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A BRIEF REVIEW OF DUSTY PLASMA EFFECTS IN THE SOLAR SYSTEM

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RESUMEN

Dusty plasmas are commonly found in the solar system and in the rest of space. In this paper we briefly describe some of the more common dusty plasmas: the rings of Saturn, dust tails of comets, dust streams from Jupiter, and noctilucent clouds in the upper atmosphere. We also discuss some of the theoretical issues related to grain charging, dust particle dynamics, waves in dusty plasmas, and dusty plasma crystals.

ABSTRACT

Dusty plasmas are commonly found in the solar system and in the rest of space. In this paper we briefly describe some of the more common dusty plasmas: the rings of Saturn, dust tails of comets, dust streams from Jupiter, and noctilucent clouds in the upper atmosphere. We also discuss some of the theoretical issues related to grain charging, dust particle dynamics, waves in dusty plasmas, and dusty plasma crystals.

Key words: SOLAR SYSTEM: GENERAL — PLASMAS

1. INTRODUCTION

When dust grains are introduced into a plasma, they become charged and form a dusty plasma. The environment near a comet and dust rings in planetary magnetospheres are the most common examples of dusty plasmas in the solar system, although they also occur in the mesosphere and the ionosphere as well as near the surface of the moon (Goertz, 1989). While dusty plasmas have been studied in the context of astrophysics for many years, and the effect of electromagnetic fields on dust grains in planetary rings was vigorously investigated a decade ago, interest in dusty plasmas has grown rapidly in the last few years. In part, this has been due to new laboratory experiments that show a fascinating range of unusual phenomena (Thomas et al., 1994; Chu & I, 1994; Barkan et al., 1995; Melzer et al., 1996) as well as due to the practical importance of particulate contaminants in industrial processing plasmas (Huang et al., 1996). In addition, new computational capabilities and techniques allow these processes to be studied numerically with a high degree of realism that was unavailable just a few years ago.

In this paper, basic aspects of dusty plasma will be reviewed. Observations of dusty plasmas in space will be described, and unresolved theoretical issues will be discussed. Specifically, we will briefly describe observations from Saturn, Jupiter, comets, and noctilucent clouds. And we will address theoretical issues related to grain charging and dynamics, collective processes, and strongly coupled plasma effects. The uninitiated reader is urged to consult other reviews (Goertz, 1989; Mendis & Rosenberg, 1994; Winske, 1996; Mendis, 1997) for details of earlier work and additional references. On reading these papers, one is struck by the strong interplay of conceptual models, theoretical analyses, numerical calculations, observations from space, and laboratory experiments, all of which are needed to produce a well rounded picture of the pervasive effect of dusty plasmas in our universe.

2. OBSERVATIONS

In this section we discuss several relatively well understood dusty plasmas in the solar system, namely, the rings of Saturn and cometary dust tails. We also consider two less well known dusty plasmas: the dust streams at Jupiter and noctilucent clouds in the mesosphere.

2.1. Radial Spokes of Saturn's Rings

Planetary rings are composed of dust particles; the rings of Saturn, of course, are the best example. One of the most interesting features of the rings seen by the Voyager spacecraft was the radial spokes in the B ring (Goertz, 1989). The spokes appear bright in forward scattered light, suggesting they are micron (or smaller) grains. Consistent with observations, it is thought that the spokes are due to the electrostatic levitation of the grains. To be levitated against gravity, however, requires the grains acquire a modest amount of charge, which in turn implies a rather dense plasma in the ring. This plasma can be produced by meteor impacts on the ring. The plasma clouds, and associated levitated grains, propagate radially due to an $\vec{E} \times \vec{B}$ drift, with the azimuthal electric field arising from current closure in the ionosphere. The calculated radial velocities, $\sim 20 - 40$ km/s, are consistent with the observed optical depth of the spokes (Goertz and Morfill, 1983).

2.2. Cometary Dust Tails

The dust comprising a cometary dust tail is the most easily seen and oldest known dusty plasma. While comets have been studied for centuries, it has only been in the last decade that in situ measurements have been carried out at Giacobini-Zinner, Halley, and Gregg-Skjellerup, which have revealed the complex nature of the dust-solar wind interaction (e.g., see Johnstone et al., 1993). Near the comet, there is a region where the magnetic field is excluded, and a boundary, the ionopause, forms at the edge of the cavity. Dust grains, which range in size from less than one micron to greater than 10 microns, are subject to radiation pressure, and because they are charged, to plasma drag and the electromagnetic force. Due to variable solar wind conditions, the motional electric field in the solar wind can change direction and thus modify the appearance of the tail. Of special interest this year (1997), is Comet Hale-Bopp. While its production rate of volatile material at 4AU was comparable to that of Halley near the spacecraft encounters, and models predicted a large increase in the production rate near perihelion, depending on the rate of rotation of the nucleus (Flammer et al, 1997), it appears that evaporation of the more volatile material and the formation of a crust on the nucleus (D. A. Mendis, private communication, 1997) have resulted in less material evaporated than predicted earlier.

2.3. Dust Streams from Jupiter

A most unexpected result from the Ulysses spacecraft encounter with Jupiter in 1991-92 was the detection of dust streams from the planet. A number of streams (> 11) were observed, with a frequency of roughly 28 days (Grün et al., 1993). Later analysis shows that the grains in the streams were small (~ 0.02) micron and very energetic ($v \sim 200$ km/s) (Zook et al., 1996). While dust resulting from the breakup of Comet Shoemaker-Levy or from the gossamer ring was suggested, the most likely explanation for the streams seems to be grains emitted by volcanos on the moon Io. Some of these particles can be lofted to high altitudes, where they can acquire a (positive) charge and due to the Lorentz force, escape from the gravitational attraction of Io. In the magnetosphere of Jupiter, these grains gain energy from the rotating magnetosphere as they migrate outward. Grains that are very small are tied to the magnetic field and therefore cannot migrate, and large grains are confined by gravity. Thus, grains in only a selected range are energized and escape from the planet in a stream (Horanyi et al., 1993). The streams have also been observed more recently by the Galileo spacecraft.

2.4. Noctilucent Clouds

Finally, we discuss dust grains in noctilucent clouds (Thomas, 1991). Such clouds are seen in the summer at high latitudes near midnight. From the angle of the sun, one concludes that they are at very high altitude (~ 80 km). One mechanism to form such clouds involves dust grains, perhaps coated by ice particles. While early rocket experiments through this region failed to detect much dust, recent experiments with much more sophisticated instrumentation have shown that dust is present in significant quantities ($\sim> 10^3 \mathrm{cm}^{-3}$) with particle sizes ~ 0.1 micron (Havnes et al., 1996). Both positively and negatively charged grains have been detected. The presence of negatively charged dust reduces the local electron density, consistent with radar scattering experiments. The fact that noctilucent clouds were only observed beginning in 1885, and sightings have increased in time, suggests that the atmospheric chemistry, and perhaps the amount of dust particles from man-made sources, have changed in time.

3. THEORETICAL ISSUES

In this section, some of the theoretical aspects of dusty plasmas are examined: i.e., issues related to grain charging, single particle dust dynamics, waves and instabilities, and the formation of strongly coupled dusty plasma crystals.

3.1. Grain Charging

The most fundamental and important process that occurs when dust grains are introduced into a plasma is that they can acquire a net electrical charge. Due to the greater mobility of the electrons, the bare grain first acquires some electrons, which are later compensated by positive ions; the overall effect is usually a net negative charge on the grain. The charge on an isolated spherical grain can be calculated in the same way that one determines the charge on a small spherical probe in an equilibrium plasma, by noting that the time rate of change of the charge on the grain equals the sum of the electron and ion currents (Goertz, 1989):

$$\frac{dQ_d}{dt} = I_e + I_i \tag{1}$$

These currents are calculated assuming an isotropic Maxwellian plasma, ignoring perturbations in particle orbits near the grain surface

$$\frac{dQ_d}{dt} = -en_e\pi R_d^2\left(\frac{8k_BT_e}{\pi m_e}\right)^{1/2}e^{e\phi_s/k_BT_e} + Z_ien_i\pi R_d^2\left(\frac{8k_BT_i}{\pi m_i}\right)^{1/2}\left(1-\frac{Z_ie\phi_s}{k_BT_i}\right) \tag{2}$$

where n_j, T_j, and m_j are the number density, temperature, and mass of the $j = e$ (electrons) and $j = i$ (ions), Z_i is the charge state of the ions, ϕ_s (assumed < 0) is the potential on the surface of the grain, and R_d is the radius of the spherical grain. Setting the lefthand side of (2) equal to zero, yields an equation for the equilibrium value of ϕ_s. The charge on the grain is then

$$Q_d = eZ_d = C(\phi_s - \phi_p) \simeq R_d(\phi_s - \phi_p) \tag{3}$$

where $C \simeq R_d$ is the capacitance and ϕ_p is the plasma potential, which can be taken to be zero for an isolated grain in a neutral plasma ($n_e = n_i$). One can also solve (2) as a function of time to obtain the charging time of the grain as a function of various plasma and dust parameters (Winske & Jones, 1995).

The presence of many grains compounds the problem in several ways. First, the capacitance in (3) is modified, although this is usually not a big effect. More significantly, the plasma potential changes, especially if one is in an isolated system where as the grains acquire charge, the electron density is reduced. Assuming a thermal plasma, one solves Poisson's equation for ϕ_p including the dust

$$\nabla^2\phi_p = 4\pi e[Z_in_ie^{-Z_ie\phi_p/k_BT_i} - n_ee^{e\phi_p/k_BT_e} + Z_dn_d] \tag{4}$$

To understand the details of the charging process, a number of numerical simulations have been carried out in recent years (Choi & Kushner, 1994; Lapenta, 1995). These calculations involve a small simulation domain, typically a few Debye lengths in each of several spatial dimensions in rectangular, cylindrical, or spherical geometry. The domain is filled with a plasma, consisting of electrons and positive ions, usually taken with Maxwellian velocity distributions, although more complex distributions obtained can also be used. The simulations use particle-in-cell (PIC) techniques, in which the plasma constituents are represented as discrete macroparticles and the electromagnetic fields are solved on a spatial grid. One starts with a bare grain and calculates the buildup of the charge in time. From such calculations, one gets the charging rate of the grain, the equilibrium value of the charge, and the surface potential. From a number of simulations of this sort, one also obtains scalings for these quantities as a function of plasma and dust parameters. One can also compute cross-sections for plasma-dust interactions, by calculating the effects of heating and/or momentum transfer on test particles introduced into the simulation domain (Choi & Kushner, 1994). To test charging models, some experiments that measure the charge on isolated dust grains have recently been carried out (Walch et al., 1995; Horanyi et al., 1995) that are consistent with theory. Hopefully more will be done in the next few years.

3.2. Dust Dynamics

We next consider situations in which the dust interacts with the plasma only in a weak manner. In this case, we assume that the plasma is in equilibrium and the dust grains are test particles subject to forces determined only by the time-independent local plasma properties. A test particle approach has two distinct advantages. First, it allows very long time scales associated with the dust dynamics to be followed. And for large inhomogeneous plasmas, it can take into account differences in the dust dynamics in the various regions of the system. Second, it allows the effects of the various forces acting on the dust grains to be studied individually, as well as collectively, and new processes to be added incrementally. The disadvantage of this approach is that it is not self-consistent, so that one must find some other way (e.g., observations) to insure that the calculations make sense.

The basic equations of the test particle methods are the equation of motion for the dust particle

$$m_j \frac{d\vec{v}_j}{dt} = \sum_k \vec{F}_j^{(k)} \tag{5}$$

and a generalization of Eq. (1) for the time rate of change of the charge on the grain

$$\frac{dQ_j(t)}{dt} = I_e + I_i + I_{\text{other}} \tag{6}$$

Here, m_j, $\vec{v}_j$, and Q_j are the mass, velocity, and charge of the j-th dust grain, $j = 1, 2...M$, with M the total number of grains considered. $\vec{F}^{(k)}$ are the various forces acting on the grain, which include gravity, electric, magnetic, ion and neutral drag, radiation pressure, thermophoretic force, etc. Expressions for these forces are found in numerous places (e.g., Horanyi & Mendis, 1985) and depend to a large extent on the application. I_{other} in Eq. (6) contains contributions to the charging currents due to effects other than direct electron and ion currents, such as photoemission and secondary electron emission. As the forces depend only on fixed (in time) plasma properties and the grain size (fixed) and charge, Eqs. (5) and (6) can be advanced in time in a relatively straightforward manner.

Test particle simulations have been carried out for a number of space applications, including comets, the outer planets, and the Earth's magnetosphere, as discussed earlier. The charging of small dust grains emitted by the cometary nucleus allows them to interact with the solar wind flowing by the comet through the Lorentz force as well as by radiation pressure. Test particle simulations indicate how such electromagnetic effects can lead to wavy features in the cometary dust tail (Horanyi & Mendis, 1985). Dust is also found in planetary rings. Electromagnetic forces on charged dust along with radiation pressure lead to radial excursions in the orbit of the grains. Calculations of dust emitted from Saturn's moon Enceladus and perturbed in this manner shows many observed features of the E-ring (Horanyi et al., 1992). Other test particle simulations (Horanyi et al., 1993) have shown that charged dust can also be energized in the magnetosphere of Jupiter and escape in streams.

3.3. Dust-Plasma Instabilities

The presence of charged dust in a plasma adds additional sources of free energy that can drive new unstable modes (Rao, 1993; Rosenberg, 1996; Verheest, 1996). High frequency ($\gg$ any frequency associated with the dust) can be excited because the dust can modify the relative drift between the plasma electrons and ions or simply reduce the electron density. However, more interesting effects occur at lower frequencies, where the dust dynamics enters directly. Although the dust charge Qd can be large, typically $10^3 - 10^5 e$, and the dust mass M_d is also large ($\sim 10^{12} m_p$ for a one micron radius spherical grain), so that $Q_d/M_d \ll 1$, the dust plasma frequency, $\sim Q_d/M_d^{1/2}$, can be significant. Both electrostatic and electromagnetic modes exist, and many have been studied analytically.

One of the most interesting modes is an dust/ion acoustic instability driven by the relative drift between the dust and plasma (Rao, 1993). Such a situation occurs in the E-ring in the inner magnetosphere of Saturn, where the plasma corotates with the planet while the dust follows Kepler orbits. The relative drift speed between the plasma and the dust is of the order of the ion thermal speed, which is sufficient to drive the instability (Rosenberg, 1993). This process can be modeled with a particle-in-cell code in which both the plasma ions and dust ions are treated as particles and the electrons are assumed to have a Boltzmann distribution (Winske et al., 1995). The growth rate of the instability is roughly the plasma frequency of the dust ions, $\omega_d = (4\pi n_d Q_d^2/m_d)^{1/2}$, while the wavelength is on the order of the Debye length. Rapid growth of the instability leads to saturation at a relatively low level of fluctuations, $e\delta\phi/T_i \sim 1$. The plasma ions at small positive velocities are affected most, as some of these ions are trapped by the waves, which eventually causes them to cease growing. The plasma ions are only heated slightly in this process. However, the amount of ion heating seems sufficient to explain the observed temperature increase with radius at Saturn. The dust ions, on the other hand, are merely modulated by the waves, although when averaged in space, this modulation appears as a strong heating of the dust. The same process can be studied in the laboratory. Barkan et al. (1995) have observed that large amplitude waves with properties of the dust acoustic mode are readily excited.

3.4. Strongly Coupled Plasma Effects

In the last few years, it has been shown in the laboratory that dust grains in a plasma can form into a regular crystalline lattice (Thomas et al., 1994; Chu & I, 1994; Melzer et al., 1996). By adjusting the parameters of the discharge, the plasma crystal can be changed into a liquid or a gaseous state. Typically, because of the effect of gravity, the structure is only a few layers thick, but forms over a large enough region that it can can be easily seen with laser scattering techniques. The possibility that such structures could form in a dusty plasma when the electrostatic potential energy of the grains exceeds their random thermal energy had been suggested theoretically several years ago (Ikezi, 1986), but has only been observed recently.

To model such systems can be quite challenging, if the plasma dynamics are included in the process. However, one can make the simplifying assumption that the plasma merely provides shielding of the bare dust charges so that the potential surrounding each charge is a screened Coulomb potential

$$V(r) = \frac{Q_d^2}{r} \exp(-r/\lambda_D) \tag{7}$$

where λ_D is the Debye length. One can then carry out a simulation of N such particles interacting via such potentials (Hammerberg et al., 1994). One also needs to include additional physics that is unique to the experimental devices in which they are created. First, these crystals are formed in rf discharges, with the dust grains collecting into traps, where the ion drag, neutral drag, gravitational, and electrical forces balance (Huang et al., 1996). The effect of these forces must be included in the simulations through some sort of trap potential. Second, rf discharges are only weakly ionized, and the interaction of dust grains with neutrals that cool the grains seems a necessary ingredient to obtain a crystalline state. Third, the effect of shielding of grains in the lower rows of the crystal by grains in the top row needs to be included to achieve the observed vertical alignment of grains in the crystal (Schweigert et al., 1996). Some small scale calculations of this sort have been carried out (Melandso & Goree, 1996), and we are in the process of doing some of our own calculations.

4. CONCLUSIONS

In conclusion, we have shown that the study of dusty plasmas in the solar system continues to be an area of active research. While the investigation of dust streams at Jupiter and the nature of noctilucent clouds are relatively new areas, work continues in analyzing the cometary environment. Although the study of planetary rings is relatively inactive, this is expected to change with the launch of the Cassini mission later this year. Theoretical efforts to understand the observations, as well as more basic plasma physics issues related to grain charging, instabilities involving dust, and strongly coupled plasma effects in dusty plasmas, have increased in the last few years. Interest has been enhanced because of questions raised by new laboratory experiments, practical issues related to plasma processing and the application of numerical simulation methods to model dusty plasma processes.

Because of the limited scope of this paper, we have not been able to address some topics. For example, we have not touched on issues related to grain growth, coagulation of smaller grains, and the electrostatic disruption of grains (e.g., see Mendis & Rosenberg, 1994). While such processes have been addressed in the past theoretically, it may now be possible to numerically study grain charging, dust particle and plasma dynamics, as well as grain growth, coagulation and disruption, together on a fundamental level. This evidently requires better physics models and the ability to extend present dust charging simulations much longer in time. However, given the computational resources now available, such a study seems certainly feasible.

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