Colloquium: Fundamentals of dust-plasma interactions

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Dusty plasmas are ubiquitous in low-temperature laboratory discharges as well as in the near-earth environment, planetary rings, and interstellar spaces. In this paper, updated knowledge of fundamentals of collective dust-plasma interactions and several novel phenomena are presented that have been observed in laboratories and in space dusty plasmas. Mechanisms that are responsible for the charging of dust grains are discussed, and the fact that the dust charge perturbation is a new dynamical variable in a dusty plasma. The underlying physics of different forces that act on a charged dust grain is reviewed. In dusty plasmas, there are new attractive forces (e.g., due to wakefield and ion focusing effects and dipole-dipole interactions between unevenly charged dust rods). Furthermore, in the presence of an ensemble of charged dust grains, there are collective dust-plasma interactions featuring new waves (e.g., the dust acoustic wave, the dust ion-acoustic wave, the dust lattice wave, etc.), new instabilities, and coherent nonlinear structures (dust acoustic and dust ion-acoustic shocks, dust voids, and dust vortices), which are also discussed. Theoretical models for numerous collective dust-plasma interactions are compared with existing observations from laboratories and space environments.

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CONTENTS

I. INTRODUCTION

The interplay between plasmas and charged dust grains has opened up a new and fascinating research area, that of a dusty (or complex) plasma. Dusty plasmas are fully or partially ionized low-temperature gases comprising neutral gas molecules, electrons, ions, and submicron- and micron-sized charged dust grains. The latter can be billions of times heavier than the ions and acquire several thousands of electron charges. The dust grain charging occurs due to a variety of physical processes (Mott-Smith and Langmuir, 1926; Sodha and Guha, 1971; Goertz and Ip, 1984; Whipple *et al.*, 1985; Barkan *et al.*, 1994; Walch *et al.*, 1994, 1995; Rosenberg and Mendis, 1995; Rosenberg *et al.*, 1996, 1999; Fortov *et al.*, 1998; Boeuf and Punset, 1999; Sikafoose *et al.*, 2000; Ostrikov *et al.*, 2001; Merrison *et al.*, 2004; Ignatov, 2005; Ticoş *et al.*, 2006), including the collection of background plasma electrons and ions by dust grains, photoelectron emission, secondary electron emission, thermionic emission, triboelectric charging and contact electrification,

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etc. In dust filled whirlwinds and dust storms, dust particles (e.g., sand) become electrified when they rub each other as they are carried out by the winds (Kok and Renno, 2008), transferring positive and negative charge in the same way you build up static electricity if you shuffle across a carpet. Thus, one has the possibility of charging dust grains both negatively and positively. The dust grains act as a source of electrons when they are charged positively due to the irradiation of ultraviolet (uv) radiation or by thermionic emission. The dust grain charging is a new nonstationary physical process in a dusty plasma, which marks a distinction between the latter and the usual multicomponent electron-ion plasma containing two ion species. The dust component, which increases the complexity of the system even further, is responsible for the name "complex plasma."

Dusty plasmas are ubiquitous in different parts of our cosmic environment (Goertz, 1989; Mendis and Rosenberg, 1992, 1994; Barabash and Lundin, 1994; Bliokh, 1995; Grün *et al.*, 1996; Shukla *et al.*, 1996; Mendis, 1997; Bingham and Tystovich, 1999; Graps *et al.*, 2000; Verheest, 2000; Tsurutani *et al.*, 2003), such as in the planetary ring system of Saturn, in Jupiter's moon Io and in the dust rings of the Martian moon Phobos, in circumsolar rings and interplanetary media, in cometary comae and tails, in supernova remnants, and in interstellar molecular clouds. The dark bands of dust, which block parts of the Orion, Lagoon, Coalsack, Horsehead, and Eagle nebulae, indicate that dust must have been abundant in the nebulae that coalesced to form the Sun, planets, and other stars. During the Voyager 1 and 2 flybys of the outer planets and the ICE flyby of the comet Giaobini-Zinner, the plasma wave instrument detected small dust particles striking the spacecraft (Gurnett *et al.*, 1983, 1997; Tsintikidis *et al.*, 1996; Horányi, 2000; Horányi *et al.*, 2004). Dust is thought to be responsible for the "spokes" that were detected in Jupiter's B and F rings by the Voyager 1 and 2 spacecrafts in the early 1980s (Collins *et al.*, 1980; Smith *et al.*, 1981, 1982), by the Hubble Space Telescope from 2004 until October 1998 (McGhee *et al.*, 2005), and again in Saturn's B ring by the Cassini spacecraft in 2005 (Mitchell *et al.*, 2006). Charged dust grains play a significant role in the Martian and terrestrial dust devils (Renno *et al.*, 2003; Farrell *et al.*, 2004), as well as near the terminator of the moon (Borisov and Mall, 2006).

Meteoritic dust is thought to be present in the Earth's mesosphere at altitudes of ~80–95 km. It has been conjectured that in the cold summer mesopause ice can grow on meteoritic dust particles, with the icy dust particles possibly influencing the charge balance of the region (Cho and Kelley, 1993; Zhou and Kelley, 1997; Kelley *et al.*, 1998; Havnes and Sigernes, 2005). The presence of charged dust particles in the polar summer mesopause has been invoked to explain aspects of the very strong polar summer radar echoes referred to as polar mesosphere summer echoes, which occur at altitudes between 80 and 93 km. Recently, the presence of charged dust in the mesosphere has been detected by direct rocket probe measurements, where both negatively and positively charged dust grains have been reported (Havnes *et al.*, 1996a, 1996b, 2007; Eidhammer and Havnes, 2001; Smiley *et al.*, 2002, 2006; Mendis *et al.*, 2004; Lynch *et al.*, 2005; Rapp *et al.*, 2005). The role of charged dust in mesospheric electric fields has been discussed by Zadorozhny (2000). Special modes of rocket engine operation inject into the atmosphere large amounts of combustion products (at times on the order of hundreds of kilograms), which can have the form of solid particles or ice (Platov *et al.*, 2003, 2004). Since the dust is ejected into the ionosphere with high speed relative to the background plasma (on the order of km/s), the dust may drive instabilities as it becomes charged (Bernhardt *et al.*, 1995). The formation of an artificial dusty plasma in the ionosphere was also revealed during the Spacelab 2 mission when the space shuttle orbital maneuver system engines were fired (Bernhardt *et al.*, 1995), and the formation of discrete large droplets and smaller, submicron fog was observed during a liquid water dump by the Discovery space shuttle (Pike *et al.*, 1990). Since dust particles are a main element of interest in the solar system and in the interstellar medium, there are a number of future missions (viz., the European Space Agency ROSETTA mission) for detecting dust on comet 46P/Wirtanen in 2012.

Dusty plasmas also occur in the flame of a humble candle, in the zodiacal light, in cloud-to-ground lightning in thunderstorms containing smoke-contaminated air, in volcanic eruptions, and in ball lightning. It has been suggested by Abrahamsson and Dinniss (2000) and Abrahamsson (2002) that ball lightning is caused by oxidation of nanoparticle networks from normal lightning strikes on soil; recent laboratory experiments by Dikhtyar and Jerby (2006) seem to support this theory.

Dusty plasmas are encountered in industrial applications (Selwyn *et al.*, 1989) as well, e.g., in such technologies as microelectronics (Vladimir and Ostrikov, 2004) involving carbon nanotubes (Levchenko *et al.*, 2007; Pal' *et al.*, 2007), as precipitation of aerosol particles in the combustion products of electric power stations, in plasma spraying, and in electrostatic painting. By adjusting the pressure and temperature in a reactive plasma, one can also monitor the growth of carbon with diamond structure (Nishimaru *et al.*, 2003). Furthermore, there are also emerging applications of charged dust objects in microbiology (Laroussi *et al.*, 2003), in medicine (Stoffels *et al.*, 2003), as well as in nanomedicine (Roy *et al.*, 2005). Specifically, an electrophysical process (Laroussi *et al.*, 2003), which involves the electrostatic tension on charged bodies (the bacteria cells) in a cold dusty plasma, may be responsible for killing bacteria (Gram negative and Gram positive).

Dust grains with size distributions have also been observed in fusion plasmas (Winter, 1998; West *et al.*, 2006). Charged dust grains, which may be created due to the sputtering of tokamak walls and which are composed of the berelium and carbon tiles, could also be radioactive. It is, therefore, likely that a small fraction of dust grains might play a unique role in understanding the transport processes in high density and low-temperature tokamak edges (Krasheninnikov *et al.*, 2004; de Angelis, 2006; Krasheninnikov, 2006; Smirnov *et al.*, 2007). Charged dust grains in tokamak edges are lifted from the bottom of the fusion machine and undergo acceleration (Castaldo *et al.*, 2007), because of the sheath electrostatic and ion wind forces. In tokamaks, the dust charge state is not known. Furthermore, recent laboratory experiments (Ticoş *et al.*, 2008) have demonstrated simultaneous acceleration of hundreds of graphite and diamond dust particles to hypervelocities by collimated plasma flows ejected from a gun.

A major boost to dusty plasma research came after the theoretical prediction of the dust acoustic wave (DAW) by Shukla (1989) and Rao *et al.* (1990). The DAWs have been observed by a large number of laboratory experiments (Chu *et al.*, 1994; Barkan *et al.*, 1995; Pieper and Goree, 1996; Prabhakara and Tanna, 1996; Merlino *et al.*, 1998; Molotkov *et al.*, 1999; Thomas and Watson, 1999; Thompson *et al.*, 1999a; Fortov *et al.*, 2000, 2003, 2004a; Samarian *et al.*, 2001). The prediction of the dust ion-acoustic wave (DIAW) (Shukla and Silin, 1992) was also verified by experiments (Barkan *et al.*, 1996; Nakamura *et al.*, 1999). Furthermore, it should be noted that Ikezi (1986) theoretically predicted the Coulomb crystallization of charged dust grains interacting via a repulsive Yukawa force in a plasma, when the Coulomb coupling parameter Γ_d [the ratio between the Coulomb interaction energy density $q_d^2 \exp(-\kappa_d)/d$ and the dust thermal energy density T_d, where q_d is the dust charge, $\kappa_d = d/\lambda_D$ is the ratio between the intergrain spacing d and the dusty plasma Debye radius λ_D, and T_d is the dust temperature] exceeds 170. Clearly, large Γ_d at room temperature is achieved when dust grains acquire tens of thousands electrons on their surface. This theoretical prediction was verified experimentally with the observations of the dusty plasma crystal (DPC) (Chu and I, 1994a, 1994b; Hayashi and Tachibana, 1994; Melzer *et al.*, 1994; Thomas *et al.*, 1994; Hayashi, 1999) composed of ordered charged dust particles (e.g., micron-sized polymer spheres). The latter appear in the form of the body-centered-cubic (bcc) and face-centered-cubic (fcc) dust crystal structures for certain experimental parameters (Tsytovich *et al.*, 2008). There also exist observations of particles arranged in simple hexagonal structures where the dust particles are on a triangle lattice, with one particle above another in the vertical direction. The phenomena of phase transition in dust plasma crystals have also been observed in laboratory experiments (Thomas and Morfill, 1996). The discovery of the DAW and DPC have been essential milestones in dusty plasma physics.

A dusty plasma is significantly different from a multi-ion plasma in that the presence of massive charged dust grains produces new collective phenomena on completely different time and space scales (Verheest, 2000; Shukla, 2001, 2002, 2003; Mendis, 2002; Shukla and Mamum, 2002; Fortov *et al.*, 2004b, 2005a; Merlino and Goree, 2004; Ishihara, 2007; Tsytovich *et al.*, 2008). An example is the low-frequency DAW (Rao *et al.*, 1990) in which the dust mass provides the inertia, while the restoring force comes from the pressures of the inertialess electrons and ions. In laboratory dusty plasma discharges (Barkan *et al.*, 1995; Pieper and Goree, 1996; Prabhakara and Tanna, 1996; Merlino *et al.*, 1998; Molotkov *et al.*, 1999; Thompson *et al.*, 1999a; Thomas and Watson, 1999; Fortov *et al.*, 2000), the DAW frequency is typically 10–20 Hz and the typical wavelength is half a centimeter, which makes it possible to produce video images of the dust acoustic wavefronts (Barkan *et al.*, 1995; Merlino *et al.*, 1998; Thompson *et al.*, 1999a). New effects are introduced by the dust charge fluctuation dynamics (Jana *et al.*, 1993; Melandsø *et al.*, 1993; Varma *et al.*, 1993; Rao and Shukla, 1994; Ma and Shukla, 1995; Shukla, 1996; Morfill, Ivlev, and Jokipii, 1999; Ivlev *et al.*, 2000; Shukla and Resendes, 2000; Stenflo *et al.*, 2000), dust-dust interactions (Rosenberg and Kalman 1997; de Angelis and Shukla, 1998, 1999; Kaw and Sen, 1998; Murillo, 1998; Winske *et al.*, 1999), dust mass and size distributions (Havnes *et al.*, 1990; Brattli *et al.*, 1997), dust grain rotation (Mohideen *et al.*, 1998; Mahmoodi *et al.*, 2000), and the plasma boundary (Shukla and Rosenberg, 1999; Mamun and Shukla, 2000), which are unique for a dusty plasma. Furthermore, in strongly coupled dusty plasmas there exist dust lattice waves (DLWs) (Melandsø, 1996; Farokhi *et al.*, 1999, 2000; Shukla, 2000b), whose counterparts exist only in solids (Kittel, 1996). The DLW has also been excited in laboratory dusty plasma experiments (Homann *et al.*, 1997, 1998; Morfill *et al.*, 1997; Thomas *et al.*, 1998) In the DLW, the restoring force comes from the Debye-Hückel interaction, while the dust mass provides the inertia. Furthermore, dusty plasmas support a variety of nonlinear structures, including the dust acoustic (Melandsø and Shukla, 1995) and dust ion-acoustic (Luo *et al.*, 1999, 2000; Nakamura *et al.*, 1999; Shukla, 2000c) shock waves, as well as dust acoustic Mach cones (Havnes *et al.*, 1996c; Samsonov *et al.*, 1999, 2000; Dubin, 2000; Melzer *et al.*, 2000; Zhdanov *et al.*, 2004) dust microbubbles in dusty plasma liquids (Chu *et al.*, 2003), and dust vortical motions (Fujiyama *et al.*, 1997; Iizuka *et al.*, 1998; Law *et al.*, 1998; Sato *et al.*, 1998, 2000; Morfill *et al.*, 1999; Agrawal and Prasad, 2003; Fortov *et al.*, 2005b, 2006; Ratynskaia *et al.*, 2006)

This Colloquium presents an overview of some important aspects of dust-plasma interactions, and describes the underlying physics of several new phenomena (e.g., the dust grain attractive force caused by the wakefield and ion focusing, the dust inertia induced waves, and dust structures at kinetic levels) that have been predicted and observed in dusty plasmas. To start with, we discuss the properties of dusty plasmas as well as present numerous dust charging mechanisms and forces that act on the charged dust particles. We then continue by examining the features of several new low-frequency electrostatic waves and their excitations via instabilities, and of a few nonlinear structures. The discussions are exemplified with numerous observations and experimental results. The paper is organized in the following fashion. In Sec. II, we discuss the general properties of dusty plasmas, including the typical spatiotemporal scales of dusty plasmas, and illustrate various dust charging mechanisms. Different forces on the dust particle dynamics are discussed in Sec. III. Section IV contains the physics of dusty plasma waves (e.g., DAW, DIW, DLW), and their excitations via instabilities in an unmagnetized plasma. We also discuss the properties of nonlinear waves and structures, such as the dust acoustic and dust ion-acoustic shocks, dust voids, and dust structures or vortices. Finally, Sec. V contains a summary of our investigation, and future perspectives of dusty plasma physics.

II. PROPERTIES OF DUSTY PLASMAS

In this section, we discuss the properties of dusty plasmas. Specifically, we present typical spatial and temporal scales that are involved in dusty plasmas, and discuss the formation and charging of dust grains.

A. Typical parameter ranges for dusty plasmas

The constituents of dusty plasmas are neutral gas molecules, electrons, ions, and massive (compared to the ions) charged dust grains. There are three characteristic length scales for such an admixture of dust and plasma. These are the dust grain radius R, the dusty plasma Debye radius λ_D, and the average intergrain distance d. The latter is related to the dust number density n_{d0} by $d=(3/4\pi n_{d0})^{1/3}$. The dusty plasma Debye radius λ_D is given by (Shukla, 1994)

$$\frac{1}{\lambda_D^2}=\frac{1}{\lambda_{De}^2}+\frac{1}{\lambda_{Di}^2}, \tag{1}$$

where $\lambda_{De}=(T_e/4\pi n_{e0}e^2)^{1/2}$ and $\lambda_{Di}=(T_i/4\pi n_{i0}e^2)^{1/2}$ are the electron and ion Debye radius, respectively, T_e and T_i are the electron and ion temperatures in the energy unit, n_{e0} and n_{i0} are the unperturbed electron and ion number densities, and e is the magnitude of the electron charge. When $T_e\sim T_i$ and $n_{e0}\sim n_{i0}$, we have $\lambda_{De}\sim\lambda_{Di}$, while for $T_e\gg T_i$ and $n_{i0}>n_{e0}$ we have $\lambda_D\sim\lambda_{Di}\ll\lambda_{De}$. In dusty plasmas, we typically have $R\ll\lambda_D$. One can treat the dust from a particle dynamics point of view when $R\ll\lambda_D<d$, and in that case we have a plasma containing isolated screened dust grains, or a dust in a plasma. On the other hand, collective effects of charged dust grains become important when $R\ll d<\lambda_D$. Here charged dust grains, which are essential ingredients of the total plasma mixture, can be treated as a dust fluid similar to multiply charged negative (or positive) ions in a multispecies plasma. The equilibrium quasineutrality condition in the presence of negatively charged dust grains is given by

$$Z_i n_{i0}=n_{e0}+Z_{d0}n_{d0}, \tag{2}$$

where Z_i is the ion charge state and Z_{d0} is the number of charges residing on the dust grain. When most of the electrons from the ambient plasma are attached onto the dust grain, we have $Z_{d0}n_{d0}\gg n_{e0}$. Here the dusty plasma may be regarded approximately as a two-component plasma composed of negatively charged dust grains and positive ions; the latter shield the negative dust grains. Such a situation may be common in planetary systems (e.g., F ring of Saturn), as well as in some low-temperature dusty plasma discharges. On the other hand, in uv irradiated dusty plasmas the grains emit electrons and they can be charged positively. Then the shielding of positive dust grains comes from the electrons, and at equilibrium we have (Shukla, 2000a) $n_{e0}=Z_i n_{i0}+Z_{d0}n_{d0}$.

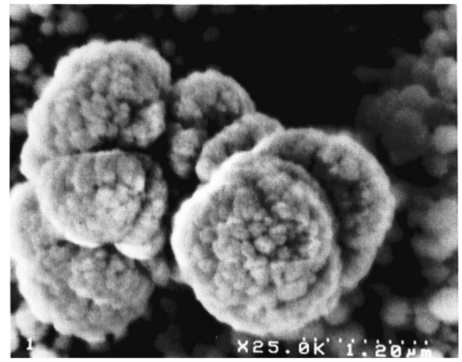

FIG. 1. Carbon grains grown in a plasma at 5.5×10^{-4} bar argon pressure and at a temperature of 300–600 K. The grains have a wide size distribution of $\sim$10 nm to $\sim$1 μm. From Praburam and Goree, 1995.

B. Formation of dust grains

Understanding the formation of dust grains in our solar system as well as in laboratory experiments is of fundamental interest. Planets form from the nebula of gas and dust that comprises the nascent solar system. Inelastic, adhesive collisions between these dust particles form kilometer-sized planetesimals, which then collide under the influence of their mutual gravity to form planets (Blum *et al.*, 2000). On the other hand, in low-temperature laboratory plasma discharges dust particles can be grown using reactive gases like silane or by ion bombardment on materials. Several groups (Praburam and Goree, 1995; Holland *et al.*, 1996; Mikikian *et al.*, 2006) have studied the growth of dust particles in laboratory discharges. For gas densities and temperatures that are typical of the nebula from which the solar system was formed (Praburam and Goree, 1995; Holland *et al.*, 1996), Fig. 1 shows an example of carbon grains grown in the experiment of Goree (1995) at a low temperature of 300–600 K. The dust particles look like tiny cauliflowers pressed together in irregular strings—a growth pattern that offers clues to the rate at which dust particles in interstellar space turned into the clumps of matter that are large enough to assemble into planets due to gravity.

C. Dust grain charging

Dust particles are charged due to a variety of processes including the bombardment of the dust grain surface by background plasma electrons and ions, photoelectron emission by uv radiation, ion sputtering, secondary electron production, etc. In low-temperature laboratory dusty plasmas dust particles usually acquire a negative charge because the thermal speed of the electrons is much higher than that of the ions. The dust grain charging process depends on the charging cross section, which is determined by the impact parameter of the electrons and ions that approach the dust grain to distances smaller than the dust particle size. Thus, the charging cross sections for the electrons and ions are given by, respectively,

$$\sigma_e(q_d,v) = \pi R^2\left(1 + \frac{2eq_d}{Rm_e v^2}\right) \tag{3}$$

and

$$\sigma_i(q_d,v) = \pi R^2\left(1 - \frac{2eq_d}{Rm_i v^2}\right), \tag{4}$$

for $v^2 > 2e|q_d|/Rm_e \equiv v_*^2$, whereas for $v^2 < v_*^2$ we have $\sigma_e(q_d,v)=0$; here $v=|\mathbf{v}|$ and q_d is the dust charge. Clearly, the electrons must have a minimum speed v_* in order to arrive at the dust grain surface. The charging equation is given by

$$\frac{\partial q_d}{\partial t} = I_e + I_e \equiv I_d(q_d), \tag{5}$$

where

$$I_d(q_d) = \sum_{s=e,i} q_s \int v\sigma_s(q_d,v) f_s(\mathbf{v}) d^3v \tag{6}$$

is the plasma current through the dust particle surface, $\mathbf{v}_d$ is the dust particle velocity, $q_e=-e$, $q_i=Z_i e$, and $f_s(\mathbf{v})$ is the velocity distribution of the particle species s.

If the dusty plasma is close to equilibrium, then the distribution function f_s can be approximated by a Maxwellian distribution (f_{s0}) with the drift velocity $\mathbf{v}_0$ between the plasma and dust particles. We then have

$$f_{s0} = \frac{n_{s0}}{(2\pi v_{ts}^2)^{3/2}} \exp\left[-\frac{(\mathbf{v}-\mathbf{v}_0)^2}{2v_{ts}^2}\right], \tag{7}$$

where n_{s0} and $v_{ts}=(T_s/m_s)^{1/2}$ are the unperturbed number density and the thermal speed of the particle specie s, respectively.

Assuming that the streaming velocities of the electrons and ions are much smaller than their respective thermal speeds, we have the following expressions for the equilibrium electron and ion currents (Mott-Smith and Langmuir, 1926; Sodha and Guha, 1971; Shukla, 1996), respectively:

$$I_{e0} = -\pi R^2 e\left(\frac{8T_e}{\pi m_e}\right)^{1/2} n_{e0} \exp\left(\frac{eq_{d0}}{RT_e}\right) \tag{8}$$

and

$$I_{i0} = \pi R^2 e\left(\frac{8T_i}{\pi m_i}\right)^{1/2} n_{i0}\left(1 - \frac{eq_{d0}}{RT_i}\right). \tag{9}$$

On the other hand, if the ion streaming speed v_0 is much larger than the ion thermal speed, then the approximate expression for the ion current is (Shukla, 1996)

$$I_{i0} \approx \pi R^2 e n_{i0} v_0\left(1 - \frac{2e\phi_g}{m_i v_0^2}\right), \tag{10}$$

where we have introduced the grain mean charge $q_{d0} = C\phi_g \approx R\phi_g$. Here C is the grain capacitance, which for spherical isolated grains is simply R, and $\phi_g < 0$ is the grain surface potential taken with respect to the plasma potential ϕ_0. This model for the grain charge applies to the case in which the grains are sufficiently far apart in comparison with the Debye radius λ_D of the dusty plasma.

At equilibrium we have $I_{e0}+I_{i0}=0$, and we obtain from Eqs. (8) and (9) the following expression:

$$v_{Te} \exp\left(\frac{e\phi_g}{T_e}\right) = \frac{n_{i0}}{n_{e0}} v_{Ti}\left(1 - \frac{e\phi_g}{T_i}\right), \tag{11}$$

which determines the surface potential ϕ_g of an isolated dust grain. The electrons are initially collected by a dust grain, due to their higher thermal speed relative to the ions. Since the grain is electrically floating (Allen, 1992; Lampe, 2001; Lampe *et al.*, 2001), it charges to a negative surface potential, $\phi_g < 0$, which decreases the electron collection and enhances the ion collection. A sphere in a thermalized hydrogen plasma floats at $\phi_g = -2.51T/e$, where we have assumed that $T_e = T_i = T$ and $n_{i0} \approx n_{e0}$.

On the other hand, when the spacing between the grains is comparable to or less than λ_D, the dust grains are closely packed. Here the difference $\Phi = \phi_g - \phi_0$ between the surface potential ϕ_g and the plasma potential ϕ_0 has a smaller magnitude than in the case with $d \gg \lambda_D$, and consequently the average charge on a dust grain q_{d0} is smaller than for an isolated dust grain (Goertz, 1989). For this case, we replace ϕ_g in Eq. (11) by Φ and replace n_{i0} and n_{e0} by the Boltzmann distributed ions and electrons, $n_i = n_{i0}\exp(-e\phi_0/T_i)$ and $n_e = n_{e0}\exp(e\phi_0/T_e)$, respectively, to obtain

$$n_{e0} v_{Te} \exp\left[\frac{e(\phi_0+\Phi)}{T_e}\right] = n_{i0} v_{Ti} \exp\left(-\frac{e\phi_0}{T_i}\right)\left(1 - \frac{e\Phi}{T_i}\right), \tag{12}$$

which together with the quasineutrality condition $Z_i e n_{i0} = e n_{e0} - q_d n_{d0}$, or

$$n_{i0} \exp\left(-\frac{e\phi_0}{T_i}\right) = n_{e0} \exp\left(\frac{e\phi_0}{T_e}\right) - R\Phi n_{d0}, \tag{13}$$

yields the values of ϕ_0 and Φ. Barkan *et al.* (1994) described the results of a laboratory experiment on the charging of dust grains in a fully ionized, steady-state plasma column. By varying the ratio d/λ_D between the intergrain spacing and the Debye radius, they observed a quantitative agreement with the predicted reduction (Goertz and Ip, 1984; Whipple *et al.*, 1985) of the grain charge for the case of closely packed grains ($d/\lambda_D < 1$). Ratynskaia *et al.* (2004) experimentally determined dust particle charge in a bulk dc discharge plasma at elevated pressures (20–100 Pa). Havnes *et al.* (1990) derived formulas for dust charges and plasma potentials in plasmas with dust charge distributions. The effect of negative ions on the charging of dust particles in a single-ended Q machine was investigated by Kim and Merlino (2006). Analysis of the current-voltage characteristics of a Langmuir probe revealed evidence for the reduction in the magnitude of the negative dust charge and the transition to positively charged dust as the relative concentration of residual electrons is reduced in the dusty plasma with negative ions. However, one distinguishing feature of a dusty plasma compared to a negative ion plasma is the fact that the charge on the dust is not fixed, but varies in response to variations in the plasma potential.

III. FORCES ACTING ON THE DUST GRAINS

There are a number of forces (Whipple, 1981; Nitter, 1996; Shukla and Mamun, 2002; Bleeker *et al.*, 2005) that act on dust grains, and which control their dynamics. These are the force due to gravity, the self-gravitational force, the thermophoretic force, the electrostatic and electromagnetic forces, the radiation pressure force, and the drag forces of neutral atoms and ions that bombard the dust grain. Furthermore, mutual interactions between charged dust particles produce the near-field Debye-Hückel (DH) potential (also referred to as the Yukawa potential), the modified DH potential due to the overlapping Debye spheres, the dipole-dipole potential between large dust particles having a nonuniform charge distribution, and the far-field wake potential around a dust grain in a plasma with streaming ions. In the following, we present a short overview of these forces and their importance in different physical settings.

A. Force of gravity

A dust particle in the plasma is subject to gravity and the exerted force is proportional to the dust particle mass density $\rho_d = n_d m_d$ ($\rho_d \simeq 2.3\ \mathrm{g/cm^3}$ for amorphous silicon). For a spherical dust particle, the gravity force reads

$$\mathbf{F}_g = \frac{4\pi R^3}{3}\rho_d \mathbf{g}, \tag{14}$$

where $\mathbf{g}$ is the gravitational acceleration. The gravitational force is important in radio-frequency discharges, where the dust particle is pulled downward toward the lower electrode.

In a self-gravitating system, the force acting on a dust grain is

$$\mathbf{F}_g = -\frac{G\rho_d M\mathbf{r}}{r^3}, \tag{15}$$

where $G = 6.672\times10^{-8}\ \mathrm{dyn\,cm^2\,g^{-2}}$ is the gravitational constant and $\mathbf{r}$ is the distance to the dust grain from the central body of mass M. The central body may be a nearby planet, a star, or a satellite. Roughly speaking, in our solar system the dynamics of dust grains with radius larger than 1 μm are dominated by the gravitational force, while sub-μm dust is dominated by electrodynamic and radiation pressure forces (Grün and Landgraf, 2001). For a distribution of masses, the force is

$$\mathbf{F}_g = -\rho_d \nabla \psi, \tag{16}$$

where the potential ψ is obtained from the gravitational Poisson equation

$$\nabla^2 \psi = 4\pi G \rho_d. \tag{17}$$

The self-gravitational force may be important for molecular clouds (Verheest, 2000) and dust elevated above Saturn's rings (Mitchell *et al.*, 2006).

B. Thermophoretic force

In the presence of the neutral gas temperature gradient ∇T_n, the dust particles feel a force $\mathbf{F}_T$, which is referred to as the thermophoretic force. A gas temperature gradient is produced by heating or cooling of one of the electrodes, and causes a dust particle movement to cooler regions of the plasma. Gas molecules in the hotter region have large velocities and hence impart more momentum to the dust particles than gas molecules in the cooler region. This causes a net force in the direction of $-\nabla T_n$. When the mean free path of the neutral particles is larger than the dust particle radius R, the thermophoretic force acting on a spherical dust particle in a monatomic gas reads (Talbot *et al.*, 1980)

$$\mathbf{F}_T = -\frac{8\sqrt{2\pi}R^2}{15 v_{tn}}\left[1 + \frac{5\pi}{32}(1-\alpha)\right]\kappa_T \nabla T_n, \tag{18}$$

where $v_{tn} = (T_n/m_n)^{1/2}$ is the average thermal speed of the neutral atoms, κ_T is the translational part of the thermal conductivity, and the accommodation coefficient α is of order unity for surface and gas temperatures between 300 and 500 K. A more general expression for the thermophoretic force has been given by Daugherty and Graves (1995).

The effect of the neutral temperature gradient on dust structure formations in a positive column of a glow discharge dusty plasma has been studied experimentally by Balabanov *et al.* (2001) and Vasilyak *et al.* (2005). It was found that the thermophoretic force plays an essential role in the formation of different shapes of plasma-dust structures. Rothermal *et al.* (2002) showed that the thermophoretic force may lift up micron-sized dust particles in plasmas under microgravity conditions. Possible technological applications of thermophoresis may include size-selective fine particle production in a reactive

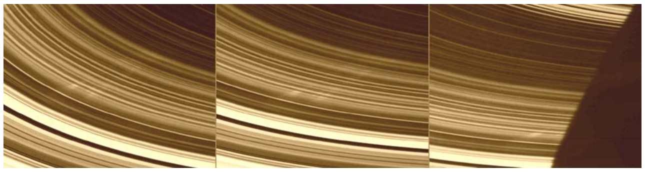

FIG. 2. (Color online) Spokes observed 2005 in Saturn's B ring by the Cassini spacecraft. Images courtesy of NASA/Jet Propulsion Laboratory.

plasma and surface plating of nanoparticles. It has been proposed that the theromophoretic force may also play a decisive role in production of semiconductors (Jellum *et al.*, 1991), as well as in fabrication of amorphous solar cells (Cabarrocas *et al.*, 1998).

C. Electrostatic force

In the presence of an electric field $\mathbf{E}$ in the plasma, the force acting on a conducting dust particle is

$$\mathbf{F}_e = q_d \mathbf{E}_{\mathrm{eff}}, \tag{19}$$

where the effective electric field in the plasma is (Fortov *et al.*, 2004b)

$$\mathbf{E}_{\mathrm{eff}} = \mathbf{E}\left[1 + \frac{R/\lambda_D}{3(1+R/\lambda_D)}\right]. \tag{20}$$

An increase in $\mathbf{E}_{\mathrm{eff}}$ compared to $\mathbf{E}$ is associated with the plasma polarization in the vicinity of the dust particle, which is induced by the external electric field. However, the plasma polarization effect is small for $R/\lambda_D \ll 1$.

The electric force acting on a negatively charged dust grain is upward, away from the electrode that is on the bottom in the plasma sheath, and dust grains can be levitated on account of a balance between the upward electric force and downward gravity force. Under microgravity conditions, negatively charged dust grains will always be upheld in the plasma sheath.

Furthermore, the lifting of dust grains by the electrostatic force is also thought to be responsible for the "spokes" in Jupiter's B and F rings detected by the Voyager 1 and 2 spacecrafts in the early 1980s (Collins *et al.*, 1980; Smith *et al.*, 1982), by the Hubble Space Telescope from 2004 until October 1998 (McGhee *et al.*, 2005), and by the Cassini spacecraft in 2005 (Mitchell *et al.*, 2006). The spokes, depicted in Fig. 2, appear as radial markings on the rings. The markings observed by Voyager 2 were bright for forward-scattered light but dark for backward-scattered light (Smith *et al.*, 1982), and this led to the idea that the spokes consist of micron-sized icy particles that are lifted above the ring disk by the electrostatic force.

D. Radiation pressure force

In the presence of the electromagnetic radiation, dust grains are subject to the radiation pressure force

$$\mathbf{F}_r = \frac{\pi r_d^2 I_0}{c}\hat{\mathbf{R}}, \tag{21}$$

where I_0 is the photon energy flux along the direction $\hat{\mathbf{R}}$. This approximate expression is valid when all photons are absorbed by the dust grain and the dust grain is much larger than the wavelength of the radiation. More general expressions have been given by Bliokh (1995) for cases in which the dust grain reflects and emits radiation. The radiation pressure force is important for submicron particles that are generated close to the Sun and are driven out of the solar system on hyperbolic orbits. Such particles (β meteorids) have been observed by the Pioneer 8, 9 and Ulysses spacecrafts (Grün and Landgraf, 2001) in the solar wind.

E. The neutral drag force

A neutral drag force results from collisions with neutral gas molecules and causes a momentum transfer from the neutral gas to the dust particles. The neutral drag force for a Maxwellian distribution of neutral gas molecules is approximated by (Baines *et al.*, 1965; Boeuf and Punset, 1999; Shukla and Mamun, 2002)

$$\mathbf{F}_{dn} = -\tfrac{8}{3}\sqrt{2\pi}R^2\rho_n v_{tn}(\mathbf{v}_d - \mathbf{v}_n), \tag{22}$$

where $\rho_n = n_n m_n$ is the mass density of the neutral molecules, and $\mathbf{v}_n$ is the velocity of the neutral molecules. Assuming that the neutral molecules are at rest ($\mathbf{v}_n = \mathbf{0}$), we observe that the neutral drag force will simply act as a damping force, and hence it will cause a deceleration of the dust particles.

F. The ion-drag force

The ion-drag force $\mathbf{F}_{\mathrm{ion}}$ in plasmas arises due to collisions between drifting ions and charged dust grains. The force basically describes the momentum transfer from the drifting ions to the dust particles on account of (i) direct collection of momentum for ions that collide with the negatively charged grain, and (ii) deflection of the ions in the electrostatic field of the negatively charged dust grain. Thus, the ion-drag force is the sum of the collection and Coulomb forces, viz., $\mathbf{F}_{\mathrm{ion}} = \mathbf{F}_{\mathrm{coll}} + \mathbf{F}_{\mathrm{Coul}}$. Barnes *et al.* (1992) presented a derivation of $\mathbf{F}_{\mathrm{ion}}$ by supposing that there is no interaction between the ions and dust particles outside the Debye sphere, and the ion mean free path is larger than the Debye radius. The last assumption is justified only for relatively low gas pressures. Assuming that the dust particles are at rest, the collection force is given by

$$\mathbf{F}_{\mathrm{coll}} = \pi b_c^2 \rho_i v_s \mathbf{v}_i, \tag{23}$$

where $\rho_i = n_i m_i$ is the ion mass density, $\mathbf{v}_i$ is the ion streaming velocity, $v_s = (v_i^2 + 8T_i/\pi m_i)^{1/2}$ is the mean speed of ions approaching the dust particle, and $b_c = R(1 - 2Z_i e\phi_f/m_i v_s^2)^{1/2}$ is the maximum impact parameter for dust-ion collision from the orbital motion limited probe theory. Here ϕ_f is the floating potential of the dust particle. The orbital motion limited treatment is justified if the potential can be treated as spherically symmetric and $R < \lambda_D$.

The Coulomb (also referred to as the orbital force) force can be written as

$$\mathbf{F}_{\mathrm{Coul}} = 4\pi b_{\pi/2}^2 \Gamma \rho_i v_s \mathbf{v}_i, \tag{24}$$

where $b_{\pi/2} = q_d e / m_i v_s^2$ and $\Gamma = (1/2)\ln[(\lambda_D^2 + b_{\pi/2}^2)/(b_c^2 + b_{\pi/2}^2)]$ are the impact parameter for 90° deflection and the Coulomb logarithm, respectively.

The theory of Barnes *et al.* (1992) for the ion-drag force has been revised by Khrapak *et al.* (2002, 2003, 2005) accounting for the strong ion-dust coupling. The appropriate collection and Coulomb forces are found to be, respectively (Hutchinson, 2006),

$$|\mathbf{F}_{\mathrm{coll}}| = 2\pi R^2 n_i T_i G_0(s) \tag{25}$$

and

$$|\mathbf{F}_{\mathrm{Coul}}| = \frac{4\pi n_i Z_i^2 e^2 R^2}{T_i} G_c(u) \ln \Lambda, \tag{26}$$

where $G_0(s) = (s^2 + 1 - 1/4s^2)\mathrm{erf}(s) + (1/\sqrt{\pi})(s + 1/2s) \times \exp(-s^2)$, $s = \sqrt{m_i \mathbf{v}_f^2 / 2T_i}$, $G_c(s) = [\mathrm{erf}(s) - 2u\exp(-s^2)/\sqrt{\pi}]/2s^2$, $\mathbf{v}_f$ is the ion flow velocity, and $\Lambda = (b_{\pi/2} + \lambda_D)/(b_{\pi/2} + R)$.

Extensive particle-in-cell simulation studies by Hutchinson (2002, 2003, 2005) include the effects of ion collection by the spherical dust grain at different temperature ratios between ions and electrons and at different flow speeds. From these studies, an analytic expression for the drag force is provided, which fits the numerical results for a large range of parameters (Hutchinson, 2006). Nosenko *et al.* (2007a) measured experimentally the ion-drag force on drag grains in a low-pressure Ar plasma in the regime of strong ion-dust coupling. The result is in agreement with the theoretical model of Khrapak *et al.* (2003).

G. Potential distribution in collisional plasmas

The potential around a pointlike test dust particle in a collisional electron-ion unmagnetized plasma containing an equilibrium ion stream was calculated by Ivlev *et al.* (2004). It was found that the ion-neutral collisions, in combination with the ion drift, enhance the far-field potential. Castaldo *et al.* (2006) developed a theory for the potential around a dust particle, accounting for the ion-dust and ion-neutral collisions. They found that the dust grain screening is strongly influenced by the collisions and can substantially differ from the DH shielding. They also depicted that attraction of negatively charged dust grains can occur owing to overscreening by the ion fluxes in the presence of frictional forces. Khrapak *et al.* (2007) have shown that the electrostatic interaction potential between a pair of positively charged dust particles in a highly collisional plasma has a long-range attractive asymptote. The effect is due to continuous plasma absorption on the dust particles (Chaudhuri *et al.*, 2007). At this point, we mention that in the early 1970s Stenflo *et al.* (1973) and Stenflo and Yu (1973) had already predicted a dipolelike potential of a moving test charge in a highly collisional electron-ion plasma without dust grains.

H. The force due to the overlapping Debye spheres

The overlapping Debye spheres around dust grains produce an attractive force (Resendes *et al.*, 1998). The interaction energy of the sheath of the one grain with the bare charge of the other grain is

$$W_s(r) = -\frac{q_d^2}{2\lambda_D} \exp(-r/\lambda_D), \tag{27}$$

where the grains are assumed to have identical charges, and the DH interaction energy is

$$W_{\mathrm{DH}} = \frac{q_d^2}{r} \exp(-r/\lambda_D). \tag{28}$$

The sum $W_s + W_{\mathrm{DH}}$ exhibits a distribution that is similar to the Lennard-Jones potential, i.e., a strong repulsion at a short distance, and a weak attraction at longer distances (beyond $r = 2.73\lambda_D$).

I. Forces due to absorption of plasma particles

Long-range interactions between charged dust particles can also occur due to absorbing plasma particles. Continuous absorption of electron and ion fluxes on the dust grain produce an anisotropy in the velocity distribution functions of electrons and ions. This anisotropy is much more important for ions, especially when the electron temperature is larger than the ion temperature. The long-range repulsive electrostatic potential in a quasineutral plasma is $\phi(r) = (q_d/R)R/r^2$, so that at large distance between the grains the energy of electrostatic interaction is (Khrapak *et al.*, 2006)

$$W_{\mathrm{el}}(r) \approx \frac{q_d^2 R}{2r^2}. \tag{29}$$

The transition from the DH potential to the long-range asymptote occurs roughly at $r \sim \lambda_D \ln(\lambda_D/R)$.

There is also a long-range shadowing force associated with the continuous absorption of the plasma electrons and ions on the dust grains, since a drag is experienced by neighboring grains. It results in an attractive force between the dust grains, and is referred to as the shadowing force (Tsytovich, 1997). This effect is also mainly associated with the ions and basically represents the ion-drag force in the ion flow directed to the surface of a given grain. The attractive interaction energy associated with the shadowing force is (Khrapak *et al.*, 2006)

$$W_{\mathrm{sh}}(r) \approx -4\sqrt{\pi}(R/r) n_i T_i \lambda_D^3 \beta_T^2 W(\beta_T), \tag{30}$$

where $\beta_T = Z_d^2 e^2 / T_i \lambda_D$ and $W(x)$ is a relatively weak function of the argument. For example, in the range $0.1 \leqslant x \leqslant 10$, we have $W(x) \approx 0.3 \pm 0.1$.

J. The wake potential

The concept of the wakefield in dusty plasmas was introduced by Nambu *et al.* (1995). The oscillating wakefield arises due to the resonance interaction between the DIA and DAW and a test dust charge that moves with a speed close to the dust ion-acoustic or dust acoustic speeds. Negatively charged dust grains feel an attractive force in the negative part of the oscillatory wake potential (Nambu *et al.*, 1995; Vladimirov and Nambu, 1995; Shukla and Rao, 1996; Ishihara and Sato, 2005), where the positive ions are focused. Hence, there appears Cooper pairing of negative dust grains, which are glued by ions. The one-dimensional wake potential of a test charge in the presence of the DAW in an unmagnetized plasma is given by (Shukla and Rao, 1996)

$$\phi_w(\rho=0,\xi_t,t)=\frac{q_t}{\xi_t}\cos\left(\frac{\xi_t}{L}\right), \tag{31}$$

where $\xi_t=|z-v_t t|$, q_t is the charge of the test particle, $L=\lambda_D[(v_t-V_0)^2-C_D^2]^{1/2}/C_D$ is the effective length, v_t is the test particle velocity, V_0 is the equilibrium ion streaming velocity, $C_D=\omega_{pd}\lambda_D$ is the DAW speed, ω_{pd} is the dust plasma frequency, and ρ and z are the radial and axial coordinates in a cylindrical geometry. The wake potential can dominate over the Debye-Hückel potential due to the exponential decrease of the latter at large distances. We note that the wake potential is attractive for $\cos(\xi_t/L)<0$, which implies the alignment of dust grains in a dusty plasma with streaming ions (Vladimirov and Nambu, 1995; Shukla and Rao, 1996). For $|v_t-V_0| \sim 30$ cm/s, $\lambda_D\sim 300$ μm, and $C_D\sim 6$ cm/s, we find that $L\sim 1$ mm, which is in agreement with observations (Chu *et al.*, 1995). The concept of the wakefield and subsequent attraction of negatively charged dust grains in a linear chain have been verified both by computer simulations (Melandsø and Goree, 1995; Lampe *et al.*, 2000; Lapenta, 2000; Lemons *et al.*, 2000; Winske *et al.*, 2000) and in dusty plasma experiments (Takahashi *et al.*, 1998; Melzer *et al.*, 1999). Figure 3 shows the result of a particle-in-cell simulation by Lampe *et al.*, (2000). Near the origin, the potential is strongly negative, while a positive wake potential can be seen behind the dust grain.

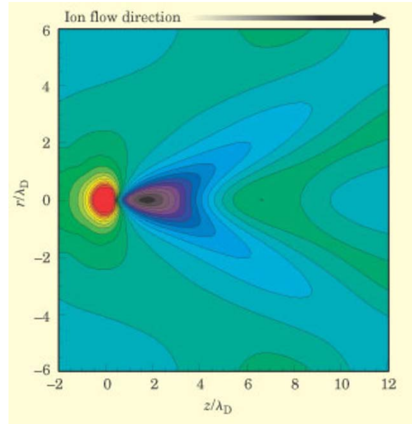

FIG. 3. (Color online) Contour plot of the potential obtained by a particle-in-cell simulation (Lampe *et al.*, 2000). The ions are flowing from left to right along the z axis, past the negatively charged dust grain located at the origin $z=0$, $r=0$. A strongly negative potential is observed at the dust grain and a positive potential in the wake behind the dust grain. From Merlino and Goree, 2004.

K. Dipole-dipole interactions

In a strongly coupled dusty plasma, we have the possibility of dipole-dipole interactions (Lapenta, 1995, 1999; Lee *et al.*, 1997; Lapenta and Brackbill, 1998; Mohideen *et al.*, 1998; Resendes, 2000; Tskhakaya and Shukla, 2004) if the dust grains are large and have an irregular shape. Here the charging of the dust rod will be uneven. The attractive dipole-dipole force between aligned dipoles separated by a distance d, taking into account the screening by the background plasma, is given by (Mohideen *et al.*, 1998)

$$F_{\rm dd}=\frac{6P^2}{d^4}(1+\kappa_d+\tfrac{1}{2}\kappa_d^2+\tfrac{1}{2}\kappa_d^3)\exp(-\kappa_d), \tag{32}$$

where $P=E_0R^3$ is the induced dipole moment. The latter appears because the sheath electric field E_0 induces a polarization on the dust grains.

The attractive dipole-dipole force may be responsible for attracting large particles and for subsequent formation of dust structures (Mohideen *et al.*, 1998), as well as planetesimals or planetary seedlings (Blum *et al.*, 2000; Bingham and Tystovich, 2001).

L. Interactions between magnetic particles

If the dust particles have magnetic properties, they get magnetized in the external magnetic field, and would obtain a magnetic moment (Jackson, 1975)

$$\mathbf{m}=\frac{(\mu-1)}{(\mu+2)}R^3\mathbf{B}, \tag{33}$$

where μ is the magnetic permeability. Such a magnetized dust grain is subjected to a magnetic force

$$\mathbf{F}_m=(\mathbf{m}\cdot\boldsymbol{\nabla})\mathbf{B}. \tag{34}$$

The induced magnetic dipoles of magnetized particles interact with each other via a dipole magnetic force. The magnetic interaction potential is $U_{\rm mag}=-\mathbf{m}\cdot\mathbf{B}$. The interaction potential of two magnetic dipoles is (Samsonov *et al.*, 2003b)

$$U_{\rm mag}=\left[\frac{\mathbf{m}_1\cdot\mathbf{m}_2}{r^3}-\frac{3(\mathbf{m}_1\cdot\mathbf{r})(\mathbf{m}_2\cdot\mathbf{r})}{r^5}\right], \tag{35}$$

where $\mathbf{r}$ is the radius vector between the grains, and the subscript 1 or 2 denotes different dust particles. If the dipole moments are parallel and have equal magnitude, the magnetic interaction force of identical dipoles (m_1

$=m_2=m$) is given by (Samsonov *et al.*, 2003b)

$$\mathbf{F}_{\mathrm{mag}} = -\nabla U_{\mathrm{mag}} = \frac{3m^2}{r^4}[-\mathbf{n}_r(5\cos^2\theta - 1) + 2\mathbf{n}_m \cos\theta], \tag{36}$$

where $\mathbf{n}_m$ and $\mathbf{n}_r$ are the unit vectors in the direction of the magnetic moment and $\mathbf{r}$ ($\mathbf{m}=m\mathbf{n}_m$ and $\mathbf{r}=r\mathbf{n}_r$), respectively, and θ is the angle between $\mathbf{n}_m$ and $\mathbf{n}_r$. If the dust particles levitate in the same plane with their magnetic moments perpendicular to this plane ($\theta=\pi/2$), the interaction force is repulsive, i.e., $F_{\mathrm{rep}}=3m^2/r^4$, while if the dust grains are arranged in a line along the same axis as their magnetic moments ($\theta=0$), we have the attractive interaction force $F_{\mathrm{attr}}=-6m^2/r^4$.

IV. WAVES AND STRUCTURES IN DUSTY PLASMAS

The addition of an ensemble of charged dust particles in an electron-ion plasma can modify or even dominate the wave propagation, the wave instability, the wave scattering, etc. The modifications occur since there is a departure from the conventional quasineutrality condition in an electron-ion-dust plasma due to the presence of charged dust grains. In dusty plasmas, there also appear new waves that are associated with the dust particle dynamics at kinetic levels. In this section, we discuss the physics of the dust acoustic, dust ion-acoustic, and dust lattice waves, which have been experimentally observed. The amplitudes and spectra of dusty plasma fluctuations provide novel diagnostic tools, as demonstrated by Ratynskaia *et al.* (2007). Nonlinear waves and structures in dusty plasmas arise when the wave amplitudes are large so that the nonlinearities come into the picture. When the nonlinearities balance the dissipation (due to a kinematic viscosity associated with the dust charge fluctuation), we have the possibility of shock waves (Popel *et al.*, 2004). Bare solitons and vortices, which are localized excitations, are formed due to a balance between the medium nonlinearities and the wave dispersion. While solitons can form in one space dimension, vortices are associated with multidimensional perturbations in a nonlinear dispersive media. In the following, we discuss important nonlinear waves and structures in dusty plasmas.

A. Dust ion-acoustic waves

The existence of the dust ion-acoustic wave (DIAW) in an unmagnetized plasma was theoretically predicted by Shukla and Silin (1992), although a previous work (D'Angelo and Song, 1990) on electrostatic waves in magnetized dusty plasmas had discussed the properties of the DIAW. The latter in an unmagnetized dusty plasma occurs in the frequency range kv_{Td}, kv_{Ti}, ω_{pd}, $\nu_{in} \ll |\omega| \ll kv_{Te}$, ω_{pi}, where ω_{pi} is the ion plasma frequency. During the ion plasma period ($2\pi/\omega_{pi}$), the inertialess electrons follow the Boltzmann distribution, while the ions are inertial and the dust grains remain stationary. The restoring force in the DIAW comes from the electron pressure, and the ion mass provides the inertia. The dust effect enters through the equilibrium quasineutrality condition, which dictates that $n_{i0} > n_{e0}$ when the dust grains are negatively charged. The electron density depletion occurs since a fraction of the background plasma electrons are attached onto the dust grains during the dust grain charging.

1. Linear dust ion-acoustic waves

In the presence of the DIAW in a dusty plasma, the electron susceptibility χ_e is given by Eq. (43), while the ion susceptibility reads (Nakamura *et al.*, 1999)

$$\chi_i \approx -\frac{\omega_{pi}^2}{\omega(\omega + i\nu_{in}) - 3k^2 v_{Ti}^2}, \tag{37}$$

where ν_{in} is the effective ion collision (with dust and neutrals) frequency.

Neglecting the dust charge fluctuation effect, we obtain the frequency of the DIAW for $|\omega| > \nu_{in}$ as (Shukla and Silin, 1992)

$$\omega = \frac{k\lambda_{De}\omega_{pi}}{(1 + k^2\lambda_{De}^2)^{1/2}}, \tag{38}$$

which for $k^2\lambda_{De}^2 \ll 1$ reduces to

$$\omega = kC_s, \tag{39}$$

where $C_s=(n_{i0}/n_{e0})^{1/2}(T_e/m_i)^{1/2}$ is the dust ion-acoustic speed. We note in Eq. (39) that the DIAW phase speed ω/k increases with the relative concentration of negatively charged dust grains, where we have $n_{i0} > n_{e0}$.

Barkan *et al.* (1996) performed an experiment in a dusty plasma device to investigate the propagation and damping of the DIAW. They found that the phase speed of the latter increases in accordance with Eq. (39). As a consequence of the phase speed increase, the ion Landau damping rate is significantly reduced. The observed DIAW frequencies were in the range 3–5 kHz (depending on the value of $Z_d n_{d0}/n_{i0}$), which agree well with the theoretical prediction (Shukla and Silin, 1992).

The formation of DIA shock structures in dusty plasmas has been observed by Luo *et al.* (1999, 2000) and Nakamura *et al.* (1999). Luo *et al.* (1999, 2000) presented an experimental investigation of the effect of negatively charged dust grains on the DIA shock formation in a Q machine. They observed that dust ion-acoustic compressional pulses steepened as they traveled through a dusty plasma if the percentage of the negative charges in the plasma on the dust grains is greater than 75%. Nakamura *et al.* (1999) found that, in the linear regime, the phase speed of the DIA wave increases and the wave suffers heavy damping when the dust number density in an electron-ion plasma is considerably increased. Furthermore, Nakamura *et al.* (1999) found that an oscillatory ion-acoustic shock wave in a usual argon plasma transforms into a monotonic shock front when it travels through the dusty plasma column. Here the formation of the shock structure is due to a balance between the harmonic nonlinearity and the kinematic viscosity caused

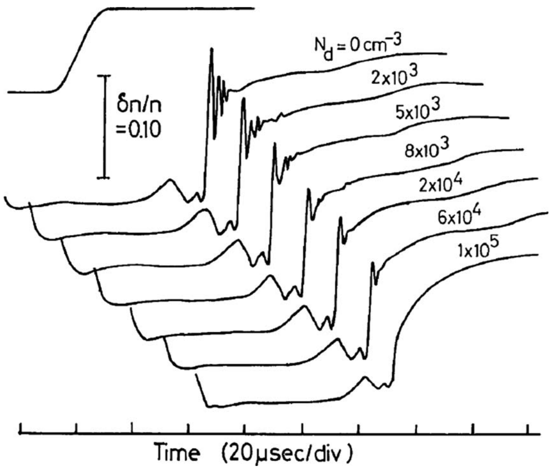

FIG. 4. Dust ion-acoustic shocks at different dust densities. At large dust densities, the oscillatory shock is transformed into a monotonic shock due to the viscosity induced by the dust charge perturbation. Larger dust densities lead to larger shock speeds. From Nakamura *et al.*, 1999.

by the dust charge perturbation. The dynamics of the shock structure associated with DIA waves is modeled by the Korteweg–de Vries–Burgers equation (Mamun and Shukla, 2002)

$$\frac{\partial\Phi}{\partial\tau} + A\Phi\frac{\partial\Phi}{\partial\xi} + B\frac{\partial^3\Phi}{\partial\xi^3} - C\frac{\partial^2\Phi}{\partial\xi^2} = 0, \tag{40}$$

where $\Phi = e\phi/T_e$, and the coefficients A, B, and C are given by Mamun and Shukla (2002). Equation (40) has been derived from the hydrodynamic equations (comprising the Boltzmann electron density distribution and the continuity and momentum equations for the ions), together with the dust charge fluctuation and Poisson equations, by employing the standard reductive perturbation method and the stretched variables $\xi = \epsilon^{1/2}(x - \lambda t)$ and $\tau = \epsilon^{3/2}t$, where ϵ is a smallness parameter and x and t are in units of the electron Debye length and the ion plasma period. The C term in Eq. (40) accounts for the dust charge perturbation effect. When the dust charge induced kinematic viscosity dominates over the dispersion, Eq. (40) assumes the form of a Burgers equation. The latter, viz., Eq. (40) without the ∂_ξ^3 term, admits a monotonic shock profile, as observed by Nakamura *et al.* (1999); see Fig. 4.

B. The dust acoustic wave

The dust acoustic wave (DAW) is the most fundamental excitation of the dusty plasma. The existence of the DAW was predicted by Shukla (1989), and a theory for linear and nonlinear DAWs was later presented by Rao *et al.* (1990), taking into account the dust particle dynamics and Boltzmann electron and ion density distributions. In the DAW, the restoring force comes from the electron and ion pressures while the dust mass provides the inertia to maintain the DAW. The DAW has an extremely low phase speed $v_p = \omega/k$ (in comparison with the electron and ion thermal speeds) and frequency (tens of Hz in laboratories), so that its visual images are possible (Barkan *et al.*, 1995; Prabhakara and Tanna, 1996). Early observations of low-frequency oscillations with a frequency of $\sim$12 Hz and a wavelength of $\sim$0.5 cm by Chu *et al.* (1994) were later interpreted by D'Angelo (1995) as the DAW. Figure 5 displays an observation of the DAW in the experiment by Barkan *et al.* (1995), where the clearly visible DAW has a wavelength of approximately 0.6 cm and a speed of $\sim$9 cm/s, and hence a frequency of $\sim$15 Hz. The observation is in excellent agreement with the theory of Rao *et al.* (1990).

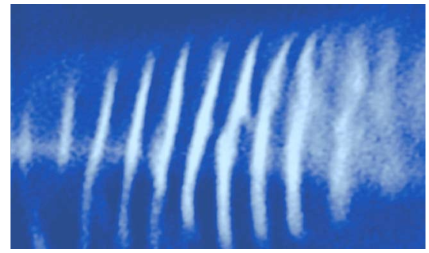

FIG. 5. (Color online) The dust acoustic wave with a wavelength of $\sim$0.6 cm, a frequency of $\sim$15 Hz, and a phase speed of $\sim$9 cm/s. From Barkan *et al.*, 1995.

1. Linear theory

Traditionally, the spectra of dusty plasma waves are obtained by Fourier analyzing the Vlasov, Poisson, and Maxwell equations, supplemented by the dust charging equation. In a dusty plasma, the properties of the electrostatic waves are determined from

$$\epsilon(\omega, \mathbf{k})\phi = 0, \tag{41}$$

where ϕ is the wave potential and

$$\epsilon(\omega, \mathbf{k}) = 1 + \chi_e + \chi_i + \chi_d + \chi_{qe} + \chi_{qi} \tag{42}$$

is the dielectric constant. Here χ_d is the dust particle susceptibility, and χ_{qe} and χ_{qi} are the linear susceptibilities associated with the dust charge fluctuation dynamics. In dusty plasmas, the electrons and ions are weakly coupled, and for $|\omega| \ll \nu_{en}| \ll kv_{Te}$, $|\omega| \ll \nu_{in}| \ll kv_{Ti}$, we have

$$\chi_e \approx \frac{1}{k^2\lambda_{De}^2} \tag{43}$$

and

$$\chi_i \approx \frac{1}{k^2\lambda_{Di}^2}. \tag{44}$$

Correspondingly, we will have the Boltzmann density distribution for the electrons and ions, namely, $n_{e1} = n_{e0}e\phi/T_e$ and $n_{i1} = -n_{i0}e\phi/T_i$, respectively.

When the dust grains are weakly coupled, we obtain for $|\omega| \gg \nu_{dn}, kv_{Td}$, the dust grain susceptibility

$$\chi_d \approx -\frac{\omega_{pd}^2}{\omega(\omega + i\nu_{dn}) - 3k^2 v_{Td}^2}, \tag{45}$$

where $v_{Td}=(T_d/m_d)^{1/2}$ is the dust thermal speed, ν_{dn} is the dust-neutral collision frequency, and $\omega_{pd} = (4\pi Z_{d0}^2 e^2 n_{d0}/m_d)^{1/2}$ is the dust plasma frequency.

For negatively charged dust grains, we have (Shukla, 1996; Shukla and Resendes, 2000)

$$\chi_{qe} + \chi_{qi} = \frac{f_d \nu_2}{k^2 \lambda_D^2 (\nu_1 - i\omega)}. \tag{46}$$

For ν_{dn}, $kv_{Td} \ll |\omega| \ll \nu_1$, we obtain the DAW frequency

$$\omega = \frac{k\lambda_d \omega_{pd}}{(1 + k^2\lambda_d^2)^{1/2}}, \tag{47}$$

which for $f_d \nu_2/\nu_1 \ll 1$ and $k^2\lambda_D^2 \ll 1$ reduces to (Rao *et al.*, 1990)

$$\omega = kC_D. \tag{48}$$

Here $C_D = Z_d (n_{d0}/n_{i0})^{1/2} (T_i/m_d)^{1/2} (1 + n_{e0}T_i/n_{i0}T_e)^{1/2}$ is the dust acoustic speed (Rao *et al.*, 1990). The effect of the dust distributions on the DAW has been examined by Verheest *et al.* (2003).

Using Eq. (48), the wave phase speed $v_p = \omega/k$ can be estimated (D'Angelo, 1995) if one knows the plasma and dust parameters. Chu *et al.* (1994) in their experiment had $R \approx 1$ μm, $n_{d0}m_d \approx 1$ g/cm^3 (and thus $m_d \approx 4 \times 10^{-12}$ g), $T_e = 2.6$ eV, $T_i = 0.26$ eV, and $T_d = 10^{-2}T_e$. The number of charges on each dust grain is $Z_d \sim 8100$. The average intergrain distance is of the order of 300 μm, from which $n_{d0} \sim 3.7 \times 10^4$ cm^{-3} is obtained. The electron number density is $n_{e0} \sim 5 \times 10^9$ cm^{-3}. For this set of parameters, Eq. (48) depicts $v_p = \omega/k \sim 7$ cm/s, which is to be compared with the observed $v_p = f_w \times \lambda_w = 12$ Hz $\times 0.5$ cm $= 6$ cm/s in the experiment. Furthermore, in a plasma with $n_{e0}T_i \ll n_{i0}T_e$, we have $C_D = Z_d (T_i/m_d)^{1/2} (n_{d0}/n_{i0})^{1/2}$. For dust grains of ~ 5 μm size, $m_d \sim 10^{-12}$ kg, $Z_d \approx 4 \times 10^4$, and $n_{d0}/n_{i0} \approx 10^{-8}$, we obtain $C_D \sim 8$ cm/s, which is in good agreement with the observations (Barkan *et al.*, 1995; Merlino *et al.*, 1998) where $v_p \sim 9$ cm/s was reported. Hence, for $\lambda_w \approx 0.6$ cm we obtain the DAW frequency $f_w \sim 15$ Hz.

A recent paper (Thomas *et al.*, 2007) reported observations of high-frequency dust acoustic waves (>100 Hz). The latter may be due to the high dust temperature (in comparison with the electron and ion temperatures) arising from the dust grain heating. In fact, Williams and Thomas (2007) reported measurements of the kinetic temperature of the dust grains in plasmas containing electrons, ions, and two components of dust. They found that the dust components have significantly larger temperature than those of the electrons and ions.

In a collisional dusty plasma, the spatial attenuation rate of the DAWs is determined from (Pieper and Goree, 1996)

$$k^2 = \frac{1}{\lambda_d^2} \frac{\omega(\omega + i\nu_{dn})}{\omega_{pe}^2 - \omega(\omega + i\nu_{dn})}, \tag{49}$$

where $k = k_r + ik_i$, k_r (k_i) is the real (imaginary) part of the wave number, and ω is real. Tsytovich *et al.* (2001) reconsidered the effect of dust-neutral collisions on the DAW dispersion relation, and found a minor modification. Stenflo *et al.* (2000) presented an investigation of the dust acoustic surface wave on a dusty plasma slab. The DAW can be used for the diagnostics of nanometer-sized dust particles in processing plasmas (Kortshagen, 1997), since the DAW phase speed is inversely proportional to $\sqrt{m_d}$, which depends on the dust particle radius.

2. Dust acoustic waves in strongly coupled plasmas

Electrostatic waves in strongly coupled dusty plasmas have been theoretically investigated (Rosenberg and Kalman, 1997; de Angelis and Shukla, 1998, 1999; Kaw and Sen, 1998; Murillo, 1998; Winske *et al.*, 1999). Strongly coupled dusty plasmas can be in the crystalline (solid) or liquid phases. Rosenberg and Kalman (1997) investigated the effect of strong dust coupling on the DAW by supposing that charged dust grains interact with each other via the Yukawa potential

$$\phi_D(r) = \frac{q_d^2}{r} \exp\left(-\frac{r}{\lambda_D}\right), \tag{50}$$

with the exponential factor taking into account the screening of the dust charge by the plasma electrons and ions, which are weakly correlated. The quasilocalized charge approximation was then used to derive the frequency of the DAW (Rosenberg and Kalman, 1997),

$$\omega = \omega_{pd}\left[\frac{k^2d^2}{k^2d^2 + \kappa_d^2} + D(k,\Gamma)\right]^{1/2}, \tag{51}$$

in the liquid phase. Here $\kappa_d = d/\lambda_D$ is a measure of the charge screening by the plasma, and the term arising from strong coupling is given by $D(k \to 0) \approx f_s k^2 d^2$ with $f_s \approx -(4/45)(0.9 + 0.05\kappa_d^2)$ when $\kappa_d \leq 1$ and $\Gamma = Z_d^2 e^2/dT_d \gg 1$. In the regime $kd \ll \kappa_d$ (i.e., $k\lambda_d \ll 1$), Eq. (51) gives $\omega \approx kC_D(1 + f_s\kappa_d^2)^{1/2}$. The latter shows that the effect of strong dust coupling is to reduce the DAW phase speed, since $f_s < 0$. The decrease of the phase speed when κ_d increases may be related to an increase in the compressibility of the dust fluid as the range of the intergrain potential decreases. In the regime $kd \gg \kappa_d$ (i.e., $k\lambda_D \gg 1$), Eq. (51) gives $\omega \approx \omega_{pd}(1 + f_s \kappa_d^2 k^2 \lambda_D^2)^{1/2}$, which shows that the effective dust plasma frequency is reduced due to a decrease of the effective dust charge with stronger screening. The DAW dispersion relation of Murillo (1998) and Winske *et al.* (1999) in the strong-coupling limit is $\omega = kC_D/(1 + k^2\lambda_D^2)^{1/2}(1 + k^2d^2/16)^{1/2}$, which does not depend explicitly on Γ.

The dust-Coulomb wave (DCW) appears in dusty plasmas when the dust charge fluctuation is more important than the thermal pressure of ions and electrons (Rao, 1999). The phase speed of the DCW is given by (Mendonça *et al.*, 2001),

$$C_{\mathrm{DCW}} = \frac{q_d}{\sqrt{m_d R}}. \tag{52}$$

On the other hand, Kaw and Sen (1998) employed a generalized hydrodynamic description, which incorporates the nonlocal viscoelasticity with memory effects arising from the strong correlation among dust particles, and they obtained the dust susceptibility

$$\chi_d = -\frac{\omega_{pd}^2}{\omega^2 - \gamma_d \mu_d k^2 v_{Td}^2 + i\omega k^2 \eta_* / (1 - i\omega\tau_m)}, \tag{53}$$

where γ_d is the adiabatic index, $\mu_d = 1 + U(\Gamma)$ is the compressibility, $U(\Gamma) = E_c / n_{d0} T_d$ is the so-called excess internal energy, E_c is the correlation energy, $\eta_* = (4\eta_s/3 + \xi_b)/m_d n_{d0}$ and $\tau_m = (4\eta_s/3 + \xi_b)/[n_{d0} T_d (1 - \gamma_d \mu_d) + 4U(\Gamma)]$, and η_s and ξ_b are the coefficients for the shear and bulk viscosity, respectively. For longitudinal low-frequency waves ($\omega \ll k v_{Te}, k v_{Ti}$), the linear dielectric responses of the weakly coupled electrons and ions (which obey the Boltzmann law) are given by Eqs. (43) and (44). Thus, from $1 + \chi_e + \chi_i + \chi_d = 0$, we obtain, for $|\omega| < \tau_m \ll 1$,

$$\omega^2 = k^2 \left(\gamma_d \mu_d v_{Td}^2 + \frac{\omega_{pd}^2 \lambda_D^2}{1 + k^2 \lambda_D^2} \right) - i\omega \eta_* k^2. \tag{54}$$

On the other hand, for $|\omega| \tau_m \gg 1$, one obtains

$$\omega^2 = \frac{k^2 C_d^2}{1 + b} \left[1 + \gamma_d \mu_d \frac{\lambda_{dd}^2}{\lambda_D^2} (1 + b) \left(1 + \frac{4}{15} U(\Gamma) \right) \right], \tag{55}$$

where $b = k^2 \lambda_D^2$ and $\lambda_{dd} = v_{Td} / \omega_{pd}$ is the Debye radius.

Kaw and Sen (1998) have shown that their generalized hydrodynamic description also admits a low-frequency "shear" mode that is either a purely damped wave $\omega \approx -i\eta_* k^2$ for $|\omega| \ll \tau_m^{-1}$ or a propagating wave $\omega \approx k(\gamma_d E_c / n_{d0} m_d)^{1/2}$ for $|\omega| \gg \tau_m^{-1}$. The latter is analogous to elastic wave propagation in solids with the correlation energy E_c playing the role of the elastic modulus. Transverse shear waves have been experimentally observed (Nunomura *et al.*, 2000; Pramanik *et al.*, 2002) in strongly coupled dusty plasmas. They were excited by applying a chopped laser beam to a 2D dusty plasma. Measurements of the dispersion relation reveal an acoustic, i.e., nondispersive, character over the entire range of measured wave numbers, $0.2 < kd/\pi < 0.7$. Later works (Kalman *et al.*, 2000; Mamun *et al.*, 2000; Murillo, 2000; Ohta and Hamaguchi, 2000; Bandyopadhyay *et al.*, 2007) have focused further on the DAW dispersion relation in a strongly coupled unmagnetized dusty plasma.

Nunomura *et al.* (2005) obtained experimentally the spectra of longitudinal and transverse waves in liquid ($\Gamma \approx 1$) and solid ($\Gamma \gg 1$) two-dimensional dusty plasmas. The phonon spectra of both longitudinal and transverse modes broadened (especially at high wave numbers) as the dust kinetic temperatures increased, indicating increased damping. Furthermore, Nosenko *et al.* (2007b) reported observations of shear waves in 2D dusty plasma systems that seem to agree with 2D theory (Kalman *et al.*, 2004).

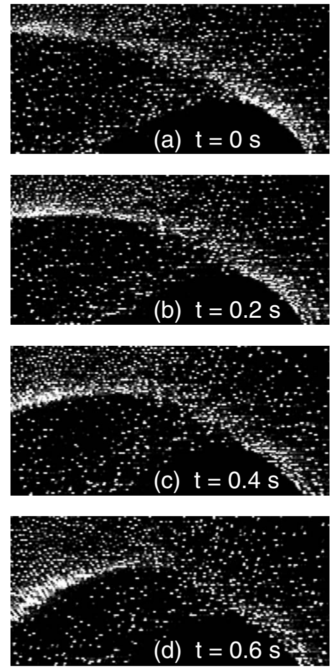

FIG. 6. The formation and propagation of a dust acoustic shock wave observed in the PKE-Nefedov laboratory on board the International Space Station (ISS). The shock wave propagates from top to bottom of the left part of the frames, and has a maximum speed of ~1 cm/s. From Samsonov *et al.*, 2003a).

3. The dust acoustic shock wave

Dust acoustic shocks under microgravity conditions were first observed by Samsonov *et al.* (2003a) with the PKE-Nefedov experiment on board the International Space Station (ISS). Figure 6 shows the propagation of a shock wave characterized by a sharp boundary over which the dust number density increases by a factor of 3, and a propagation speed of ~1 cm/s yielding a Mach number of 1.2–1.4. The shock melting of a two-dimensional Coulomb crystal was observed by Samsonov *et al.* (2004); see Fig. 7. The crystal consisted of a

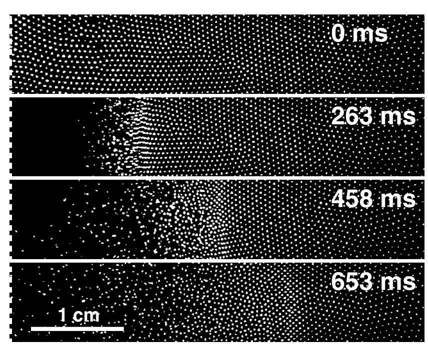

FIG. 7. Shock melting of a two-dimensional Coulomb crystal. Particles are pushed from left to right so that a sharp shock with linear front is formed. Behind the shock, visible at $t = 263$ and 458 ms, the initially hexagonal lattice melts and the particle positions become unordered. At later times ($t = 653$ ms), the amplitude of the perturbation has decreased and the shock disappeared. From Samsonov *et al.*, 2004.

hexagonally ordered monolayer of plastic microspheres. The large-amplitude perturbation pushed the particles to the right so that a sharp, linear shock front was formed. Behind the shock, the lattice melted and the particle positions became unordered.

There are also experimental demonstrations of nonlinear longitudinal and transverse dust lattice oscillations in a two-dimensional screened Coulomb crystal (Avinash *et al.*, 2003; Nunomura *et al.*, 2003). The nonlinearities in the experiments are associated with the generation of harmonics due to the self-interaction of the waves.

C. The dust lattice wave

Two wave modes have been identified in dust lattices due to the vibrations of charged dust grains that are interacting among themselves via the DH repulsive force. These are the longitudinal (compressional) and transverse (shear) waves in which dust particles are displaced parallel and perpendicular to the direction of the wave vector **k**, respectively. In both waves, the restoring force comes from the DH repulsion, while the dust mass provides the inertia to sustain the waves.

1. Linear theory

The theory for the longitudinal dust lattice wave (DLW) was developed by Melandsø (1996). The dispersion relation of the DLW is obtained from the equation of motion for a charged dust particle

$$\frac{d^2x_n}{dt^2} + \nu_{dn}\frac{dx_n}{dt} = \frac{F_c}{m_d}, \tag{56}$$

where $\nu_{dn} \approx 2\sqrt{2} n_g R^2 c_g$ is the dust-neutral collision frequency according to the Epstein drag law, n_g is the neutral gas density, $R \ll \lambda_m$ is the mean free path of the gas molecules, c_g is the thermal speed of the gas molecule, and (Melandsø, 1996)

$$F_c = \frac{q_d^2}{d^3}(2 + 2\kappa_d + \kappa_d^2)\exp(-\kappa_d)(x_{n-1} - 2x_n + x_{n+1}) \tag{57}$$

describes the force acting on the nth particle due to its interaction with neighboring particles in the presence of the DH interaction potential.

Following the standard approach (Kittel, 1996) for longitudinal waves on an infinite linear chain, we obtain from Eq. (56) the dispersion relation for the DLWs as

$$\omega^2 + i\omega\nu_{dn} = \omega_{\mathrm{DL}}^2, \tag{58}$$

where

$$\omega_{\mathrm{DL}}^2 = \frac{4q_d^2}{m_d d^3}(2 + 2\kappa_d + \kappa_d^2)\exp(-\kappa_d)\sin^2(kd/2) \tag{59}$$

is the squared dust lattice frequency (Melandsø, 1996).

On the other hand, Vladimirov *et al.* (1997) theoretically predicted the transverse (vertical) oscillation of dust grains interacting through the shielded DH law in a sheath region of a dust plasma crystal. The vibrational mode dispersion relation is given by (Vladimirov *et al.*, 1997)

$$\omega^2 = \frac{\gamma}{m_d} - \frac{4q_d^2}{m_d d^3}(1 + \kappa_d)\exp(-\kappa_d)\sin^2(kd/2), \tag{60}$$

where γ is a constant assuming linear variation of the sheath. The coupling between longitudinal and transverse modes is possible due to the particle-wake interactions and vertical dust charge gradient (Yaroshenko *et al.*, 2005).

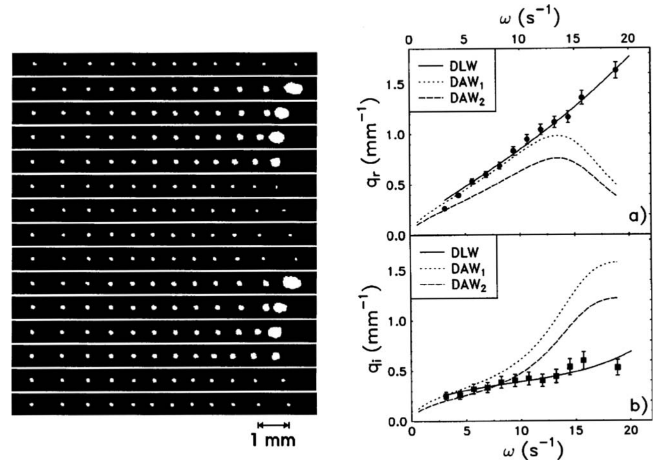

FIG. 8. Experimental results of dust lattice waves. Left panel: A sequence of 15 snapshots of the linear arrangements of dust grains, recorded with a CCD camera. The first particle on the right is excited periodically by the radiation pressure of a laser diode. Right panel: Measured dispersion relation denoted by square symbols, the theoretical dispersion relation for a DLW (solid line), and theoretical dispersion relations for DAWs with parameters similar to the experiment (dashed and dotted lines). From Homann *et al.*, 1997.

2. Observations of dust lattice waves

The longitudinal DLW in dust plasma crystals has been observed in several experiments (Homann *et al.*, 1997, 1998; Morfill *et al.*, 1997). Figure 8 shows the experimental results of Homann *et al.* (1997), where 12 particles are trapped in the lower sheath of a parallel plate rf discharge operated in helium. The rightmost particle is pushed periodically with an exciting laser, where the switching frequency was varied between 0.4 and 3 Hz. The observed wave number q versus frequency ω in the right panel of Fig. 8 shows excellent agreement with the theoretical dispersion curve of DLWs, while the dispersion curves for the DAWs deviate strongly from the experiment for large ω. Knowledge of the dust lattice frequency is useful in deducing the screening of the particles in the rf sheath.

3. Waves in dust crystals: Collisional effects

Experimental observations of the dust-acoustic-like wave propagation in a dust crystal were presented by Ticoş *et al.* (2004). The oscillations, which were excited at

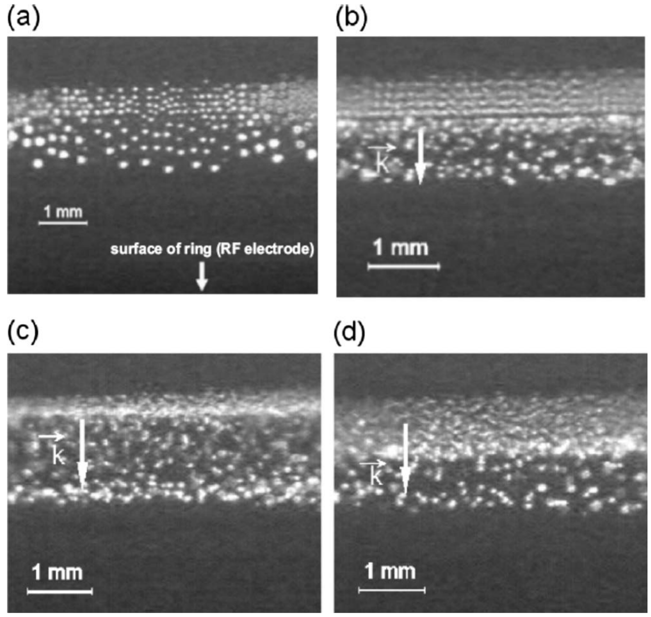

FIG. 9. Collective oscillations in a dust crystal at different pressures: (a) No oscillations at $P=0.198$ Torr, (b) waves propagating in the lower crystal planes at $P=185$ Torr and (c), (d) (separated in time by 16 ms) wavefront propagating at $P=0.160$ Torr. From Ticoş *et al.*, 2004.

low neutral gas pressures, could be observed to propagate downwards through the crystal layers as depicted in Fig. 9. The experimental results agreed qualitatively with a model of the collisional two-stream instability (Rosenberg, 1996; Winske and Rosenberg, 1998) involving the streaming of ions against dust grains. The growth rate of the dissipative instability depends on the ion-neutral and dust neutral collision frequencies. The latter increase with increasing neutral pressure, and for large enough neutral pressure the streaming instability vanishes, as seen in the experiment.

4. Mach cones in dust crystals

Mach cones are V-shaped disturbances produced by a supersonic object moving through a medium. They occur in gases and solid matters. Mach cones in dusty plasmas were first predicted by Havnes *et al.* (1995). They have been observed experimentally in two-dimensional unmagnetized dust crystals (Havnes *et al.*, 1996c; Samsonov *et al.*, 1999, 2000; Dubin, 2000; Melzer *et al.*, 2000; Zhdanov *et al.*, 2004). The Mach cones, which have super dust acoustic speed and are created by pushing a test dust particle by a focused laser beam in a dust crystal assembly, are often double and sometimes triple, first compressive then rarefactive, etc. An example of the dust acoustic Mach cones (Melzer *et al.*, 2000), excited by sweeping a focused laser beam at different speeds through the dusty plasma crystal, is shown in Fig. 10. Clearly seen is the prominent double structure of the Mach cones, especially for the laser speeds of 23.4 and 29.3 mm/s, and a careful analysis of the latter case also reveals a third, weaker Mach cone behind the two strong

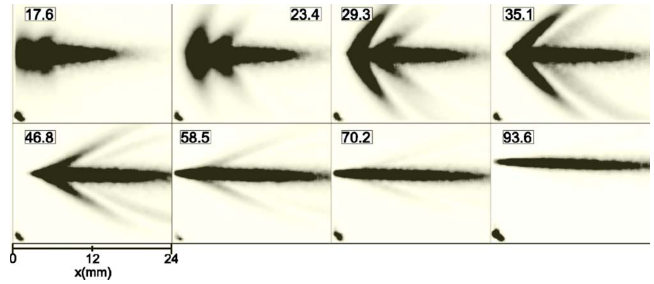

FIG. 10. (Color online) Mach cones excited by the radiation pressure of a focused laser beam swept at different speeds (indicated in mm/s in the boxes) from the right to the left, through a two-dimensional dusty plasma crystal. The velocity field $v=|\mathbf{v}|$ is indicated with the gray-scale map, where black corresponds to a particle speed $v>4$ mm/s. Clearly seen is the prominent double structure of the Mach cones (especially for the laser speed 29.3 mm/s), while a careful study also reveals the existence of a third, weaker cone behind the two stronger ones. From Melzer *et al.*, 2000.

ones. Physically (Dubin, 2000), the Mach cones may arise due to the constructive interference between the dust lattice waves in a dusty plasma crystal.

D. Instabilities in dusty plasmas

Havnes (1988) studied the instability of an electron-ion-dust plasma in the presence of streams of dust grains. He showed that the free energy stored in the latter is coupled to the electrostatic oscillations, which may be relevant for understanding the origin of fluctuations during solar wind plasma flow and cometary dust interactions. Later, Bharuthram *et al.* (1992) and Rosenberg (1993) discussed the possibility of dusty plasma wave excitation in the presence of equilibrium ion drifts in a uniform dusty plasma. Specifically, Bharuthram *et al.* (1992) discussed the effect of dust on ion-ion two-stream instabilities, while Rosenberg (1993) investigated the dust ion-acoustic and dust acoustic instabilities. The appropriate dispersion relation for the DAW in the kinetic regime reads (Rosenberg, 1993; Shukla, 2000d)

$$1+\frac{1}{k^2\lambda_D^2}+i\frac{1}{k^2\lambda_{Di}^2}\sqrt{\frac{\pi}{2}}\frac{\Omega}{kv_{Ti}}-\frac{\omega_{pd}^2}{\omega^2}=0, \tag{61}$$

where $\Omega=\omega-\mathbf{k}\cdot\mathbf{u}_{i0}$, and $\mathbf{u}_{i0}=e\mathbf{E}_0/m_i\nu_{in}$ is the streaming ion drift speed in the presence of a constant electric field $\mathbf{E}_0$. Equation (61) admits an oscillatory instability of the DAW when $u_{i0}\cos\theta>|\omega|/k$, where θ is the angle between $\mathbf{k}$ and $\mathbf{E}_0$. The real part of the frequency is $\omega_r=kC_D/(1+k^2\lambda_D^2)^{1/2}$, while the growth rate of instability reads

$$\omega_i\approx\sqrt{\frac{\pi}{8}}\frac{\omega_r^3}{\omega_{pd}^2}\frac{1}{k^2\lambda_{Di}^2}\frac{u_{i0}}{v_{Ti}}. \tag{62}$$

For $n_{i0}/n_{e0}\gg 1$ and $T_e\gg T_i$, Eq. (62) for the growth rate ($\sim\omega_r$) of the ion streaming driven DAW ($\omega_r/2\pi\sim 15$ Hz, $\omega_r/k\sim 9$ cm/s, and $2\pi/k\sim 0.6$ cm) is consistent with observations (Barkan *et al.*, 1995; Merlino *et al.*, 1998; Molotkov *et al.*, 1999; Fortov *et al.*, 2000), which have $u_0 = eE_0/m_i\nu_{in} \sim 2\times10^5$ cm/s for $E_0 \sim 1$ V/cm.

The dispersion relation in the ion-dust two-stream regime is (Rosenberg, 1996; Winske and Rosenberg, 1998)

$$1 + \frac{1}{k^2\lambda_{De}^2} - \frac{\omega_{pd}^2}{\omega(\omega + i\nu_{dn})} - \frac{\omega_{pi}^2}{\Omega(\Omega + i\nu_{in})} = 0, \tag{63}$$

which for $\nu_{in} \ll |\Omega|$ and $\nu_{dn} \ll |\omega|$ becomes

$$1 - \frac{\omega_{pi}^2}{A_s\Omega^2}\left(1 - i\frac{\nu_{in}}{\Omega}\right) - \frac{\omega_{pd}^2}{A_s\omega^2} = 0, \tag{64}$$

where $A_s = 1 + (k\lambda_{De})^2$. In the absence of ion-dust collisions, Eq. (64) for $\mathbf{k}\cdot\mathbf{u}_{i0} \gg |\omega|$ gives $\omega_r \sim \omega_i \sim (\omega_{pi}\omega_{pd}^2)^{1/3}/\sqrt{A_s}$, with a maximum growth rate at $ku_{i0}\cos\theta \sim \omega_{pi}/\sqrt{A_s}$. Furthermore, in a collisional dusty plasma with $\omega \ll ku_{i0}\cos\theta\omega_{pi}/\sqrt{A_s} \sim \nu_i$, Eq. (64) has the approximate solution (Rosenberg, 1996; Winske and Rosenberg, 1998)

$$\omega \approx \omega_{pd}\frac{1+i}{\sqrt{2}A_s^{3/4}}\left(\frac{\omega_{pi}}{\nu_{in}}\right)^{1/2}, \tag{65}$$

which admits a dissipative instability.

The excitation of the DAWs and their saturation via trapping ions in collisional dusty plasmas have been investigated by computer simulations (Winske, 2004). The DAW drag force acting on the dust grains is found to be much larger than the ion-drag force. Recently, Piel *et al.* (2006) presented experimental evidence of dust density waves propagating at an arbitrary angle with respect to the ion flow direction in a collisional dusty plasma under microgravity conditions. Here a dissipative instability driven by an ion beam plays a crucial role in exciting the dust density waves. Finally, streaming instabilities involving both the longitudinal and transverse waves may also arise in a strongly coupled unmagnetized collisional dusty plasma (Kalman and Rosenberg, 2003).

E. Dust voids and vortices

In strongly coupled dusty plasma systems, there are indications of probe-induced dust particle circulation (Law *et al.*, 1998), the formation of a dust void, as well as a dust vortex (Fujiyama *et al.*, 1997; Iizuka *et al.*, 1998; Sato *et al.*, 1998, 2000; Morfill *et al.*, 1999; Agrawal and Prasad, 2003; Fortov *et al.*, 2005b, 2006). A dust void, which is a micrograin-free region in the central part of the discharge where the dusty plasma has been generated, has been observed in several dusty plasma experiments, in particular under microgravity conditions (Morfill *et al.*, 1999, 2002) as well as on ground (Mikikian and Boufendi, 2004; Mikikian *et al.*, 2007). The formation of a dust void is also seen around negatively biased probes in a dusty plasma (Thompson *et al.*, 1999b; Klindworth *et al.*, 2004; Thomas *et al.*, 2004). A negatively biased probe repels the negative dust grains and would form a dust-free region (a dust void) around the probe. Figure 11 shows an example of a dust cloud, in the plasma crystal experiment PKE-Nefedov on the ISS, revealing the self-

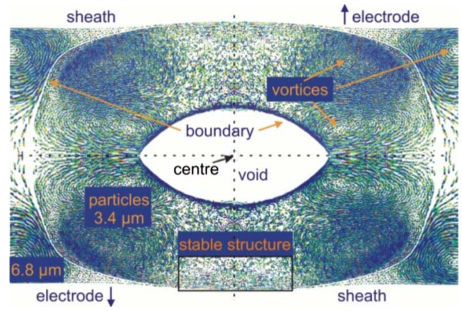

FIG. 11. (Color online) Dust cloud observed in the PKE-Nefedov laboratory on board the ISS. The trajectories of 6.8 and 3.4 μm particles observed over 3 s are displayed, revealing several salient features, including dust vortices as well as a dust-free void in the center of the cloud, and a sharp boundary between dust of different sizes. Image courtesy of the PKE-Nefedov team (Nefedov *et al.*, 2003).

organization of the particles into dust vortices and a dust-free void in the center of the cloud. It has been proposed that a dust void could be either a self-consistent nonlinear equilibrium plasma state involving trapped ions and the associated ion hole (Mamun *et al.*, 2002; Jovanović and Shukla, 2003; Shukla and Eliasson, 2004) or may result from the balance between the sheath electrostatic and anomalous ion-drag forces acting on charged dust grains (Khrapak *et al.*, 2002).

A dust void admits an interesting dynamics in that it can become unstable [due to the so-called heartbeat instability (Mikikian and Boufendi, 2004; Mikikian *et al.*, 2005, 2007)] against the low-frequency dust acoustic perturbations. The heartbeat instability gives rise to successive contractions and expansions of a dust void in the central part of a dense dust cloud. Figure 12 shows the contraction and expansion sequence of a dust cloud under microgravity conditions on board the ISS. It seems likely that the heartbeat instability may be due to perturbations in the ionization rate of neutrals, which in turn disturbs (Shukla and Morfill, 1999) the balance between the electrostatic and ion-drag forces which may have set up a void in the experiment of Mikikian *et al.*, (2007).

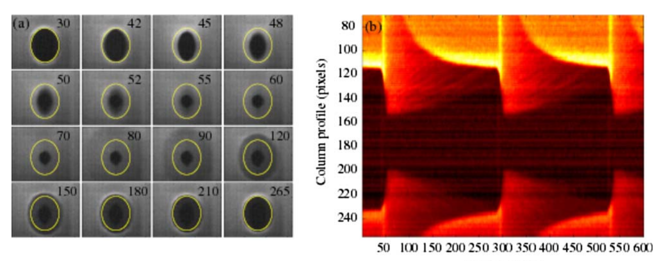

FIG. 12. (Color online) The heartbeat instability of a dust void observed in the PKE-Nefedov laboratory on board the International Space Station (ISS). (a) Images of the dust void during one contraction-expansion sequence. The bright lines denote the position of the stable open void. (b) Time evolution of the central column profile in the vertical line passing through the void center. From Mikikian *et al.*, 2007.

The dust void can be used as an obstacle in a flowing dusty plasma to study the liquidlike flow of the dusty plasma around the obstacle, the wake and vortex formation behind the obstacle, etc. on a kinetic level (Morfill *et al.*, 2004). However, a recent experiment (Lipaev *et al.*, 2007) under microgravity conditions on board the ISS reveals that a dust void could be closed by appropriate tuning of the discharge parameters (e.g., by applying sufficiently low discharge pressure and very low voltages to the electrodes).

V. DISCUSSION AND OUTLOOK

In this Colloquium, we have presented an overview of the current status and critical assessment of important aspects of dust-plasma interactions, as well as of the discoveries and the progress that have been made during the past decade. Our aim has been to provide a coherent account of the underlying physics of the dust grain charging and the forces that act on charged dust grains, in addition to presenting new linear and nonlinear wave phenomena in an unmagnetized dusty plasma. Specifically, we have focused on several aspects of collective phenomena including new waves (e.g., the DAW, the DLW), new intergrain forces, as well as several forms of nonlinear structures (e.g., DA and DIA shocks, dust voids, and dust vortices) in dusty plasmas. Several of the collective effects described in this Colloquium have indeed been observed in laboratories and in space. More works in dusty plasma physics will emerge in the future, because there are planned experiments involving (i) the high-pressure dusty plasma created by electron beams (Pal *et al.*, 2005), (ii) the dusty plasma containing negative ions (Klumov *et al.*, 2003; Kim and Merlino, 2006, 2007; Merlino and Kim, 2006), (iii) the cryogenic dusty plasma (Fortov *et al.*, 2002; Rosenberg and Kalman, 2006; Antipov *et al.*, 2007) [low-pressure dc glow discharge plasma at temperatures of liquid nitrogen ($T=77$ K) and liquid helium ($T=4.2$ K), having the dust particle density of the order of 10^9 cm^{-3}; dust-neutral collisions are rare in such plasmas], and (iv) low-pressure dusty plasmas in an external magnetic field on ground and on board the ISS. In such environments, we have to revise our understanding of the dust grain charging, intergrain short- and long-range forces, dust Coulomb crystallization, etc. New experiments in dusty magnetoplasmas should capture the physics of the phenomena that are also occurring in the Earth's mesosphere as well as in interstellar spaces. Furthermore, there exist plenty of new observations from the ISS and Cassini missions regarding the excitation of waves [both linear (Schwabe *et al.*, 2007) and nonlinear] and large-scale structures (Tokar *et al.*, 2006; Williams *et al.*, 2006; Postnikov and Loskutov, 2007), which ought to be understood with the help of theoretical and numerical models (Shukla *et al.*, 2003). We hope that the present Colloquium will motivate students and researchers to examine new aspects of collective dust-plasma interactions in nonuniform dusty magnetoplasmas (both weakly and strongly coupled) in order to understand the existing and forthcoming observations from laboratories, as well as from lunar and planetary systems and interstellar spaces, where micron- or nanometer-sized dust particles are ubiquitous.

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