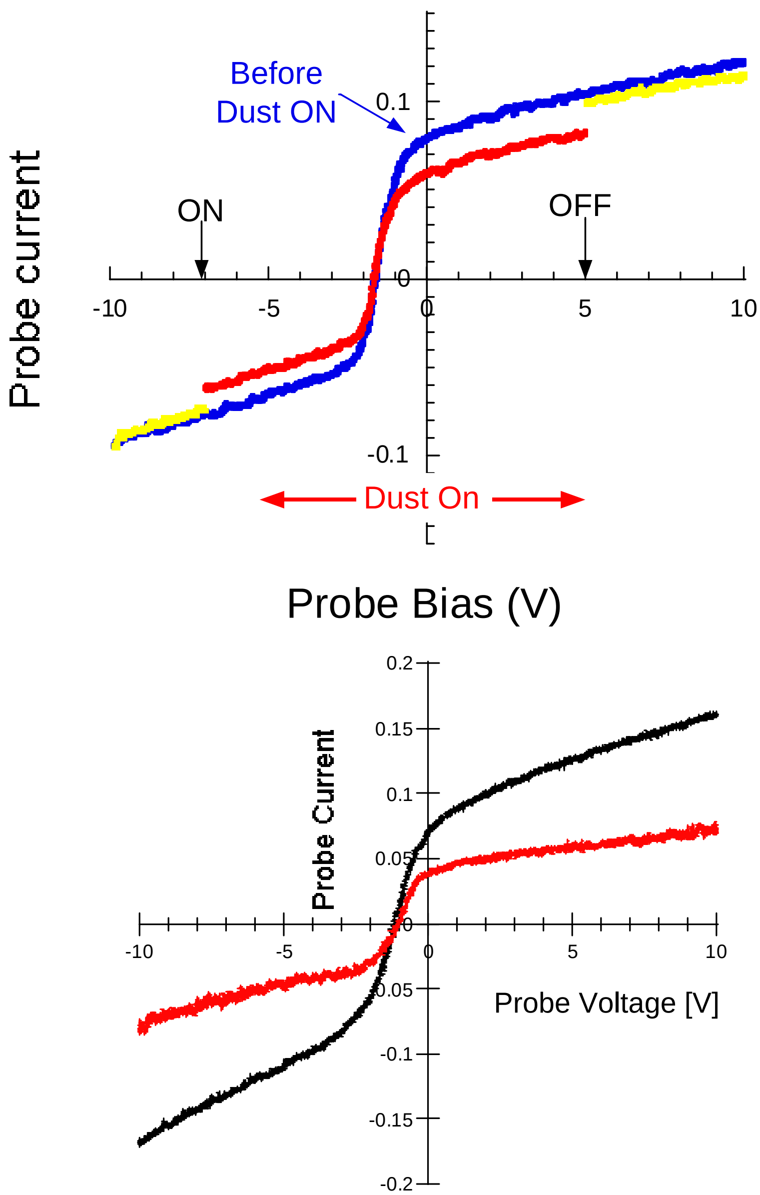

Fig. 10.—Upper plot-Langmuir probe characteristic obtained in a positive ion/negative ion plasma befroe during and after the dispersal of dust into the plasma. Bottom plot- expanded version of upper plot before dust (black) and in the presence of dust (red).

6. Summary and conclusions.—A method for producing positive charged dusty plasma has been described. This method relies on attaching the relatively mobile electrons to negative ions having a mass greater than the mass of the positive ion species. The presence of the negative ions can reduce the charge on the dust (*de-charging*) and even allow the more mobile positive ions to charge the dust positively.

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