Dust acoustic waves in a direct current glow discharge

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An experimental investigation of dust acoustic (DA) waves in a dc glow discharge plasma is described. The glow discharge is formed between a 3 cm anode disk and the grounded walls of a 60 cm diameter vacuum chamber which is filled with nitrogen gas at a pressure of about 100 mTorr. Dust located on a tray in the chamber is attracted into the plasma where it is trapped electrostatically. The dust acoustic waves were produced by applying a modulation signal (5–40 Hz) to the anode. The wavelength of the DA waves was measured from single frame video images of scattered light from the dust grains. The measured dispersion relation is compared with theoretical predictions. © *1997 American Institute of Physics.* [S1070-664X(97)04907-0]

I. INTRODUCTION

A dusty plasma is a plasma consisting of electrons, positive ions, and charged dust grains. In typical laboratory dusty plasmas, the dust grains are in the micron-size range and are negatively charged. Dusty plasmas have been produced either by dispersing dust grains into a plasma[1,2] or by ''growing'' dust in plasmas made from certain chemically reactive gases such as oxygen and silane.[3] In situations where a substantial fraction of the negative charge in the plasma resides on heavy dust grains, many of the properties of the collective plasma wave modes are modified,[4,5] even when the charged dust merely falls through the plasma. When the dust grains are actually confined in the plasma, i.e., when they are balanced against gravity by electric fields, new, very low frequency dust wave modes appear. One such mode is the so-called dust acoustic (DA) wave, which was first discussed theoretically by Rao *et al.*,[6] and subsequently by others.[7,10] The dust acoustic wave is a new type of sound wave in which the inertia is provided by the heavy charged dust and the tension provided by the ion and electron pressures, with the resulting phase velocity

$$v_{\mathrm{ph}}=\frac{\omega}{K}=\left[\frac{kT_d}{m_d}+\frac{kT_i}{m_d}\,\frac{\epsilon Z^2}{1+(T_i/T_e)(1-\epsilon Z)}\right]^{1/2}, \qquad (1)$$

where ω is the wave angular frequency, K the wave number, T_d, T_e, and T_i are, respectively, the dust, electron, and ion temperatures, $\epsilon=n_d/n_i$, the density of the dust grains relative to the ions, Z the charge on a dust grain (in units of the electron charge e) and finally, m_d, the mass of the dust grains. This dispersion relation (1) was obtained from a fluid analysis[6,11] and is valid in the limit $(K\lambda_{\mathrm{D}})^2 \ll 1$, where λ_{D} is the plasma Debye length [$\lambda_{\mathrm{D}}^{-2}=\lambda_{\mathrm{De}}^{-2}+\lambda_{\mathrm{D}i}^{-2}$, where $\lambda_{\mathrm{De}(i)}$ is the electron(ion) Debye length].

To date, there have been only a few experiments dealing with DA waves in dusty plasmas. For example, Chu *et al.*[12] reported large amplitude low frequency (12 Hz) fluctuations in an rf dusty plasma which were later interpreted by D'Angelo[11] as dust acoustic (DA) waves. Barkan *et al.*[13] reported observations of very low frequency wave modes which were spontaneously excited in a dusty plasma in which the dust grains were confined in an anode double layer. Visual images of these waves could be obtained due to the scattering of light from the dust grains. The waves typically had phase velocities ≈9 cm/s, frequencies ≈15 Hz, and wavelengths ≈0.6 cm. The general features of these waves appeared to be the same as those of dust acoustic waves. In particular, the measured phase velocity was in good agreement with the theoretically predicted one. However, the comparison between theory and experiment was of a preliminary nature since, at that time, no measurement of the dust density was available. Observations of macroscopic very low frequency modes of a charged dust cloud in a gaseous discharge were reported by Praburam and Goree.[14] Prabhakara and Tanna[15] trapped negatively charged dust particles in a hot filament plasma discharge which was exposed to a layer of dust. Coherent fluctuations in the 1–15 Hz range were observed in the spectrum of scattered HeNe laser light.

In this paper we report observations of dust acoustic waves in a dusty plasma that was produced by trapping negatively charged dust grains in a dc glow discharge. This present investigation is a substantial extension of our earlier work on DA waves[13] in that (1) the full dispersion relation was measured over a wide frequency range, and (2) reliable estimates, based on measured quantities, of the size of the dust grains, their charge, and number density were used in the comparison with theory.

This paper is organized as follows: Sec. II contains a description of the experimental setup and the results of the measurements of some of the important plasma and dust parameters. The general features of the dust acoustic waves are described in Sec. III, and the results of the measurement of the dispersion relation are presented. A discussion of the results and comparison with theoretical predictions are given in Sec. IV. Sec. V contains the conclusions.

II. EXPERIMENTAL DEVICE AND METHODS

In order to observe dust acoustic waves, the dust grains must be confined in the plasma for times longer than a typical wave period. Devices which simply allow dust to fall through the plasma are generally unsuitable, since the residence time of a dust grain in a typical laboratory device is ~0.1 s. Thus it is necessary to provide some mechanism for balancing the negatively charged dust against gravity.

The dc glow discharge device, shown schematically in

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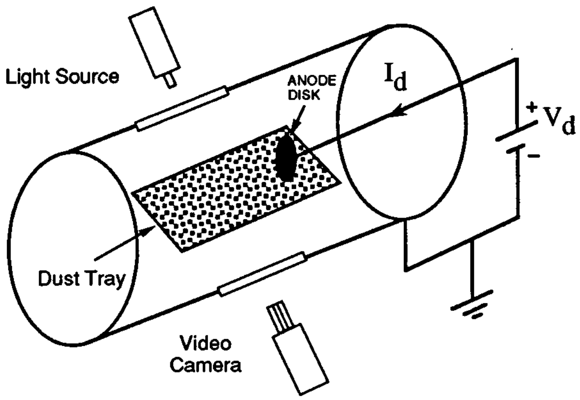

FIG. 1. Schematic diagram of the glow discharge device. The dust is attracted into the glow discharge from a tray located beneath the anode. The dust cloud is viewed, either visually or with a video camera, in the scattered light from the source.

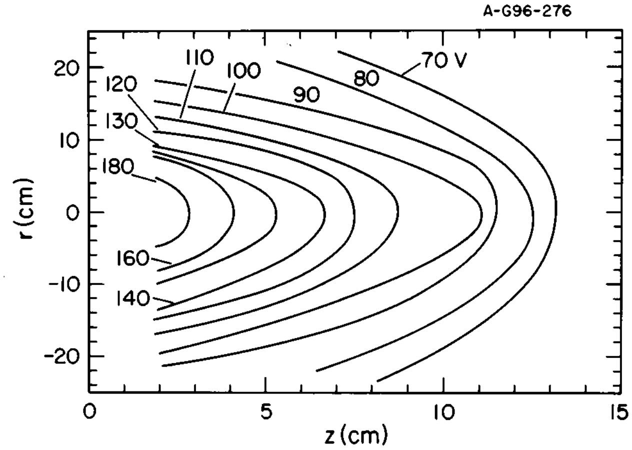

FIG. 3. Contours of the floating potential of a Langmuir probe in the midplane of the glow discharge. In this diagram the anode is located at $z=0$. The dust cloud is usually trapped in the region up to about 5 cm from the anode.

Fig. 1, proved to be effective for both attracting dust into the plasma and levitating it. The glow discharge was formed between a positively biased cold anode disk (32 mm diameter) and a grounded vacuum chamber (60 cm diameter and 90 cm long). The anode was located on the axis of the chamber and approximately 10 cm from the center of the chamber. The discharge was produced in nitrogen at a pressure $P \approx 70-100$ mTorr. The discharge voltage and current were typically: $V_d \approx 300-400$ V and $I_d \approx 25-35$ mA. A longitudinal magnetic field of 90 G helped to confine the plasma radially.

The plasma density and electron temperature were determined from measurements taken with a double Langmuir probe. This probe consisted of two tantalum disks, 8 mm in diameter, separated by 5 mm. A typical double probe $I-V$ characteristic taken at a point 2.5 cm on axis (approximately where the DA wave observations were made), in front of the anode, is shown in Fig. 2. The data are indicated as circles, whereas the solid line is a plot of the theoretical double probe relation,[16] $I=I_{is}\tanh(\mathrm{eV}/2kT_e)$. The data are best fit to this relation for $T_e \approx 2.5$ eV.

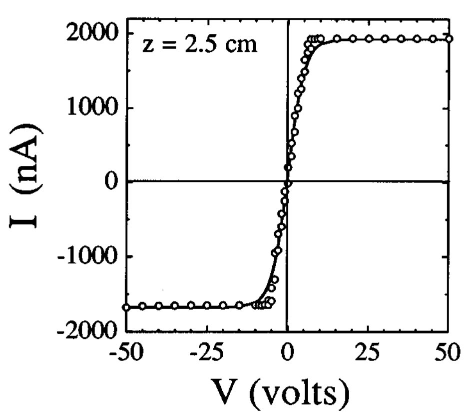

FIG. 2. Double Langmuir probe characteristic used for the determination of the electron temperature, T_e, and plasma density, n_i. The circles are the experimental data points, while the solid line is the theoretical probe characteristic $I=I_{is}\tanh(\mathrm{eV}/2kT_e)$, for $T_e=2.5$ eV.

The ion density, n_i, was estimated from the ion saturation current, I_{is}, using $I_{is}=e\ n_i\ v_{i,\mathrm{th}}A$, where A is the probe collecting area and $v_{i,\mathrm{th}}$ is the ion thermal speed. Although the ion temperature, T_i, was not measured, we expect that, as a result of frequent collisions with the neutral gas molecules, the ions will be relatively cold, $T_i \approx 0.03-0.1$ eV so that $v_{i,\mathrm{th}}=(kT_i/m_i)^{1/2} \approx (3-6)\times 10^4$ cm/s for an N_2^+ plasma. The measured ion saturation current then corresponds to an ion density $n_i \approx (4-8)\times 10^8\ \mathrm{cm}^{-3}$.

To get a qualitative picture of the dc electric fields within the glow discharge, the floating potential of a movable Langmuir probe (4 mm diameter disk) was measured at several positions within the discharge. The resulting electric potential contours are shown in Fig. 3. These data correspond to the conditions: $V_d \approx 400$ V, $I_d \approx 25$ mA, $P \approx 80$ mTorr, and $B=90$ G. The potential in the center of the glow is on the order of $+200$ V with respect to the walls. It should be noted that although the floating potential and space potential may differ quantitatively, we expect that for the plasma conditions here, the spatial distribution of the floating potential is a reasonable approximation of the spatial distribution of the plasma space potential. The role of the potential structure of the glow discharge in attracting and confining dust will be discussed below.

To introduce dust into the plasma, an electrically floating, rectangular metal tray ($15\ \mathrm{cm}\times 25$ cm) was placed about 3 cm below the anode disk, as indicated in Fig. 1. About 25 g of kaolin (aluminum silicate) dust were spread over the surface of this tray. When the discharge was turned on, some of the dust was attracted into the glow and trapped here. Presumably the top layer of dust, which is exposed to the plasma, becomes negatively charged due to the collection of electrons. These negatively charged dust grains are then attracted into the positive glow plasma and levitated there by dc electric fields in the glow (see Fig. 3). Light scattered from the dust cloud could be easily seen when the dust was illuminated by a high intensity lamp. Video images of the dust cloud were recorded on VCR tape using a standard

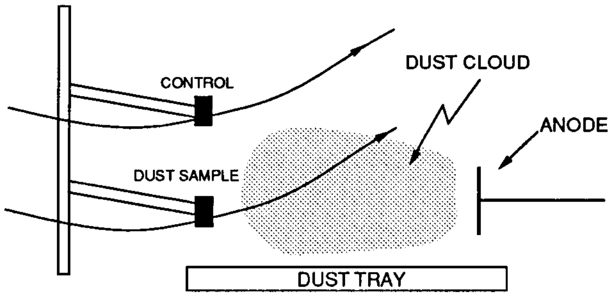

FIG. 4. Schematic of the instrument used for *in-situ* collection of dust grains. Dust grains are collected when the lower arm is swept through the dust cloud.

video camera (30 frames/s). For quantitative measurements, the light scattered from the dust grains was imaged onto a photodiode.

By collecting dust grains within the discharge and analyzing them using scanning electron microscopy (SEM), information on the size of the dust grains and their number density was obtained. A schematic diagram of the setup used to collect dust grains within the plasma is shown in Fig. 4. A rod on which two horizontal arms are mounted was inserted vertically into the vacuum chamber. Pieces of SEM specimen tape (double-sided) were fixed on the ends of the arms. When the rod was rotated through its axis, the lower arm swept through the dust cloud collecting dust grains along its path. The upper arm was used as a control monitor to check that grains were not being collected before the arm was rotated through the cloud. After the sample was collected, it was removed from the vacuum chamber and an SEM photograph of it was made. Several samples were taken and analyzed to ensure that typical results were obtained. An SEM photograph of one of the samples is shown in Fig. 5. Most of the grains fall in the size range of 0.5 to 1 μm, with an average of 0.8 μm. By counting the number of grains on the SEM photograph (of known area) and estimating the path

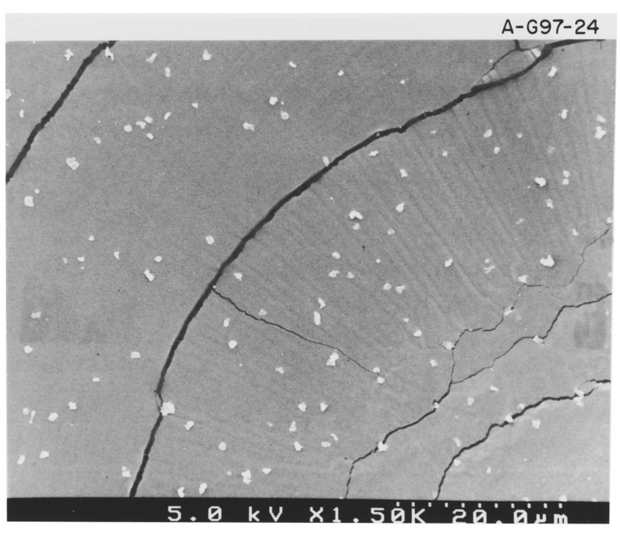

FIG. 5. Scanning electron micrograph (SEM) of dust grains collected from the glow discharge plasma. The total represented area of the micrograph is 73 μm$\times$54 μm.

along which the grains were collected, we obtain an approximate figure of 2×10^5 cm^{-3} for the average grain number density.

III. RESULTS

While observing the dust cloud one could see vertical bands of scattered light of enhanced intensity propagating away from the anode. Analysis of the video images of these spontaneously produced fluctuations showed that they propagated at a velocity $\approx$12 cm/s. From single frame video images of the fluctuations, a wavelength of 0.6 cm was determined, which combined with a velocity of 12 cm/s, corresponds to a frequency of 20 Hz. These fluctuations are identified as dust acoustic (DA) waves. The propagating bright bands are the wave crests, the regions of higher dust density which produce enhanced light scattering. These spontaneously excited DA waves are similar to those observed previously by our group using a somewhat different setup.[13]

To investigate the dispersion properties of the waves, a sinusoidal voltage modulation was applied to the anode (in addition to the dc bias) at frequencies in the range of 5–40 Hz. For a sufficiently large modulation amplitude, the DA waves could be driven at the frequency of the applied signal. For each driving frequency the wavelength was measured from a single frame video image. Examples of single frame images of DA waves corresponding to frequencies of 16, 22, and 30 Hz are shown in Fig. 6. A plot of the measured wave number, K, vs angular frequency, ω, is shown in Fig. 7. Over this frequency range the waves exhibit no dispersion, $\omega/K = v_{\mathrm{ph,exp}} \approx \mathrm{constant} \approx 12$ cm/s.

In the photographs of Fig. 6, the contrast was adjusted to accentuate the wave crests in order to determine their positions accurately. Thus this type of visual data cannot be used for a quantitative determination of the wave amplitude. Photodiode signals of low frequency fluctuations in the forward scattered light from a narrow axial region within the dust cloud are shown in the top trace of Fig. 8. To confirm that these fluctuations are not due to density striations in the discharge, the illumination of the dust grains was turned off and the light emission from the plasma was observed with the photodiode. The signal corresponding to this plasma emission is shown as the lower trace in Fig. 8, which was recorded on a ten-times more sensitive voltage scale. To determine the actual amplitude of the DA wave fluctuations, i.e., the ratio $\Delta n_d/n_d$, additional measurements of both the ac and dc components of the scattered light from the dust were made. Typically $\Delta n_d/n_d \approx 20\%-30\%$, although even larger amplitudes were sometimes seen.

IV. DISCUSSION

An experimental method for generating dust acoustic waves in a dc glow discharge plasma was presented. By controlling the frequency of the DA waves in the 5–40 Hz range and measuring the resulting wavelengths by analyzing the video images, the dispersion relation, ω vs K, was determined and compared to the theoretical dispersion relation, Eq. (1).

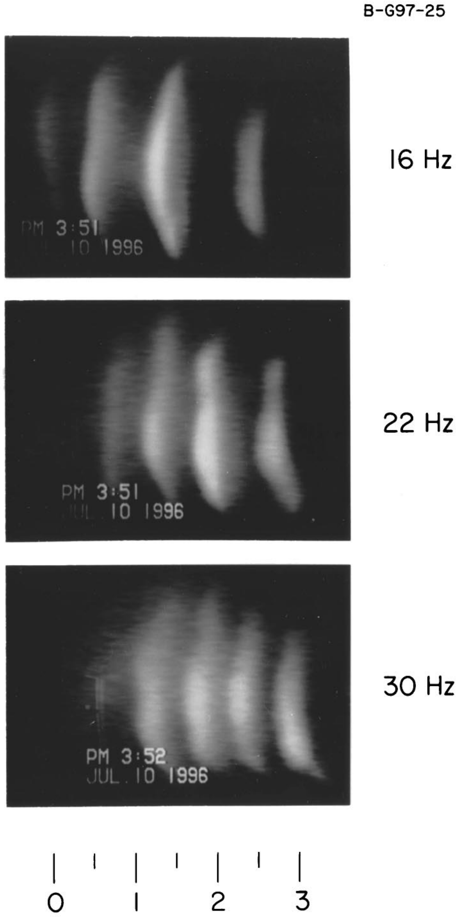

FIG. 6. Single frame video images of dust acoustic wave crests at frequencies of 16, 22, and 30 Hz.

For spherical dust grains of 0.8 μm diameter $m_d \approx 6 \times 10^{-16}$ kg. The relative concentration of dust grains, $\epsilon = n_d / n_i \approx (2\times 10^5)/[(4-8)\times 10^8] = (2.5-5)\times 10^{-4}$. The Z of the dust grains is computed using $Z = Q_d / e = (4\pi\epsilon_0\, a\, U)/e$, where U is the potential of a dust grain relative to the plasma space potential. In computing U, one needs to take into account the effect of close packing of the dust grains[17] i.e., the fact that the charge on a collection of dust grains in a plasma may be smaller, in magnitude, than that of an isolated grain. For $T_i = 0.03$ eV and $T_e = 2.5$ eV we find that $U \approx -5$ V, so that the magnitude of $Z \approx 1300$. [For these values of ϵ and Z the quantity of ϵZ (the fraction of negative charge per unit volume on dust grains)$\approx$0.3–0.65.] Since we have no way of determining the temperature of the dust grains, T_d, we can only make reasonable guesses. If the dust grains were in thermal equilibrium with the neutral gas molecules at about room temperature, the effect of T_d in Eq. (1) would be negligible. If, on the other hand, the dust grains were heated by the waves T_d could be much higher. However, it is not likely that the dust grain temperature could be elevated much above 1 eV by this process. We can get a rough estimate of the effect of wave heating of the dust grains by setting $kT_d \approx (1/2) m_d (v_{d1})^2$, where v_{d1} is the perturbed dust velocity due to the DA wave. For an acoustic perturbation v_{d1} is related to the wave amplitude, n_{d1}/n_{d0}, by $v_{d1} \approx (\omega/K)(n_{d1}/n_{d0}) \approx v_{\rm ph}(n_{d1}/n_{d0})$. For $n_{d1}/n_{d0} \approx 0.5$ and $v_{ph} \approx 12 \times 10^{-2}$ m/s, we find that $T_d \approx 1$ eV. A $T_d \approx 1$eV produces only a small contribution to $v_{\rm ph}$ in Eq. (1).

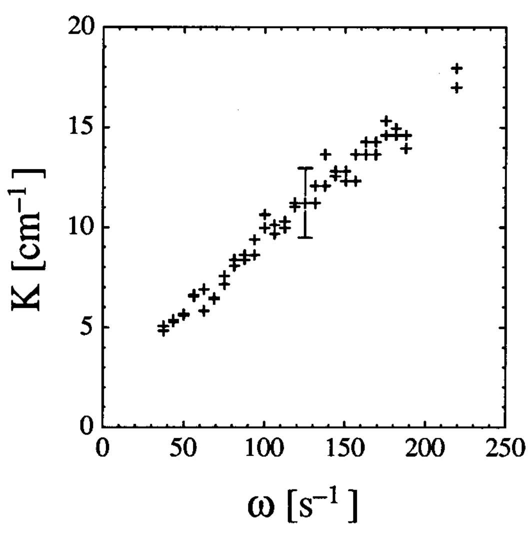

FIG. 7. Experimentally obtained DA wave dispersion relation, wave number K vs angular frequency ω.

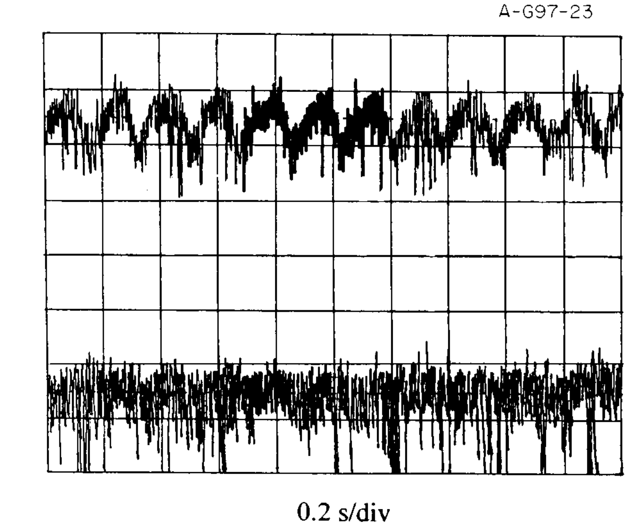

FIG. 8. Photodiode signals of light scattered from dust grains in a DA wave (upper trace, 10 mV/div) and for comparison, light emission from the glow discharge (lower trace, 1 mV/div). These data show that the low frequency fluctuations are associated with dust density fluctuations.

Then using $m_d \approx 6 \times 10^{-16}$kg, $T_i \approx 0.03-0.1$ eV, $\epsilon \approx (2.5-5)\times 10^{-4}$, and $Z \approx 1300$, in Eq. (1), we obtain $v_{\rm ph} \approx 6-15$ cm/s, as compared to a measured value $v_{\rm ph,exp} \approx 12$ cm/s. We note that Eq. (1) should be valid over the entire range of measured wavelengths in Fig. 7, since for the largest values of K, $(K\lambda_{\rm D})^2 \approx 0.01$.

V. CONCLUSIONS

In summary, we have presented experimental observations of very low frequency waves propagating in a glow discharge plasma which contains significant amounts of negatively charged dust grains. These waves have the general features of the dust acoustic waves that have been recently discussed in the literature.[6–13] In particular, the phase velocity obtained from measurements of the dispersion relation was in good agreement with the theoretically predicted one. We emphasize that compared to our preliminary work on DA waves,[13] all of the relevant quantities entering into the dispersion relation have now been estimated with substantial reliability, so that a more definitive comparison with theory was possible.

One may inquire as to whether or not the fluid analysis, to which our experimental results were compared, was appropriate for our dusty plasma. From the visual observations, it appeared that the charged dust behaved as a fluid, i.e., the grains showed no tendency to form ''dust crystals.'' Thus in our case, we would not expect to find any major deviations from fluid-like behavior.[18] We point out, however, that there have been a couple of experiments[19,20] which specifically investigated wave propagation in dusty plasmas in the so-called strong-coupling regime.

ACKNOWLEDGMENTS

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