Waves and Instabilities in Dusty Plasmas

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Abstract. This review article is divided into five parts. The Introduction contains some examples of dusty plasmas in the Universe and in the laboratory. This is followed by a brief section describing the mechanisms by which dust particles acquire an electrical charge in plasmas. The next section provides theoretical background for understanding the effect of dust on waves and instabilities in dusty plasmas. A description of some of the experimental studies of waves in dusty plasmas is then given. A few concluding remarks are then made.

INTRODUCTION

Dust represents much of the solid matter in the Universe and often coexists with the ionized gas forming a dusty plasma. The need to understand dusty plasmas stems from the fact that the dust acquires an electrical charge, and is thus subject to electromagnetic as well as gravitational forces. Perhaps the most striking example of this was found in the Voyager 2 images of Saturn's rings. Fig. 1 is an image of Saturn's B ring showing radially elongated structures (spokes) [1]. The spokes, which

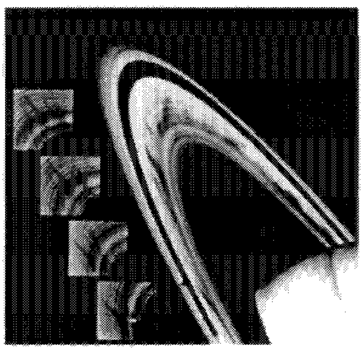

FIGURE 1. Voyager 2 image of spokes in Saturn's B ring. In insets show a sequence of images showing spoke formation. The time separations between the images are 10, 15, and 10 minutes, respectively.

CP694, *Radio Frequency Power in Plasmas: 15th Topical Conference on Radio Frequency Power in Plasmas,* edited by Cary B. Forest

are believed to contain micron size grains, appear quickly, extend radially for thousands of kilometers and disappear, all in a period of about half of a ring revolution around the planet. They are believed to be due to the levitation of the particles just above the rings by their interaction with Saturn's magnetic field or by electrostatic forces arising from ring-particle collisions [2]. The dusty plasma community is anxiously awaiting the arrival of higher resolution images of the rings when the Cassini-Huygens satellite encounters Saturn in July 2004.

Dust particles are often present in laboratory plasmas as well, either by choice or by circumstance. An example of a dusty plasma formed by circumstance is provided by the semiconductor manufacturing industry. Semiconductor processing facilities often use a parallel plate RF discharge as a plasma source for etching and deposition of silicon wafers. Typically, the plasma is formed by a mixture of the reactive gas silane (SiH_4) with argon and oxygen. In the resulting chemical reaction, SiO_2 particles (dust) are formed which grow in size over time. These dust particles become negatively charged in the plasma and become trapped in positive potential regions of the discharge. Eventually, some of the particles fall onto the wafer, contaminating it and rendering it useless. A photograph of dust clouds surrounding wafers in a typical processing device is shown in Fig. 2 [3]. As improvements to the cleanroom environments dramatically reduced external sources of wafer contamination, it became obvious that the largest source of contamination was due to the plasma process itself.

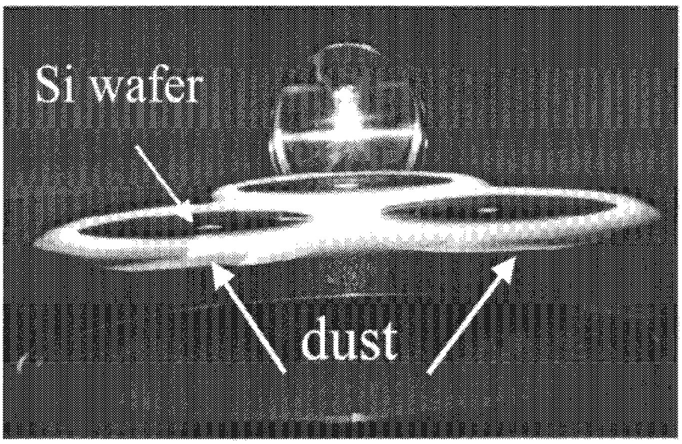

FIGURE 2. Photograph of rastered laser light scattered from dust particles formed during operation of a 200 mTorr Ar plasma processing tool. The dust particles are trapped in rings surrounding the Si wafers. The wafers in the foreground are 5.7 cm diameter and the one in the background is 8.3 cm.

Dust has also been found in fusion devices [4]. After periods of operation, particles ranging in size from fractions of millimeters to sub microns are found at the bottom of the vacuum vessel. The source of these particles is believed to be evaporation and sublimation of wall material which has been exposed to high thermal loads. Sputtering from particle impacts is also an important particulate source. Dust particles may also be generated by growth and agglomeration in the edge plasma regions. This process may be of particular concern for future long pulse devices. Some of the dust is ferromagnetic, so that it can easily be sucked into the main volume of the discharge vessel and accumulate on the inner wall where the magnetic field is strongest. From the plasma physics point of view, the smaller particles are of particular concern since they would be expected to remain at the edge of the plasma where they could alter the balance between the electrons and protons.

These are just a few examples of dusty plasmas. Other examples of dusty plasmas are discussed in a number of review articles that have appeared [2, 5, 6] as well as a recent monograph [7].

CHARGING OF DUST PARTICLES

The first consideration in dealing with dusty plasmas is to understand how the particles get charged. There are basically three processes that must be considered: (1) absorption of electrons and ions from the plasma, (2) secondary emission, and (3) UV induced photoelectron emission. Each process can be represented by a flux or current to the particle, and since the dust is electrically floating, the net current due to all processes must be zero, or

$$\sum I = I_e + I_i + I_{\sec} + I_{pe} = 0 \tag{1}$$

where the various terms represent the contributions from electrons, ions secondaries, and photoelectrons, respectively. Photoelectron emission is an important contribution for dust particles in a strong UV environment, but is typically not important in laboratory plasmas. Similarly, secondary emission is usually not important in low temperature plasmas. Under these conditions an isolated particle in a typical low temperature laboratory plasma will acquire a negative surface potential V_s relative to the plasma because of the higher mobility of the electrons. V_s is determined by the balance of electron and ion currents, $I_e + I_i = 0$. The electron current is given by

$$I_e = -4\pi a^2 e n_e \left(\frac{kT_e}{m_e}\right)^{1/2} \exp\left(\frac{eV_s}{kT_e}\right), \tag{2}$$

where a is the radius of the particle, T_e is the electron temperature, n_e is the electron density and m_e is the electron mass. For the ion current to the particle, the orbital motion limited (OML) model is usually used:

$$I_i = 4\pi a^2 e n_i \left(\frac{kT_i}{m_i}\right)^{1/2} \left(1 - \frac{eV_s}{kT_i}\right) \tag{3}$$

where T_i is the ion temperature, n_i is the ion density and m_i is the ion mass. The OLM model is valid in the limit where the particle radius is small compared to the Debye length. For the case of an isothermal hydrogen plasma, equations (1) – (3) give the particle's surface potential $V_s = -2.5kT_e/e$. The particle charge Q_d is determined from the capacitance model $Q_d = 4\pi\varepsilon_0 a V_s$. For a 1 micron diameter particle in a 2 eV hydrogen plasma the charge is then $Q_d = -1736$ e. This charging model applies strictly to the case of an isolated dust grain in a plasma has been verified experimentally [8]. In the case in which the dust grains are 'closely packed' so that the Debye sheaths of individual grains overlap, the particle charge is reduced [9].

LOW FREQUENCY WAVES IN DUSTY PLASMAS -THEORY

The presence of charged dust in a plasma influences the collective behavior in two ways. First, the excitation and propagation characteristics of the usual wave modes are modified even at frequencies at which the particles do not participate directly in the wave motion. This comes about through the effect on the plasma quasineutrality condition, which for negatively charged particles is

$$n_i = n_e + Z_d n_d \tag{4}$$

where, $Z_d = Q_d/e$ and n_d is the dust particle density. Second, new very low frequency (few Hz) modes appear in which the dust particles participate in the wave dynamics. Since the dust particles can be imaged, the characteristics of these "dust modes" can be observed visually and recorded on tape.

The characteristics of waves in dusty plasmas have some similarities to waves in plasmas containing negative ions with important differences. The charge on a dusty plasma is not necessarily constant. Since the charge depends on the difference between the particle and plasma potential, the charge will fluctuate in response to fluctuations in the plasma potential. Another unique property of a dusty plasma is the fact that there may be a large distribution of dust sizes which results in a distribution of particle masses and charge. Theoretical work on dusty plasmas with broad size distributions is only in the preliminary stage.

A review of theoretical work on waves in dusty plasmas with particular emphasis on space plasmas was presented by Verheest [10].

The simplest approach to understanding wave phenomena in dusty plasmas is to apply the fluid equations, treating the dust as a third fluid component. This approach was used by D'Angelo in 1990 [11] to obtain a dispersion relation for low-frequency electrostatic waves in a magnetized dusty plasma (see also Merlino *et al.* [12]). Two types of low-frequency electrostatic modes are possible: acoustic modes which propagate along the magnetic field (perpendicular wavenumber $K_\perp = 0$) and cyclotron modes which propagate at a large angle to the magnetic field with a perpendicular wavenumber $K_\perp >> K_\parallel$. Each type of mode is further subdivided into modes in which either the dust only provides a static background of negative charge or modes in which the dust particles participate directly in the wave dynamics (dust modes).

Dust Ion-Acoustic (DIA) and Dust Acoustic (DA) Waves

The dust ion acoustic mode is the usual ion acoustic mode that is modified by the presence of negative dust that is considered as a static background. The frequency of this mode is too high for the dust particles to respond. The DIA dispersion relation is given by

$$\frac{\omega}{K_{\parallel}} = \left[\frac{kT_i}{m_i} + \frac{kT_e}{m_i(1-\varepsilon Z_d)} \right]^{1/2} \equiv C_{DIA} \tag{5}$$

where the quantity $\varepsilon Z_d = (n_{do}/n_{io})Z_d$ is the fraction of negative charge in the plasma on the dust particles. For the case in which no dust is present $\varepsilon = 0$, and equation (5) reverts to the usual ion acoustic velocity. In the presence of dust the phase velocity increases with increasing εZ_d.

The dust acoustic mode [13] is a very low frequency acoustic mode involving longitudinal dust density fluctuations. For this mode the electron and ion inertia can be neglected. The dispersion relation is

$$\frac{\omega}{K_{\parallel}} = \left[\frac{kT_d}{m_d} + \varepsilon Z_d^2 \frac{kT_i}{m_d} \frac{1}{1+(T_i/T_e)(1-\varepsilon Z_d)} \right]^{1/2} \equiv C_{DA} \tag{6}$$

where T_d is the temperature of the dust fluid. Since the DA velocity, C_{DA} depends on the dust mass, m_d, the frequency of these waves can be quite low.

Electrostatic Dust Ion-Cyclotron (EDIC) Waves and Electrostatic Dust-Cyclotron (EDC) Waves

The electrostatic dust ion-cyclotron mode is the ion-cyclotron mode with a frequency $\omega \sim \Omega_i$ (the ion-cyclotron frequency), that is modified by the presence of negatively charged dust. At this relatively high frequency, the dust is considered to be immobile and the dispersion relation is

$$\omega^2 = \Omega_i^2 + K_{\perp}^2 C_{DIA}^2 \tag{7}$$

where C_{DIA} is the dust ion acoustic speed defined in equation (5). The frequency of this mode increases with increasing εZ_d.

The electrostatic dust-cyclotron mode occurs in a dusty plasma in which the dust grains are magnetized. It is a low frequency "dust mode" in which the dust particles participate in the wave motion. The EDC dispersion relation is

$$\omega^2 = \Omega_d^2 + K_\perp^2 C_{DA}^2 \tag{8}$$

where Ω_d is the dust cyclotron frequency and C_{DA} is the dust acoustic velocity defined in equation (6).

Wave Excitation and Damping

Ion acoustic waves are subject to ion Landau damping which is particularly strong in plasmas with $T_e = T_i$. This occurs because the wave phase velocity is close to the ion thermal velocity resulting in strong wave-particle resonance. In the presence of negatively charged dust however, the wave phase velocity increases as the fraction of negative charge on the dust increases, as seen from equation 5. With increasing phase velocity, the importance of Landau damping due to wave-particle interactions is reduced, so that propagation of ion acoustic waves becomes possible even in a plasma with equal ion and electron temperatures. This conclusion based on considerations of the dispersion relation derived from fluid theory, has also been confirmed from kinetic theory calculations which showed that the damping rate of the waves was drastically reduced when a sufficient amount of negatively charged dust was present [14].

The DA mode is one in which the wave inertia is provided by the heavy dust particles whereas the electrons and ion pressures provide the wave restoring force. This mode can be driven unstable by electrons and ions drifting with respect to the dust particles. This scenario may occur, for example, in planetary ring systems in which the plasma co-rotates with the planet, while the dust particles move in Keplerian orbits at a much slower speed. Calculations, based on the Vlasov equation show that relatively weak drifts, on the order of the dust acoustic speed (much less than the ion or electron thermal speed) are needed to excite the DA mode.

Electrostatic ion-cyclotron (EIC) waves can be excited in a plasma by an electron drift (relative to the ions) along the magnetic field. The critical electron drift velocity, v_{ec}, required to excite the EIC instability has been computed from kinetic theory. The results show that v_{ec} decreases as more negative charge is carried by the dust particles, thus the instability is easier to excite in a dusty plasma [15].

The kinetic instability of the EDC mode in the presence of streaming ions has also been investigated [7]. The calculations show that, as one might expect, the EDC waves would grow if the ion streaming velocity exceeded the parallel phase velocity, $\omega/K_{||}$, where the mode frequency $\omega \cong \Omega_d$, the dust cyclotron frequency.

LOW FREQUENCY WAVES IN DUSTY PLASMAS – EXPERIMENTS

In this section we discuss some of the experimental work on waves in dusty plasmas. Two devices used to produce dusty plasmas, a Q machine and a discharge plasma are described. Experimental results on the dust ion acoustic (DIA) wave, electrostatic dust ion cyclotron (EDIC) wave and dust acoustic (DA) wave will be presented. At this point there have been no experimental observations of the EDC mode due to the difficulty in producing a dusty plasma in which the dust particles are magnetized. We conclude this section with a brief introduction to waves in strongly coupled dusty plasmas.

Dust Ion Acoustic Wave Experiment

The effect of negatively charged dust on the propagation of ion acoustic waves was studied in the dusty plasma device (DPD) shown schematically in Fig. 3. The DPD utilizes a single-ended Q machine as the plasma source and a rotating dust dispenser. The plasma is formed by contact ionization of potassium or cesium atoms from an atomic oven on a 6 cm diameter tantalum hot plate (~2200K) which also provides thermionic electrons. The plasma is confined by a uniform axial magnetic field with a strength up to 0.35 T. Typically, the electron and ion temperatures are $T_e = T_i \approx 0.2$ eV and the plasma density is in the range of $10^8 - 10^{10}$ cm^{-3}. Aluminum silicate powder in the micron size range, initially loaded into the bottom of the dust cylinder, is dispersed into the plasma by rotating the dispenser around the plasma column. As the dust falls through the plasma it acquires a negative charge. Further details of the operation of the DPD can be found elsewhere [16]. The fraction of negative charge on the dust, εZ_d, is determined from Langmuir probe measurements of the reduction in the electron saturation current that occurs when the dust is present as compared to the case with no dust [9]. The dust density can be controlled to some extent by varying the rotation speed of the cylinder.

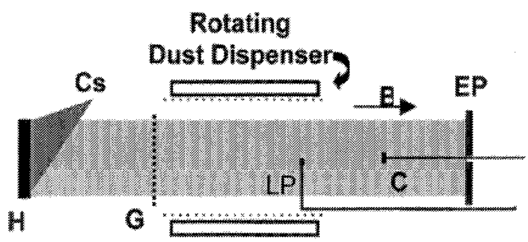

FIGURE 3. Schematic diagram of the dusty plasma device (DPD). The rotating dust dispenser is used to disperse dust into the plasma.

Ion acoustic waves were launched into the plasma by means of a grid (G) that was located ~ 3 cm in front of the dust dispenser and oriented perpendicular to the magnetic field. The grid was biased at several volts negative with respect to the plasma potential and a sinusoidal tone burst of frequency ~ 20 – 80 kHz and 4 – 5 V peak-to-peak amplitude was applied to it. This produced a density perturbation that traveled down the plasma column as an ion acoustic wave. Using an axially movable Langmuir probe the phase velocity ($v = \omega/K_r$), wavelength (λ), and spatial attenuation length ($\delta =$

$2\pi/K_i$) were measured as a function of εZ_d (K_r and K_i are the real and imaginary parts of the wavenumber). The results are shown in Fig. 4. The phase velocity increases with increasing εZ_d while the spatial damping length decreases with increasing εZ_d. In the absence of dust (εZ_d = 0) ion acoustic waves are heavily damped and do not propagate more than one wavelength. However, when the negative dust is present, the phase velocity is increased so that Landau damping is significantly reduced.

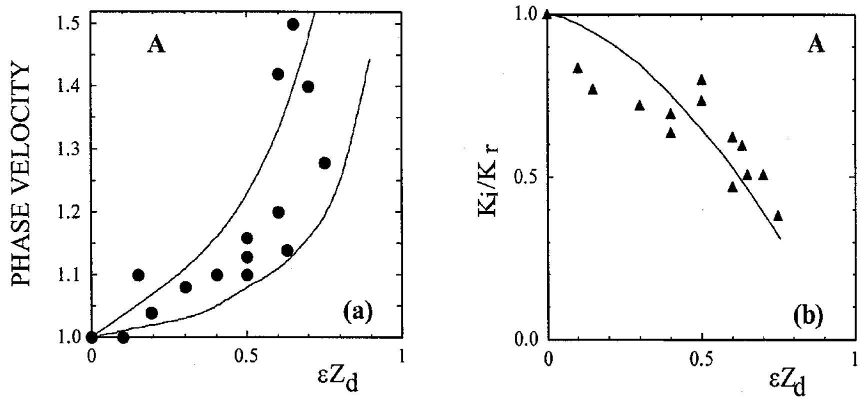

FIGURE 4. Properties of grid-launched ion acoustic waves in a dusty plasma. (a) Phase velocity versus εZ_d, normalized to the value with no dust present. The solid lines are theoretical predictions from fluid theory for two assumed values of the plasma drift speed. (b) Ratio of the inverse wave damping length to wavenumber versus εZ_d. All values are normalized by the value with no dust present. The solid curve is the prediction of kinetic theory.

Electrostatic Dust Ion-Cyclotron Wave Experiment

Unlike the IA waves which were launched into the plasma, the EIC waves were excited by driving an electron current along the magnetic field of the Q machine. The experimental setup was identical to that shown in Fig. 3, except that the grid was removed. A 5 mm diameter collector (C) was located near the end of the dust dispenser and was biased at ~ 0.5 – 1 V above the space potential to draw electron current. In a Q machine, this will produce an electron drift that is sufficient to excite EIC waves with a frequency slightly above the ion-cyclotron frequency which propagate nearly perpendicular to the magnetic field. The effect of the negative dust was studied by measuring the wave amplitude A_{nd} with no dust present and then turning the dust dispenser on an measuring the wave amplitude A_d with the dust present. The ratio A_d/A_{nd} is then an indication of the effect of the dust. This measurement was repeated for several values of εZ_d and the results are shown in Fig. 5. These results show that it becomes increasingly easier to excite EIC waves as more of the negative charge is carried by the dust. This result is in line with the theoretical calculation of Chow and

Rosenberg [15] that the presence of negative dust reduces the critical electron drift for excitation of the EDIC mode.

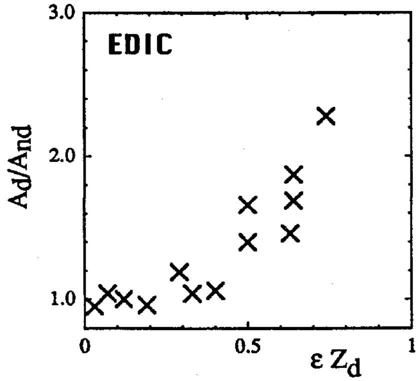

FIGURE 5. The electrostatic dust ion cyclotron wave amplitude as a function of εZ_d. The amplitudes are normalized to the EIC amplitude when no dust is present.

Dust Acoustic Wave Experiment

Observation of the dust acoustic (DA) wave requires that the dust particles be trapped within the plasma for a sufficient time. The dusty plasma device shown in Fig. 3 does not meet this requirement since the dust is continuously falling through the plasma column. We found that a simple DC glow discharge was ideal for this purpose, since the space potential within a DC glow discharge is positive with respect to the walls of the device. As a result, the plasma contains regions in which there are electric fields of appropriate strength and direction to levitate negative particles. A schematic of the DC glow discharge device used to observe DA waves is shown in Fig. 6. The

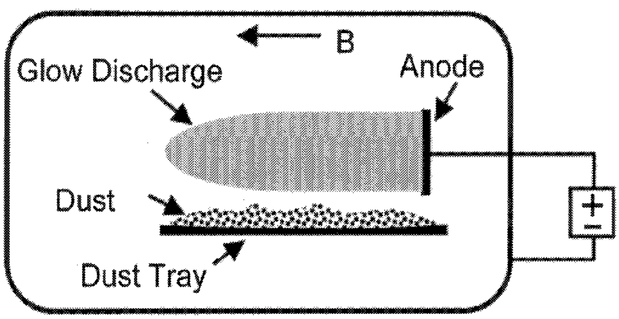

FIGURE 6. Schematic of the DC glow discharge device used to trap negative dust particles. Dust initially located on a tray below the anode is attracted into the plasma and levitated by the electric field associated with the glow.

glow discharge is formed in nitrogen at a pressure of ~ 100 mTorr by applying a positive potential of 200 – 300 V to a 3 cm diameter anode disk located in a large vacuum chamber. A longitudinal magnetic field of 0.01T is applied to provide radial confinement, which results in the formation of a cylindrical glow discharge. Aluminum silicate powder on a tray below the anode is attracted into the discharge and trapped in the positive potential region. The dust particles in the plasma are illuminated from behind by a high intensity lamp and imaged with a video camera.

Dust acoustic waves are excited spontaneously in the plasma, probably due to an ion-dust streaming instability. The waves appear as vertically elongated regions of enhanced intensity scattered light which propagate in the horizontal direction away from the anode. A single frame image of a DA wave captured on video tape is shown in Fig. 7. From analysis of the single frame images of this type, the wavelength and

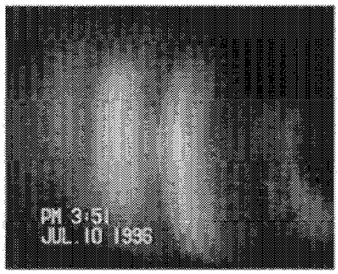

FIGURE 7. Single frame video image of a dust acoustic wave excited spontaneously in a DC glow discharge. The brighter regions are the wave crests which correspond to dust density enhancements.

phase velocity can be measured. The DA wave dispersion relation was obtained by applying (in addition to the DC bias) a sinusoidal modulation signal to the anode in the frequency range of 5 – 30 Hz to fix the DA wave frequency. For each applied modulation frequency, a video recording of the waves was obtained from which the wavelength was measured. The resulting dispersion relation, K versus ω is shown in Fig. 8.

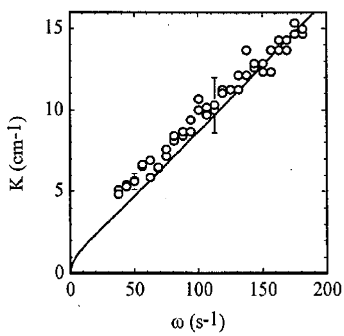

FIGURE 8. Measured dust acoustic wave dispersion relation. The wave phase velocity is 12 cm/s. The solid line is the prediction of fluid theory.

The measured dispersion relation was compared with one obtained from fluid theory (Eq. 6) modified to include the effect of collisions between the dust particles and the neutral atoms. Over this range of frequencies $K \propto \omega$, as expected for longitudinal compressional waves.

Waves in Strongly Coupled Dusty Plasmas

In ordinary electron/ion plasmas the ratio of the interparticle potential energy to thermal kinetic energy,

$$\Gamma = \frac{(eZ)^2}{4\pi\varepsilon_o \, d \, kT} \tag{9}$$

where d is the interparticle spacing, is typically << 1. However, in a dusty plasma, Z can be on the order of thousands, and the so-called coupling parameter Γ can be much larger than one. In this case the dust particles actually arrange themselves in a regular lattice array [17]. The presence of short scale correlations gives rise to novel modifications of the collective behavior in these plasmas. Unlike ordinary plasmas which exist in the fluid state, these liquid and solid-like plasmas can accommodate both compressional waves and shear waves [18,19].

CONCLUDING REMARKS

Dusty plasmas are ubiquitous in the Universe, and it is now realized that they are not that uncommon in the lab as well. Methods have now been devised to create dusty plasmas for experimental study. This review has concentrated on how the presence of charged dust modifies the excitation and propagation characteristics of a number of well-known electrostatic waves in plasmas. In the presence of negatively charged dust, both ion-acoustic and ion-cyclotron waves are more easily excited. This result is well understood on the basis of fluid and kinetic theories, and has been verified by laboratory experiments. New waves, which involve in an essential manner the dynamics of the dust particles themselves, have also been investigated. Visual observations of the so-called dust acoustic wave have been presented here. Finally, we note that the presence of collective and coherent fluctuations in the density of a dust cloud may provide a mechanism for structuring on small scales.

ACKNOWLEDGMENTS

The work on dusty plasmas at the University of Iowa was supported by the Office of Naval Research and the National Science Foundation.

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