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A WHITE PAPER ON DUSTY PLASMAS

The Proceedings of a Workshop on Dusty Plasmas
Held at the University of California at San Diego

February 10-11, 1986

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Compiled and Edited by Elden C. Whipple

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S U M M A R Y

"Dusty Plasmas" is the name given to plasmas heavily laden with charged dust grains which together with the surrounding ions and electrons constitute a new kind of plasma regime. Such plasmas exist in the rings of planets, in the atmospheres of comets, and in interstellar dust clouds. The dust grains are strongly coupled to the fields and particles in the plasma through their electrical charges. As a result the motions of the grains may be dominated by electric and magnetic forces, and collective effects can play an important role. This field of study is receiving increased attention because of the observations of dust during recent spacecraft missions to the planets and comets, together with the dawning recognition that the evolution of dusty plasma clouds in space may be quite different from that of non-dusty clouds.

A workshop on dusty plasmas was held at the University of Californa in San Diego on Feb. 10-11, 1986, to review recent work in this field and to make recommendations on the kind of research that is needed in the immediate future. The principal recommendations are:

1. The most urgent need is for experimental investigations of:

   (1) Impact effects such as erosion products of grains impacting ices and other materials at high velocities (> 10 km/sec).
   (2) Electron and ion emission yields on particle and photon impact, especially the effects of small grain sizes.
   (3) Grain/grain collision processes such as fragmentation, adhesion, and their dependence on grain size, charge, and composition.
   (4) Laboratory studies, including micro-gravity experiments as on the Shuttle, of grain formation and growth in a plasma.
   (5) Release of dust in space with measurements of the dust motions, dust/plasma interactions, and grain growth and/or fragmentation.
   (6) Laboratory study of molecule/charged grain interactions such as molecular excitation and the stimulation of infrared emission.

2. Theoretical studies should be extended to investigate:

   (1) The motion of charged dust grains in the earth's magnetosphere, with emphasis on the dispersal of particulate debris.
   (2) The time-dependent motion of dust grains in the environments of the planets and of comets.
   (3) The evolution of dusty plasma clouds with an emphasis on their significance for the formation of solar systems.
   (4) Collective effects in a dusty plasma such as plasma depletion, grain/grain interactions, and the existence of new wave modes.
   (5) Numerical simulation studies of the growth, interactions, and motions of grains in a plasma.

I. INTRODUCTION

A workshop on "Dusty Plasmas" was held at the University of California at San Diego (UCSD) on February 10-11, 1986. The purpose of the workshop was to have an organized presentation and discussion of work on dusty plasmas which has been carried out both at UCSD in the last three years and also at other institutions.

The timing of the workshop seems to have been particularly appropriate in view of the recent fly-by of Comet Giacobini-Zinner in September, 1985, the Voyager encounter with Uranus in January, 1986, and the rendez-vouz of the Japanese, Soviet, and European spacecraft with Comet Halley in March, 1986. In all of these events, dust was detected in considerable quantities in the environments of these solar system bodies, and plasma effects are being invoked to explain many of the observations.

The workshop concentrated on reviewing the work that has been accomplished and focussed particularly on future research that is still needed. This white paper describes the work that has been accomplished and the research that is needed in the various areas represented at the workshop. The authors of each section and their institutions are identified at the beginning of each section.

This white paper is not intended in itself to be a proposal. Rather, the purpose of the white paper is educational: It is intended

(1) to summarize the present state of our knowledge of the physics of dusty plasmas in space in selected areas; and

(2) to serve as a basis for discussing the kinds of research that need to be carried out on dusty plasmas in the immediate future.

II. DUST IN PLANETARY AND COMETARY MAGNETOSPHERES

(A. Mendis, University of California at San Diego, La Jolla, CA)

1. Work accomplished

Solid bodies immersed in the plasma and radiative environments of planetary and cometary magnetospheres are electrically charged. This charging has both physical and dynamical consequences (Whipple, 1981).

The physical consequences concern electrostatic disruption and/or "chipping" of small bodies (e.g., Mendis, 1981). Also small grains may be electrostatically levitated off the surfaces of larger bodies such as comets at large heliocentric distances (Mendis et al, 1981) when struck by high speed solar wind streams (Flammar et al., 1986)

The recognition that these charged dust grains in planetary magnetospheres may experience electrical and gravitational forces of comparable magnitude led to the gravito-electrodynamic (GED) description of their dynamics (Mendis et al., 1982, 1983). This single-particle approach neglected the electrical effects of neighboring grains on the test particle and is valid when the grain separation is larger or comparable to the Debye shielding distance in the plasma. This work led to a number of interesting results including novel magneto-gravitational (1-1) orbital resonances and gyro-orbital resonances which were used to explain several peculiar features in the Saturnian ring system discovered during the Voyager 1 and 2 encounters (see Mendis et al., 1984; Grun et al., 1984, for detailed reviews).

Earlier, Hill and Mendis (1979, 1980) considered the detailed dynamics and orbital evolution of dust grains entering the Jovian magnetosphere in order to explain the micrometreroid dust distribution observed by the Pioneer spacecraft. One interesting discovery was that these dust grains gradually move toward the synchronous orbit, a result that was subsequently verified by Northrop and Hill (1983a) using the adiabatic theory. Hill and Mendis (1980) predicted that this radial "gyro-phase" drift would lead to accumulation of dust at Jupiter's synchronous orbit; something that has been very recently verified by the discovery of the so-called Gossamer ring (Showalter et al., 1986; Northrop et al., 1986).

It was also shown (Hill and Mendis, 1982) that due to the relative motion between the charged dust and the charge neutralizing, neighboring plasma, these circumplanetary rings constituted a novel type of dust ring current which had interesting ionospheric consequences (Ip and Mendis, 1983). Houpis and Mendis (1983) also demonstrated that the well known "tearing" of such resistive current discs may explain the observed fine structure of the Saturnian ring system.

More recently, Horanyi and Mendis (1985, 1986a,b) have studied the effects of electrical forces on the dynamics of the dust in tails of comets. Recent in-situ observations of the distribution of fine dust in the environments of Comets Giacobini-Zinner and Halley are consistent with the calculations.

2. Needed Research

(a) Together with M. Horanyi (of the Supercomputer Computational Institute, State University of Florida), we have started a study of the charging and dynamical evolution of the 1 to 10 micron aluminum oxide dust grains that are injected into the terrestrial magnetosphere during rocket propellant burns. The motivation for this work is to estimate the dust hazard to spacecraft in the future, particularly near geosynchronous orbit because there is a possibility that the grains may congregate toward the region.

(b) We propose to extend these studies to Uranus, whose magnetic axis is inclined at the large angle of 55 degrees to the spin axis. The reported paucity of small dust grains in the ring plane of Uranus (i.e., the equatorial plane) may be due to this large angular offset between the two axes. It seems very likely that these small grains (which are necessarily electrically charged) may be distributed over a large extended halo about a surface intermediate to the geographic and magnetic equators.

(c) In cosmogonic theories that propose the existence of a dust disc around a central body as an intermediate step for planet and satellite formation (e.g., Alfven, 1981) a major difficulty is to get the evolution to proceed beyond the ringlet stage. One needs a process of longitudinal focusing to form a single body from a ring of orbital particles. Pure gravitational theory cannot help because all bodies large and small will move with the same Kepler velocity and no collisions take place. However, when one recognizes that the grains are charged and that different size grains will have different orbital velocities (between Kepler and co-rotational) due to their different charge to mass ratio, then a natural process for longitudinal focusing exists. We propose to do a numerical simulation in collaboration with Dr. M. Horanyi and using the computational facility at the Supercomputer computational facility at Tallahassee, in order to study this problem.

(d) Most of our studies so far have used the single particle approach of GED. But collective effects in a dusty plasma are clearly very important and interesting (e.g., Whipple et al., 1985). One very interesting problem, which is connected with the propagation of EM radiation in a dusty plasma, are the various wave modes that can be excited in it. If the dusty plasma has only two components (e.g., negatively charged grains and positive ions) the results of normal electron-ion plasmas can be used with the positive ions in the dusty plasma playing the role of the electrons in a normal plasma. On the other hand, if the dusty plasma has three components (charged dust, positive ions and electrons) the situation is much more complex. This problem should be pursued, with the aim of constructing for a dusty plasma the analog of a CMA diagram of normal plasmas.

III. DUST IN PLANETARY RINGS

(T. Northrop, Goddard Space Flight Center, Greenbelt, MD)

1. Work Accomplished

An earlier estimate (Northrop and Hill, 1983b) of the age of Saturn's rings has been improved upon with a detailed model. An age determination can be based on the time it would have taken incident micrometeorites to erode the C ring down to its present optical thickness starting from the value the adjacent B ring presently has. The sharp division between these two rings is also at the demarcation between where charged erosion products of the micrometeorite impact are lost from the ring plane to the planet, and where they are retained in the ring plane to become reabsorbed, producing no net ring mass loss (i.e. in the B ring).

In the present work we have used best estimates of micrometeorite fluxes (Morfill et al., 1983) as a function of size at Saturn, and the present (scanty) knowledge of impact products of 30 km/s micrometeorites on rock.

We find the ring age to be in the range 6 million years to 67 million years, depending on assumptions regarding the micrometeorite velocities in interplanetary space. Thus the rings must be much younger than the solar system (4.5 billion years). The most important micrometeorite size for erosion turns out to be ~ 0.01 cm.

A faint ring (the "Gossamer ring") has been discerned recently at Jupiter's synchronous radius (Showalter et al., 1986). They believe the material is of micron size and is locally produced at synchronous radius (2.24 Jovian radii, or RJ) from larger bodies. We (Northrop, Mendis, Fillius, 1986) have explained the presence of the ring as a consequence of charged dust migration towards synchronous radius either from moons Amalthea (2.54 RJ) or Thebe(3.11 RJ) or outward from the main ring, which extends from 1.72 RJ to 1.81 RJ. Migration towards synchronous radius from either side of it is a consequence of charge variation on the grain at the gyrofrequency, which in turn is caused by the varying velocity of the grain through the plasma as the grain gyrates and drifts. See Northrop and Hill (1983b) for the theory. There are also counteracting drifts which turn out to be at least two orders of magnitude smaller. One is the Poynting-Robertson, or photon drag radial motion, always inward. The other and much more significant one, but still slow compared to the charge variation drift, is that due to plasma drag, and is always directed away from synchronous radius. Both the charge variation and plasma drag effects vanish at synchronous radius and the Poynting-Robertson is very small.

At Amalthea (where the plasma drag effect is going to be about at its maximum), we find for typical dust and plasma parameters that the charge variation drift is inward at ~ 600 cm/s, the plasma drag drift is outward at ~ 6 cm/sec, and the Poynting-Robertson is inward at ~ 0.1 cm/sec. Thus the charge variation drift predominates.

2. Needed Research

The most important need by far is experimental measurement of erosion products of micrometeorite impacts at ~30 km/sec on ice and other materials. The size, velocity, angular, and charge state distributions are needed, as well as the total mass excavated. It is not possible to replicate this process by laser irradiation of the surface because of the large plasma blowoff which reflects the laser light and the intense local heating of the surface by the laser.

Small projectiles of the size and with the velocity needed have not been produced in the laboratory as yet. G.-T. Devices, Inc. of Alexandria, VA. are most likely to be able to do this in about a year, using high velocity and density plasmas to accelerate the particles.

IV. COLLECTIVE EFFECTS IN A DUSTY PLASMA

(C. Goertz, University of Iowa, Iowa City, IA; T. Northrop, Goddard Space Flight Center, Greenbelt, MD; E. Whipple, University of California at San Diego, La Jolla, CA)

1. Work Accomplished

The question of the average charge on a grain in a plasma dust mixture has recently received some renewed attention. Whereas the problem is relatively straightfoward when the intergrain distance, d, is much larger than the Debye length, λ, it is more complicated when this distance is smaller than the Debye length. In that case dust paticles electrostatically screen each other and the average charge is significantly less than the single grain ($d \gg \lambda$) case. We have shown that there are two counteracting effects and have studied them quantitatively as a function of interparticle spacing, plasma Debye length, and particle radius. The proximity of neighbors increases the capacitance of a given grain and therefore increases the charge needed on the grain to reach the potential required to equalize the ion and electron currents to its surface. But the second effect is that this required potential is greatly reduced by the presence of neighboring grains, which aid in depleting the electron density in the plasma with respect to the ions. The grain need not be as negative as in the absence of neighbors to equalize the ion and electron currents to its surface. This second effect always outweighs the first one.

For estimated parameters in Saturn's spokes, we find a grain charge of about 1% of that if the grains were widely separated in a plasma of the same Debye length.

This work has now been extended to include the effects of a dust size distribution. The results of the analysis are qualitatively similar to what was obtained for grains of a single size in a plasma. The depletion of electrons and the limiting of the charge on the dust grains depends on a parameter Z which is given by $Z = 4 \pi \lambda^2 N C$ for grains of a single size. In the case of a distribution of grain sizes, the same parameter can be used with the replacement of the single grain capacitance by the average capacitance.

The (linearised) steady state Poisson equation for the dust/plasma system was solved by Goertz and Ip (1984) and Whipple et al. (1985). In both papers the density of the plasma particles was described by a Boltzmann law involving the local potential in the plasma. This only holds when collisions are frequent enough to keep the distribution function Maxwellian. Recently Havnes et al (1986) have dropped this assumption and treated the collisionless case. In that case the distribution function for attracted particles has a hole in velocity space. They have found a surprising and potentially very significant result, namely that for small dust densities ($d > \lambda$), the plasma potential is positive even though the grain charge is negative. The plasma potential increases with increasing dust density until at a certain critical density (roughly given by $d \sim \lambda$) the plasma potential jumps discontinuously to a negative value. This would suggest that as long as the dust density is subcritical the dust grains, even though they are negatively charged, would attract each other and the density would increase up to the critical value beyond which the electric force on the dust particles is repulsive. This surprising phenomenan is due to the fact that a negative dust grain is surrounded by a positive charge density in the plasma. An instability is immediately suggested by this which would lead to density fluctuations and clumping of a dust cloud where average density is subcritical.

2. Needed Research

A shortcoming of the Havnes et al. (1986) work is the neglect of elastic collisions between plasma particles and charged grains which would act to smear out the hole in velocity space and reduce the effect. Thus elastic collisions need be included. Furthermore the time dependent evolution of a dust-plasma system needs to be investigated. It seems that only a numerical simulation can lead to real progress. A realistic simulation of the problem is impossible because of the vastly different scale lengths (varying from the grain radius a to the size of the dust cloud, $a \ll d < \lambda \ll L$) and time scales (ranging from the transit time of an electron past a grain to the plasma period and the ion acoustic transit time). Clearly the actual absorption and scattering process of particles by the grains must be approximated in some way. Work on this problem is in progress at the University of Iowa. The simulation will answer questions not only about the average charge and its fluctuations but also about the time scales for obtaining equilibrium, possible instabilities of the system and the effect of secondaries and photoelectrons on the plasma density and temperature. In addition the plasma potential and hence the electrostatic force on the dust grains can be determined and compared with the analytic work of Havnes et al. If their effect is also observed when collisions are included a further investigation of the clumping instability mentioned above should be undertaken.

V. LABORATORY STUDIES OF DUST/PLASMA INTERACTIONS
(R. Hazelton and E. Yadlowsky, Hy-Tech Research Co., Radford, VA)

1. Work Accomplished

As a part of an overall effort to understand the dynamics of dusty plasmas, Hy-Tech Research has developed a system capable of measuring the interaction of small (.01 to 1 micron diameter) particles with a background plasma. To produce the particles, bismuth is evaporated in a vacuum oven and nucleated in a cooled chamber. By differentially pumping the dust cloud through a series of orifices, a beam of dust particles (up to 2000 cm^{-3}) is produced which can then be directed through a plasma with electron densities ranging from 10^7 to 10^9 cm^{-3}. The charge distribution on the grains leaving the plasma is determined using a retarding potential analyzer. This technique works for particle densities as low as 30 cm^{-3}. The charge that a particle acquires passing through the plasma is, in general, a complex function of electron temperature, density, particle velocity and particle size. However, for the special case in which all particles come to the plasma floating potential, a simple analysis applied to the RPA data gives a particle size distribution which correlated well with size distributions derived from electron micrographs of collected dust particles.

An important aspect in the evolution of dust grains is the collisional processes that occur, including elastic collisions, inelastic collisions which increase internal energies, sticking collisions, and disruptive collisions. To study these processes a second dust beam has been added to the system which collides at 90 degrees to the original beam. Rayleigh scattering using a 5 mW Helium/Neon laser has been used to determine the beam density profiles and positions. Calculations show that the average particle scatters 1/2 photon while in the scattering volume, indicating that the present system is good for measuring collective effects but not individual particles.

To measure individual, charged particles resulting from a collision, an electron multiplier detection system is being developed. Initial measurements indicate that charged particles are being detected, with continued work being required to optimize and characterize the system and measure particle collision rates.

2. Needed Research

The preceding work has developed an experimental system which is capable of producing submicron grains and introducing them into a vacuum environment. In addition, diagnostics have been developed for measuring particle charge and size distributions and diagnostics are being developed to measure individual grain parameters. This system is uniquely suited to carrying out a number of experiments which would serve to test aspects of dusty plasma theory, investigate grain accretion and disruption processes and determine many basic properties of submicron particles relevant to their interaction with the space plasma and radiation environment.

There are a number of theoretical efforts investigating the effect of dust grains on the plasma environment. These theories predict the charging characteristics of grains, and plasma depletion effects, both of which need to be and can be tested experimentally using the system and techniques which have been developed. As an example Goertz (see above) has predicted that the plasma potential of a dusty plasma embedded in a background plasma can assume either a negative or positive plasma potential depending upon the relative plasma and particle densities. Using electron beam probes, the plasma potential of a beam channel could be measured and the theory tested.

Beyond this, many properties of submicron particles such as secondary electron yields, and photoemission have not been determined and are of great importance as basic data for use in theories of dusty plasmas which require an understanding of the detailed interaction of a particle and its environment. Again experiments involving the interaction of electron, ion and photon beams with free grains are needed to provide this data base. Various silicate and carbon submicron particles are available in bulk quantities from Los Alamos National Laboratories which would allow one, for the first time, to study the properties of materials of astrophysical interest.

Finally, grain-grain interactions are of great interest to further the understanding of particle growth or disruption for both charged and uncharged grains. Although the present laser scattering system is insufficient to see individual particles, upgrading to a 1 W argon ion laser would allow one to detect individual particles after a collision and provide information about collision rates and types.

In conclusion, there are many aspects of dusty plasma theories that can and should be tested in ground based laboratory experiments. Such experiments would eventually lead to a sufficient understanding of dusty plasma processes, to allow one to design an optimal space-based experiment where the micro-gravity environment would allow long term studies of dusty plasmas.

VI. FORMATION, GROWTH, AND DISPERSION OF GRAINS IN SPACE

(J. Stephens, Los Alamos National Laboratory, Los Alamos, NM)

1. Work Accomplished

The bulk of the workshop centered on theoretical aspects of plasma-dust interactions and the behavior of dust grains in a plasma at high particle concentrations. My area of interest lies in the formation, growth, aggregation, and orbital dynamics of interstellar and interplanetary dust materials, including silicates, SiC, graphite, and ices.

The formation conditions of both refractory and icy dust materials may be significantly affected by plasma-dust interactions. G. Arrhenius discussed at the workshop possible changes in the formation temperature of dust in a plasma relative to a neutral environment due to the presence of stable ion clusters. Ion clusters may increase by orders of magnitude the rates of chemical reactions which lead to dust formation. The presence of clusters may also have a major impact on the molecular species present in the molecular gas, favoring the formation of "nonequilibrium" dust materials and promoting dust condensation sequences which are disparate from those predicted from the thermodynamics of neutral systems. Once dust grains are present in the plasma, agglomeration kinetics can be significantly enhanced due to grain charge. Under astrophysical conditions, dusts composed of various materials may assume various potentials due to material dependent secondary ion, electron, and photoelectron yields.

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Differing dust charge may lead to differential motion of dusts resulting in enhanced grain agglomeration rates relative to the corresponding neutral aggregation processes. Material-selective agglomeration of dusts may also occur due to different potentials of various dust materials. By influencing the location, timing, and kinetics of dust formation and agglomeration, and hence the opacity of the region, the presence and properties of the local plasma may have a significant effect on the thermal balance of a star or evolving protosolar nebula.

The dynamics of dust formation, growth, and agglomeration in a plasma environment has been little studied experimentally, due to the difficulty in performing experiments and the rather specialized area of interest in materials of astrophysical interest. Some data are now available on the condensation behavior of silicates and water under neutral conditions. Data has been obtained on the stability of some ion clusters using molecular beam methods. Agglomeration studies have been carried out on high temperature materials, particularly metals, and for a number of common liquids. For refractory materials of interest (silicates, SiC, graphite) dust formation and agglomeration studies have been limited by short experimental timescales, due to limits imposed by thermally driven convection, gasdynamic limits inherent in the experimental technique, and particle settling times. Short timescales require working in the high particle formation rate regime to ensure the above effects have a small effect on the experimental results. The experimental regime presently employed places constraints on the possibilities of studying plasma effects on particle formation and behavior.

2. Needed Research

In order to study the plasma effects on dust formation and dynamics, lower gas densities are required to allow relatively high charged particle concentrations. Experiments should be performed at lower particle condensation rates. Possible experimental techniques to study the effect of ions concentrations on particle formation include using pulsed laser techniques to photoionize molecular species in a gas containing condensable species in a supersaturated state and monitoring the subsequent particle nucleation and growth. For refractory dusts, extension of existing experimental nucleation methods, including shock tubes, high temperature furnaces, and molecular beam methods could be employed. Ion induced formation of ices, particularly water ice, could be studied by extending existing diffusion cell and gas expansion methods. Inducing ion and electron formation using lasers has inherent limitations due to difficulty in monitoring the various chemical species concentrations and the disequilibrium of species due to the laser pulse.

There has been considerable interest in performing particle formation and agglomeration studies in a microgravity environment which reduces thermally driven convection, extends experimental timescales, and may allow gas densities to be reduced. Greater control of the gas phase density, temperature, and charged species concentration is potentially possible, allowing lower particle formation rates in the neutral environment, providing a greater relative effect of plasma-induced particle formation. Agglomeration studies, including the effect of particle charging, may be simplified in microgravity environment, resulting from the lack of gravitational settling of the particles and much reduced gas circulation driven agglomeration. Effort is required to determine the regime in which space experiments, as opposed to Earth laboratory experiments, are most suited.

An exciting possibility for studying the particle-plasma interactions applicable to astrophysical environments is to release well characterized particles in Earth orbit and monitor the behavior of the particles and local plasma. Phenomena such as grain orbital dynamics and grain alignment due to interaction with electric and magnetic fields are particularly well suited to in situ experiments. Work is now being pursued at the Los Alamos National Laboratory to study the ground-based facilities and spacecraft required to release well-characterized dust materials in Earth orbit and monitor the dust orbital dynamics and dust-plasma interactions. Modeling is being carried out to evaluate the probable behavior of dust released in Earth orbit and the observations necessary to monitor various phenomena of interest. By releasing various dust materials, including refractory dusts, volatile dusts, and special dust materials (for example superparamagnetic dust) it is hoped to elucidate the properties and dynamics of dusts in astrophysically related environments. The results may be applicable to cometary processes, dust formation and processes in protosolar nebula, and dust rings surrounding planets.

VII. SIMULATION STUDIES OF DUSTY PLASMAS

(T. Armstrong, University of Kansas, Lawrence, KS)

1. Work Accomplished

Small, solid particles are expected to coexist with plasmas in a variety of natural systems. Cool stars, comets, planetary rings, the interplanetary and interstellar media are familiar examples. Protostars and the early solar system are several others. Apparently the formation of most of the solid bodies in the cosmos is due to the condensation and accretion of material into solid particles which probably coexisted with at least partially ionized plasmas. The physical and chemical interactions of these small solid particles with each other and their surroundings (atmosphere, plasma, and parent body) are likely to be dominated by electrostatic and electromagnetic forces. The electrostatic state of small particles coexisting with a plasma is an important parameter to establish.

The determination of the electrostatic charge which resides on a small, solid particle in an environment which is at least partially ionized is a complicated problem. Among these complications are the effect of the shape and structure of the solid, the electrical conductivity and photo- and secondary electron yield of the material and possibly the past electrical history of the system. The energy and angular distributions of both the freely moving charges in the plasma environment and of the photo-and secondary electrons detemine the sign and magnitude of the electrical charge on the solid. Since time-stationary conditions require an electrical current balance between the particle and its environment, the electrical force in this time-stationary state will be that required to regulate the currents to the time-stationary, balanced condition. In simple geometry and with simple boundary conditions this problem can be solved by analytical techniques using current balance. However, with inner boundaries which lack symmetry or where anisotropy is introduced in the plasma distribution, analytical solution is not possible.

Numerical simulation, however, can allow the calculation of the behavior of representative cases from which insight may be gained. Our approach is to follow randomly selected incident plasma charges using numerical integration of the Newtonian equations of motion. The dominant interaction in many interesting cases is between the incident particle and the charges already present on the solid. Providing that these are the most important interactions in the system and that they can be represented by a limited number of Couloumbic interactions between the incident particle and the fixed charges, one of the more difficult and numerically challenging aspects of self-consistent plasma simulation can be circumvented -- namely, the solution of Poissons's equation for the potential in three dimensions and with a complicated interior boundary condition. If the time scale for the relaxation of the charge distribution on the solid by exchange of charge with its surroundings is shorter than the other time scales of the problem, then the simulation is further simplified in that only a time stationary state is needed. After a sufficiently large number of test particles have been presented to the system and the charge state of the solid has attained a time independent value (allowing, of course, for purely statistical fluctuation) the state of the simulation probably represents that attained in nature.

Preliminary simulations have already been run on micron-sized, electrically insulating, cubical grains in plasma conditions characteristic of low Earth orbit (except for being at rest with respect to the plasma). Time stationary states are obtained after a few tens of thousands of test particles have been injected into the system. The equilibrium electrical potential (-2.7 kTe/e) attained by the grain at low plasma temperatures is well approximated by analytical calculation for spherical grains (-2.5 kTe/e). This gives some assurance that the simulation techniques are reasonable and that the numerical representation is accurate.

2. Needed Research

The simple description given above, however, leads to a rich variety of complications when a simulation is implemented. Clearly, the characteristics of the solid material play an important role. Most prominent among these are the secondary and photoelectron emission characteristics of the material. Electrical conductivity, dielectric coefficient, and sputtering probabilities, electron affinities, and chemical characteristics of the surface all are important in some parameter domain. The geometries and scale sizes are also expected to affect the charge states which will be attained. For example, the secondary electron yield determines the effective incident plasma temperature at which grains would become positively rather negatively charged which is the usual case at low plasma temperatures. The energy spectrum of the secondary electrons determines the level to which positive electrical charging occurs.

The emission of secondary electron emission caused by plasma particles impacting on the surface of the solid changes the equilibrium potential from negative to positive if the number of secondaries escaping from the grain exceeds the number of incident electrons. For many materials of interest, especially electrically insulating, refractory materials such as silicon dioxide, the yield can be large -- as high as 8 or 10 secondaries per primary. Incident electrons must arrive at the surface of the grain with sufficient energy to produce a secondary for this process to be significant. Once secondaries are generated, they will escape unless the grain has attained sufficient positive charge to prevent their escape. The equilibrium results from the competition of the several factors which influence the electrical charge on the grain.

Clearly, mixtures of grains of different composition, streaming plasmas, plasmas with suprathermal tails, or differing electron and ion temperatures offer a rich spectrum of responses of dust grains in the presence of plasma. Naturally occurring dusty plasmas probably exhibit most of these characteristics.

VIII. THE EFFECTS OF CHARGED DUST GRAINS ON MOLECULAR EXCITATION AND INFRARED EMISSION

(R. Puetter and I. Krinsky, University of California at San Diego, La Jolla, CA)

1. Work Accomplished

It has long been known that interstellar grains have an electric charge. Simple arguments give electrostatic potentials of a few times kT of the gas. Depending on local conditions either positive or negative potentials can be obtained. Thus, for grains with a radius of 0.03 microns, the electric field, E, at the grain surface will be of the order 10^6 volts per centimeter or 3×10^3 in cgs units. Smaller particles would acquire a higher surface field, resulting in field emission. Furthermore, particle breakup will occur under such high fields, especially if the tensile strength of the particles is low such as in loose particle agregates. At the smallest sizes (e.g. a few times 10^{-3} microns) only strong refractory grain cores are able to survive particle potentials of a few volts (Hill and Mendis 1979).

The Stark broadening of a rigid rotator in an electric field can be easily calculated, giving a shift in the rotational energy, E_{rot}, of $\Delta E_{rot} = d E$ where d is the permanent dipole of the molecule. Since molecules typically have permanent dipoles on the order of a few debyes (1 debye = 10^{-18} esu cm), we find $\Delta E_{rot} / E_{rot} > 1$. Hence under these conditions the Stark effect causes any rotational sub-structure to be "washed out".

The presence of charged grains also affects the collision cross sections of charged particles. The enhancement to the collision cross section over the geometric cross section is well known and is given by $Q = 1 + (ZeV/kT)$, where e is the elementary charge, Z is the number of charges on the particle, V is the potential of the grain, and T is the kinetic temperature of the particle. Interstellar conditions give Q to be from 1 to a few hundred.

We would also like to point out that charged grains may give rise to the well known unidentified infrared (UIR) emission features seen at wavelengths of 3.3, 3.4, 3.5, 6.2, 7.7, 8.6, and 11.3 microns in a wide range of astrophysical objects (Willner et al. 1977). These features apparently originate in the interface regions between the hot H II gas and the molecular cloud material (see Willner et al. 1979 and references therein). The interface region is the only area where it is expected that charged dust and molecules can coexist. Consequently, such a spatial correlation naturally suggests a relationship between the UIR emissions and charged grains. Other explanations for the UIR emissions have been proposed but none is completely satisfactory (see Dwek, Sellgren, Soifer, and Werner 1980).

There might be several ways in which charged grains could give rise to the unidentified emission features. First, charged molecular ions might be attracted to charged grains, accelerated to several electron volt kinetic energies, and collide into the grain. Such collisions would certainly have sufficient energy to excite vibrational transitions, if not sufficient to break up the molecule. Furthermore, observations show that the 3.3 micron feature does not break up into the standard rotation-vibration structure under high spectral resolution (Grasdalen and Joyce, 1976; and Tokunaga and Young, 1980). The Stark effect would destroy the typical rotational sub-structure since adjacent rotational states would be smeared together. A second senario would involve close passage of molecules and grains. Classical calculations of molecular proportioned, dipole rigid rotators demonstrate that the torques exerted on molecules during a grain passage can change the rotational energy of the molecule on the order of the dipole-electric field energy. Once the molecule is in such excited rotational states, it might be possible for rotation-vibration coupling to distribute the energy into vibrational motion.

Calculations, however, show that in order to produce the intensity of the observed emissions, the density of particles in the interaction region needs to be enhanced over the average background (Puetter and Krinsky, 1985). An experiment has been designed and partially built in order to test the efficiency of the proposed mechanisms.

In our experiment, charged grains are represented by thin wires in a metallic brush. The wires, while larger than the interstellar grains are charged to a correspondingly higher potential in order to keep to magnitude of the electric field at the surface comparable. The experiment is designed to run at either room or cryogenic temperatures. In this manner it should be possible to determine the effects of molecules frozen onto the grain surface. Since it has been proposed that the unidentified infrared emission lines might correspond to stretching and bending modes of the various bonds of carbon and hydrogen atoms, hydrocarbons with dipole moments are primarily used as test gases.

2. Needed Research

Further investigation, especially experimental, is needed to determine the effects of charge on interstellar particles. Features discussed here, such as electrostatic grain rupture, Stark broadening, and collisional cross section enhancement may also be important in processes other than UIR emission. Indications of other mechanisms associated with dusty plasmas in the interstellar medium may come from a comparison of H I and H II regions since both are known to contain dust but at very different electric potentials.

IX. OUTSTANDING QUESTIONS

At the conclusion of the workshop the participants were asked to list what they felt were the outstanding questions about dusty plasmas that needed to be addressed. These questions (or statements) as they were given and the name of the questioner are listed below.

1. (H. Alfven) Rosseland electric fields, caused by separation of charges, and their effects on grain/plasma interactions should be investigated.

2. (H. Alfven) Every theoretical idea needs laboratory verification. Experiments should be simple with the single aim of testing a concept.

3. (R. Hazelton) Effects like a potential variation within a plasma caused by dust should be measured in the laboratory. Size effects on electron emission from grains should be measured.

4. (J. Stephens) Experiments should be extended into space to get away from wall effects, small volumes, and gravity. (Note: there is a sub-group of the Banks committee on experiments in space which is concerned with experiments using particulates.)

5. (J. Stephens) How does the chemistry of different materials affect the processes occuring at grain surfaces?

6. (C. McIlwain) Experiments involving "artificial comets" such as ejected dust clouds are worthwhile even though they are not identical to real comets, as long as they give insight into physical processes.

7. (C. McIlwain) There are many processes involving dust--apart from a plasma--which deserve investigation in their own right.

8. (C. McIlwain) We did not address in detail at this workshop some of the astrophysical regimes and processes. We need to involve more astrophysicists in this area.

9. (M. Horanyi) Access to supercomputers--in addition to the Florida supercomputer--should be sought for simulation work.

10. (M. Horanyi) The Department of Energy supports plasma physics research and we should interest them in the field of dusty plasmas.

11. (T. Northrop) The "Two-thirds Fall Down Effect" needs to be quantitatively investigated further and written up for publication.

12. (T. Northrop) Where do the Uranus ring erosion products go?

13. (T. Northrop) What are the products of hyper-velocity (5 to 50 km/sec) impacts of micrometorites on materials? Simulation studies can perhaps be done here and experimentally verified in one regime, and then extrapolated to other regimes. Perhaps lasers could be used to evaporate a spot to study some of the processes.

14. (I. Krinsky) Any dusty plasma effects that could lead to predictions of observational conseqwuences for astronomers should be pursued.

15. (A. Mendis) Experiments should be done on ice and other materials that actually occur in space (e.g. in the rings) to measure photoyields, secondary emission coefficients, etc.

16. (A. Mendis) The idea of inhomogeneous nucleation and the effects of charge on nucleation should be pursued both experimentally and theoretically.

17. (A. Mendis) Dust debris in the earth's environment needs work.

18. (A. Mendis) Different ideas on the formation of ringlets should be pursued. However, the most important problem is how a ring can be collapsed into one body (longitudinal focussing): i.e. how a cloud goes to a ring, then goes to ringlets, then goes to moons.

19. (A. Mendis) Collective effects such as waves in a dusty plasma need investigation.

20. (T. Northrop) The drag on grains due to wave radiation needs investigation.

21. (E. Whipple) The "electrostatics" of a dusty plasma needs to have the motions of grains put into the theory.

22. (E. Whipple) It would be useful to develop spacecraft-carried remote sensing techniques such as radar or lidar scattering to obtain information on dust on a macroscopic scale in space.

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