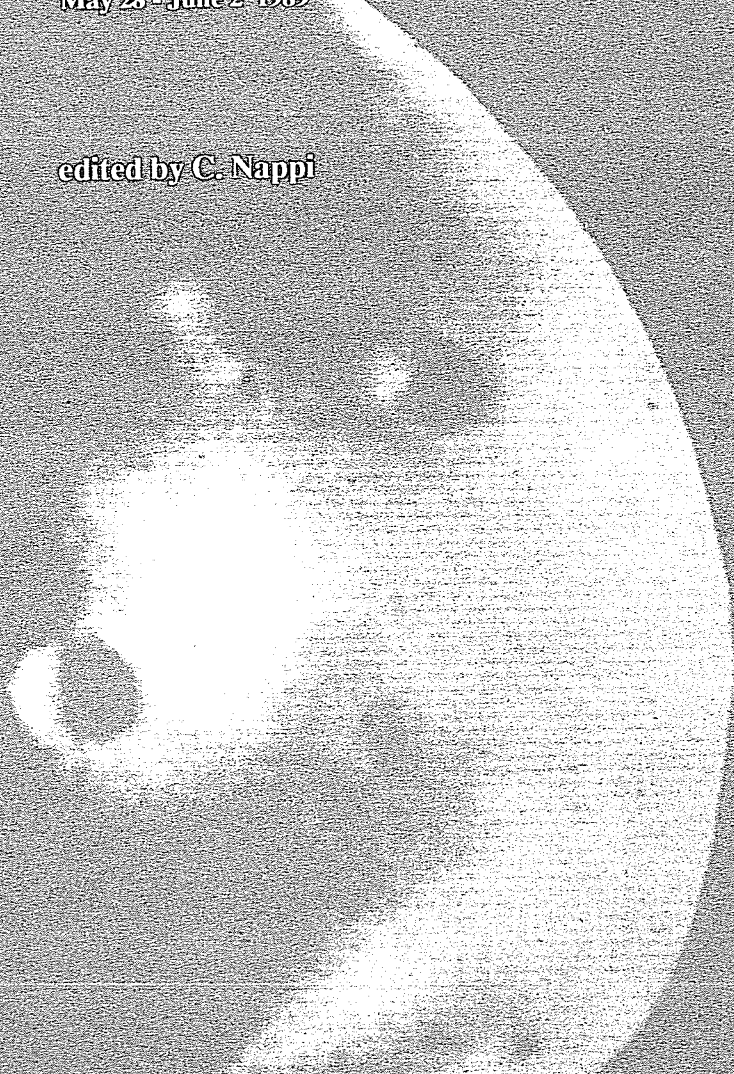
Proceedings of the

# FIRST CAPRI WORKSHOP ON DUSTY PLASMAS

May 28 - June 2 1989

edited by C. Nappi



Consiglio Nazionale delle Ricerche
Istituto di Cibernetica

Arco Felice, Napoli, Italy

# FIRST CAPRI WORKSHOP ON DUSTY PLASMA

**May 28 - June 2, 1989**

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## PREFACE

This proceedings contain a record of work presented at "First Capri Workshop on Dusty Plasmas" which took place in the island of Capri from May 28 to June 2, 1989.

I will not repeat what seems, now, a well accepted point of view on how decisive has become, in space plasma physics, the understanding of those phenomena involving charged dust as a fundamental component.

During the four days of the meeting, the partecipants experienced lectures and, more importantly, stimulating informal discussions triggered by the friendly atmosphere.

A very remarkable character of this meeting - the first in Europe in this subject, as far as I know - was the presence, besides that of space physicists, scientists from plasma theory as well as from active laboratory plasma physics, attracted by this relatively new subject. Such a combination proved to be both stimulating and fruitful.

The contributions of all partecipants, ordered as in the original agenda of the lectures, in the form of a brief communication or, in a few cases, of an extended abstract are presented.

Starting from the first workshop on this subject, organized by Dr. Elden C. Whipple at the University of California, San Diego on february 1986, considerable work has been done but much more deserves certanly to be investigated as testified by the richness of ideas and different points of view contained in the following pages.

I wish to express my sincere thanks to Mrs. Annamaria Mazzarella for her precious and continuous assistance in the organization of the meeting and to Mrs. M. Izzo and Mrs. De Feo for helping me in the editing of these proceedings.

Finally I want to thank, once more, all the participants who were involved in the success of this initiative.

The Local Organizer

*Ciro Nappi*

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## CONTENTS

# Dusty Plasmas in Space: A Review

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A dusty plasma is loosely defined as a fully or partially ionized gas containing dispersed particles of solid material. The early motivation for studying the role of dust or particulate contaminants in plasma came from astrophysics (the role of dust in interstellar clouds), from space physics (especially after the discovery of micron-sized dust grains in planetary ring environments) and from laboratory physics (plasma-wall interaction and associated contamination in tokamaks and MHD generators). Of course, dusty plasmas are ubiquitus, occurring not only in planetary rings, interstellar clouds and as an unwanted side-effect in laboratory fusion experiments. Other sites are and other problems occur in: planetary atmosphere, thunderclouds, volcanic plumes, rocket exhausts, the ionosphere - where the "dust" is either the result of meteor ablation product, condensates or man-made pollution- the zodiacal light cloud in the interplanetary medium, comets, circumstellar disks - identified by their infrared excess- cool stellar envelopes, nova ejecta, protostellar and protoplanetary clouds, where some dusty plasma processes may play key roles in understanding the formation of the solar system etc.

Each of these environments has its own characteristic "signature" in terms of its plasma and dust properties. For instance, typical conditions in interstellar clouds are: neutral gas density n $\sim 10^4$ cm$^{-3}$, ion density $n_i \sim 10^{-3}$ cm$^{-3}$, dust particle density $\sim 10^{-7}$ cm$^{-3}$, temperature T $\sim$ 10K. In the protoplanetary cloud, characteristic conditions in e.g. the formation region of Jupiter are estimated to have been: $n \sim 10^{12}$ cm$^{-3}$, $n_i \sim 1$cm$^{-3}$, $n_d \sim 10^{-2} n_i$, T $\sim$ 150K. In the ionosphere at about 80 km, where the noctilucent clouds are observed, we have typically: $n \sim 10^{14}$ cm$^{-3}$, $n_i \sim 10^3$ cm$^{-3}$, $n_d \sim$ 10cm$^{-3}$, T $\sim$ 150 K. In Saturn's E-ring, between 4 and 5 Saturn Radii distance from planet's centre, we have $n \sim 1$cm$^{-3}$, $n_i \sim 20$ cm$^{-3}$, $n^d \sim 10^{-7}$ cm$^{-3}$, and T $\sim 10^6$K and in terrestrial lightning strokes, a phenomenon intimately connected with charge transport by "dust" (ice particles or drops), the values just after the discharge are typically $n_i \sim 10^{19} cm^{-3}$, $n < n_i$, $n_d$ $10 cm^{-3}$, $T \sim 20000$ K. Recombination and expansion of the discharge channel lead to rapid changes in these values, also it is likely that the particulates in the discharge channel become evaporated.

Clearly, the field of "dusty plasmas" promises to be a very rewarding topic of research for the next decade or so, not only from the academic point of view where the emphasis is on developing the theory of the often complex collective and non linear processes, but also from the point of view of applications in astrophysics, space physics, environmental and energy research.

In this review we would like to sketch the current development of this fast growing and potentially very important research area. We will discuss the new features of "dusty" plasmas in the most general terms and then brifly mention some successful applications and effects which have already been examined.

For a systematic study of "dusty plasmas" proper account has to be taken of the new component introduced, the microphysics and the macroscopic effects usually ascribed to the moments. Quite generally, the distribution function of such a multicomponent system is $f(\mathbf{x},\mathbf{p},t,Q,m)$, and we can build up the theoretical description by starting with a monodispersive dust distribution and photoelectrons, the system being maintained by UV bombardement. Then, in order of increasing complexity, ions can be introduced, neutrals, more complicated dust size distribution etc. For the moment description care must be taken to define average quantities correctly, to properly identify systematic and random motions, to utilize hierarchies of length and time scales in the proper ordering of the therms and to physically describe correlations and correlation functions where appropriate.

The major new feature introduced by the dust, which have already received some attention, are: we are dealing with a massive component much greater then the mass of the plasma ions, this massive component has multiple charges, it introduces strong inhomogeneities in the plasma on scales of a Debye length and perturbations on longer scales, dust can act as a source or asink for the plasma, possibly introducing compositional changes, and the dust particles are subject to non-electromagnetic forces, which in principle enables the plasma collectively to capitalise on the associated energy source (e.g. gravity, friction, radiation pressure).

## Astrophysics

Most of the work here has concentrated on the role of dust in the way iy affects the opacity and the chemistry of interstellar clouds, an important example of the latter being the reaction H + H → H2, which predominantly takes place on grain surface. Other important effects which have been considered already are recombinaton on grain surfaces, which dominates over gas phase recombination at cloud gas densities greater than about 10 6 cm-3 assuming standard conditions, the role of dust in the ambipolar diffusion in magnetic field from contracting cloud, sputtering of dust in astrophysical shocks, shock structure due to the inertia and current carried by dust particles, the effects of dust on the damping of Alfvén waves and the dynamical role the dust may play in trasferring momentum, which has been obtained due to the action of radiation pressure in circumstellar environments, onto the ambient plasma. This brief summary is not exhaustive, but it is clear that the concentration has been on physical processes involving grains as a catalyst and on fluid treatments.

Nonlinear effects associated with local perturbations of the plasma by the grains have not been investigated yet, but also there are still a large number of outstanding problems requiring multi-fluid approaches as well as identifying new grain related microscopic processes of relevance to particular astrophysical stuations.

## Solar System

One of the most recent areas of interest in dusty plasmas in the solar system, and also one of the most surprising and succusful, has been the investigation of the role that micron-sized particles play in their interaction with planetary magnetospheres - both the plasma and the electromagnetic fields. A great deal of work has been done on the various charging processes of grains (e.g. photoeffect efficiencies, secondary electron emission, field emission), on the erosion processes (e.g. particle impact sputtering, photosputtering, chemosputtering), on the production of meteoroid impact plasmas etc. Work is progressing on test particle theory, calculating the orbit dynamic of charged grains, which are subject to gravitational forces, plasma drag and electromagnetic forces. This gives rise to new phenomena, e.g. gyrophase drift and gradient drifts. The gyrophase drift comes about because a dust particle cannot charge up to its equilibrium charge instantaneously - there is a dalay causing the electromagnetic force to change both the eccentricity and the energy of the particle orbits. Similar effects occur when there are gradients (in the magnetosphere) in plasma temperature, density or composition. this test particle work is of importance in understanding the tenuous rings, their life time and hence their origin, no attempt is made to incorporate backreactions or other effects on the plasma.

However, four such approaches exist, each one being problem specific, but having possibly also wider applications. the first one, chronologically, was a model for the "spokes" in Saturn's B-ring. These dark radial features are identified as consisting of small micron sized dust particles elevated above the ring plane and partially blocking the reflected light from the B-ring. The most important features that need to be explained are the rapid formation time (less than 300 s) the radial alignment at formation, and of course the production mechanism. The only model so far, which explains the available data, is the so called "plasma cloud model". A plasma cloud forms over the B-ring (possibly due to meteorite impact), and elevates and charges the resident small dust grains. If the plasma cloud corotates with Saturn's magnetic field, whereas the dust grains move essentially on slightly modified Kepler orbits, there is a charge separation driven by gravity. This drives a current that closes in the planet's ionosphere. The resultant azimuthal electric field then gives the plasma cloud a radial $\mathbf{E} \times \mathbf{B}$ drift. The plasma is thus forced by the action of the dust to move radially away from synchronous orbit. In doing so, it moves across new B-ring regions, elevates fresh dust, charges it and ultimately provides itself with its own "fuel" so that it can keep going. The "spokes" in this picture is then the manifestation of the plasma cloud path, seen in the dust which it has elevated above the ring plane - not unlike the signature of a car travelling along a desert track.

A second feature associated with the "spokes" touches on celestial mechanics. It is easy to show that electromagnetic forces acting on Saturn's main rings would be able to transfer angular momentum from the planet outside the syncronous orbit, $R_{sy}$, thus speeding up the ring, whereas inside $R_{sy}$ the ring transfers angular momentum to and evolves inward. The time scale for this transfer exceedes the age of the universe by many orders of magnitude, however, so that this process is rather ineffective. When this process is examined via the spoke dust particles and the much larger charge they carry, it turns out that electromagnetic angular momentum transport may be the dominant process determining the structure of Saturn's ring system. Not only is the angular momentum transfer time drastically shortened, giving a "ring age" of around 50 million years, but in addition it was discovered that there are small scale instabilities so that small and large csale structures are predicted which explain the observed optival depth profile of the B-ring extremely well.

Another recent application is a self consistent theory explaining Saturn's Oxigen plasma torus and the properties of the E-ring. In this picture, the E-ring particles can be treated dynamically as test particles (the ring is sufficiently diffuse). The non linear coupling to the plasma arises from the fact that they are themselves the source of the plasma (by self-sputtering) and that this determines their rate of erosion as well as the radial transport by plasma drag. This theory explains the plasma properties, such as for instance the anisotropy of the ions, as well as the observed radial optical depth profile of the E-ring.

As a last point, work has been in progress to calculate the vertical thickness of planetary rings taking into account selfconsistently the gravitational and electrical forces by calculating the ring potential and plasma potential resulting from charging of the grains. It is interesting that this latest work has led to apossibly very exciting application in so far that for some parameters of plasma temperature, density and particle sizes and densities it may be possible to obtain "Coulomb lattices", self ordering of an overall neutral plasma into a quasi solid. For this exciting application, where the plasma is self-organized, we may expect a whole new set of phenomena, both unlike plasma processes and unlike solid state processes. Particle or hybrid simulations should be performed to investigate this strange form of matter, and laboratory work, in particular, is also needed.

Outstanding problems are many in solar system dusty plasmas. We have only mentioned planetary rings above, but we should not forget the traditional field of cometary physics, and particularly our own planetary environment. Recently it has been suggested that "noctilucent clouds" may have their origin in pollution. These "clouds", located at about 80 Km and visible during the northpolar summer season, are embebbed in a partially ionized plasma. They may affect radio signals and should be studied both theoretically and experimentally with a high priority, as a way of predicting how earthbound pollution may possibly affect our environment even above the Ozone layer!

Summarizing this review we have tried to show some of the highlights in "dusty plasma physics" and have given excerpts of some of the work that has already been done in laboratories, in basic theory of microscopic processes, in collective and non linear theory, as well as some application to space and astrophysics. We have mentioned some of the outstanding problems as we see them, bearing in mind that that the whole field is still in its infancy when compared to e.g. traditional plasma physics, and correspondingly undeveloped. We have tried to show that applications in space, in laboratory and in our own environment are plentiful, providing ample scope for important applied and fundamental research.

# Probe theories relevant to dusty plasmas

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Abstract A review is given of the theories of positive ion collection by a probe.

The floating potential acquired by a charged dust particle is clearly analogous to the floating potential of a spherical probe. In this talk I shall review the relevant theories of positive ion collection by a probe. The floating potential is attained when the electron and ion currents are equalized. I shall not follow a chronological sequence but rather one of increasing sophistication, following the order shown in the table.

1. Bohm (1949) considered a sheath model which incorporated monoenergetic ions and Maxwellian electrons. He also considered a thin sheath in which ionization was negligible. The principal result of this work was that the entrance velocity of the ions at the sheath edge is given by

$$v_i \geq [kT_e/M]^{1/2} \qquad (1)$$

Although his theory leads to an inequality sign a consideration of both the plasma and the sheath leads to an equality sign.

$$v_i = [kT_e/M]^{1/2} \qquad (2)$$

Reference can be made to a paper by Caruso and Cavaliere (1962) for a further discussion of the plasma-sheath model. This "thin-sheath" calculation leads to a positive ion current which is independent of the probe potential.

2. Allen, Boyd and Reynolds (1957) performed calculations for a spherical probe assuming cold ions and radial motion. Two situations were considered, namely a thin sheath where $\lambda_d \ll r_p$ and a thick sheath where $\lambda_d \sim r_p$. In the first case Bohm's result was found again, with the equality sign, this time by considering the plasma and not the sheath. Numerical calculations were carried out for the case where $\lambda_d \sim r_p$. Subsequently the range of parameters was extended by Allen and Turrin (1964) and by Chen (1965). The calculations of Chen also included the cylindrical case. Current-voltage characteristics are obtained from these calculations.

3. In certain cases the probe current is limited by orbital motion. This theory is based on the conservation of angular momentum and the conservation of energy. Another assumption, however, is that some particles (of every speed) hit the probe at grazing incidence. It is a simple matter to derive the formulae

$$J_i = \frac{2}{\sqrt{\pi}}\, neA\, (kT_i/2\pi M)^{1/2}\, (1 - eV_p/kT_i)^{1/2} \qquad (3)$$

and $$J_i = neA\, (kT_i/2\pi M)^{1/2}\, (1 - eV_p/kT_i) \qquad (4)$$

for the cylindrical and spherical probe respectively (Lea and Allen, 1982). Historically these results were first obtained by Mott-Smith and Langmuir for the case of an infinitely large "sheath" (1926). In practice the particles may not have the trajectories assumed in this theory. They may instead graze a geometrical surface with an "absorption radius" larger than the radius of the probe. The condition which must hold for no absorption radius to exist is

$$V(r) > V_p\left(\frac{r_p}{r}\right)^2 \qquad (5)$$

4. Bohm, Burhop and Massey (1949) considered ions with a random distribution of velocities, but a single energy. The thin sheath was considered and the absorption radius found, for different values of the ion temperature. The results were

$$J_i = 0.57 \text{ neA } [kT_e/M]^{1/2} \qquad (6)$$

when the ion energy was 0.01 $kT_e$ and

$$J_i = 0.54 \text{ neA } [kT_e/M]^{1/2} \qquad (7)$$

when the ion energy was 0.5kTe.

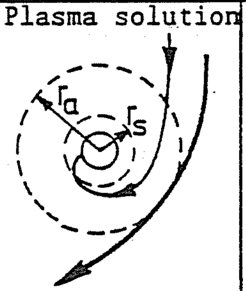
5. Bernstein and Rabinowitz (1959) extended the theory to the thick sheath case. The numerical calculations give current voltage characteristics for the probe. Again the calculations have been extended by Chen (loc.cit).

6. Laframboise (1966) has further extended the theory by including a Maxwellian distribution of particle energies. This represents the most detailed description of positive ion collection by a probe. In certain cases the current is limited by the orbital motion.

Analytical formulae which fit Laframboise's numerical results, to within about 3 per cent, have been given by Kiel (1968, 1971) and by Peterson and Talbot (1970).

7. Mention must be made here of recent experimental work by Allen, Annaratone and Allen (1988). Measurements were made with an R.F. discharge in argon, using a technique developed by Braithwaite, Benjamin and Allen (1987). It was found that there was agreement with the simple ABR theory and not with the more sophisticated theory of Laframboise (loc.cit). The detailed comparison was made using a Sonin plot (Sonin, 1966) and Chen's numerical calculations. I shall not attempt, in this lecture, to give a detailed explanation of this behaviour. We can note, however, that the plasma is not entirely collision-free nor infinitely large. This means that the (cold) ions do not have the distribution of angular momenta assigned to them in the calculations of Laframboise. One factor to be considered is the effect of ion-ion collisions (Allen, M.W., 1988). Further discussion can be found in the textbook by Chung et al (1975) and in papers by Hester and Sonin (1970), Stangeby and Allen (1971) and Lea and Allen (loc.cit). It is clear that the choice of which probe theory to employ in a particular situation is not a trivial one.

THEORIES OF POSITIVE ION COLLECTION

| Authors | Hypothesis | Equations | Symmetry | $J_+=f(V_p)$ |
|---|---|---|---|---|
| Bohm | thin sheath<br>$r_p/\lambda_D=\infty$ | $J_i=nev_i$<br>$v_i=\left[kT_e/M\right]^{1/2}$ | P | $J_+=ne\left[\frac{kT_e}{M}\right]^{1/2}$<br>constant in $V_p$ |
| Allen, Boyd and Reynolds (Chen) | $0.5\leq r_p/\lambda_D\leq 70$<br>radial motion<br>$T_i = 0$ | $\nabla^2 V=-\frac{e}{\varepsilon_o}(n_i-n_e)$<br>$n_e \propto e^{eV/kT_e}$<br>$n_i \propto \frac{1}{v_i r}$ or $\frac{1}{v_i r^2}$ | C,S | graphical curves |
| Langmuir & Mott-Smith | infinite sheath<br>$T_i\neq 0$<br>$V(r)>V_p\left[\frac{r_p}{r}\right]^2$<br>no absorption radius | $E=\frac{1}{2}mv_i^2+U_i(r,\Omega)$<br>$U_i(r,\Omega)=eV(r)+\frac{\Omega^2}{2m_i r^2}$ | C,S | analytical solution<br>$J_+ \propto \left[1-eV_p/kT_i\right]$ (spherical probes)<br>$J_+ \propto \left[1-eV_p/kT_i\right]^{1/2}$ (cylindrical probes) |
| Bohm, Burhop and Massey | thin sheath<br>$Ti\neq 0$<br>monenergetic ions,<br>absorption radius | Plasma solution<br> | S | $J_+=xne\left[\frac{kTe}{M}\right]^{1/2}$<br>$x=f\left[\frac{T+}{Te}\right]$<br>constant in $V_p$ |
| Bernstein & Rabinowitz (Chen) | thick sheath $5\leq r_p/\lambda_D\leq 15$<br>$Ti\neq 0$<br>monenergetic ions, absorption radius | Classification of the orbits<br>$\nabla^2 V=\frac{-e}{\varepsilon_o}(n_i-n_e)$ | C,S | graphical curves |
| Laframboise (Kiel; Peterson & Talbot) | wide range of: $r_p/\lambda_D$, $Ti/Te$, $V_p$<br>Maxwellian distribution of ions | $\nabla^2 V=\frac{-e}{\varepsilon_o}(n_i-n_e)$ | C,S | graphical curves<br>(several approximate analytical fits) |

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* These are the key papers summarized in the table.

Paper presented at: Workshop on Dusty Plasmas, Capri, Italy, 28 May - 1 June, 1989

# Current Collection by Objects of Arbitrary Shape in Collisionless Plasmas at Large Debye Length

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## ABSTRACT

This paper is intended as a tutorial review of some elementary ideas. Most of it is contained in Laframboise and Parker (1973). They considered charged-particle velocity distributions in potential wells having various symmetries. They considered a collisionless gas in which all particles have the same mass $m$ and charge $q$ (e.g. either the ions or electrons in a plasma), in the presence of a hypothetical potential well which has either a three-, two-, or one-dimensional configuration, as defined, respectively, by the relations: $q\phi(x,y,z) \leq 0, \phi \to 0$ as $x^2+y^2+z^2 \to \infty; q\phi(x,y) \leq 0, \phi \to 0$ as $x^2+y^2 \to \infty; q\phi(x) \leq 0, \phi \to 0$ as $|x| \to \infty$, where $\phi$ is electric potential. These wells, in general, have no other particular symmetry; e.g. the three-dimensional well need not be spherically symmetric. Assuming also that these wells contain no obstacles (such as probes or dust particles), Laframboise and Parker (1973) showed that the velocity distribution function (one-particle phase-space density) $f$, at a location $\mathbf{r} = (x,y,z)$, is given by the usual Maxwell-Boltzmann distribution:

$$f(\mathbf{v}) = n_\infty \left(\frac{m}{2\pi kT}\right)^{3/2} exp\left[-\frac{mv^2}{2kT} - \frac{q\phi(\mathbf{r})}{kT}\right] \qquad (1)$$

over the portion of velocity space excluding, respectively: the spherical region $v_x^2+v_y^2+v_z^2 < -2q\phi(x,y,z)/m$; the cylindrical region $v_x^2+v_y^2 < -2q\phi(x,y)/m$; and the interplanar region $v_x^2 < -2q\phi(x)/m$. Inside these regions, $f = 0$. Integration of these three distributions over velocity space then yielded:

$$n/n_o = \left(2/\pi^{\frac{1}{2}}\right)\left[\psi^{\frac{1}{2}} + g\left(\psi^{\frac{1}{2}}\right)\right] \geq 1; \quad j = 1 + \psi \tag{2}$$

$$n/n_o = 1; \qquad j = \left(2/\pi^{\frac{1}{2}}\right)\left[\psi^{\frac{1}{2}} + g\left(\psi^{\frac{1}{2}}\right)\right] \tag{3}$$

$$n/n_o = \left(2/\pi^{\frac{1}{2}}\right) g\left(\psi^{\frac{1}{2}}\right) \leq 1; \qquad j = 1 \tag{4}$$

in three-, two-, and one-dimensional wells, respectively, where:

$$\psi = -q\phi/kT \geq 0$$

$$g(s) = \frac{1}{2}\pi^{\frac{1}{2}} exp(s^2) erfc(s) = exp(s^2) \int_s^\infty exp(-t^2) dt$$

$$\text{and}: g(0) = \frac{1}{2}\pi^{\frac{1}{2}};\ g(s) \to 1/(2s) \text{ as } s \to \infty,$$

where $n$ is number density, $j = J/J_o, J$ is the flux onto one side of an oriented surface element, $n_o$ and $J_o$ are the values of $n$ and $J$ when $\phi = 0, k$ is Boltzmann's constant, and $T$ is temperature. $J_o$ is therefore the random flux $n_\infty (kT/2\pi m)^{\frac{1}{2}}$, where $n_\infty$ is number density at infinite distance from the well; by definition $n_\infty = n_o$. If the $j$ in Eqs. (2) and (3) are multiplied by the surface area of a probe at whose surface $\psi$ has the value $\psi_p$, the Mott-Smith and Langmuir (1926) expressions for orbit-limited flux collection by a spherical or cylindrical probe, respectively, are recovered, without any assumptions about rotational symmetry of the respective potential wells.

In making the connection between these results for obstacle-free potential wells and their use for probes, Laframboise and Parker (1973) also generalized the orbit-limited condition, which in its most basic form for the three-dimensional case states that all of the positive-total-energy $(E = \frac{1}{2}mv^2 + q\phi > 0)$ orbits which end at any given point on the probe, shall have originated at infinity rather than elsewhere on the probe, and therefore are populated rather than empty. This definition implies that the orbit-limited flux is an upper bound for collisionless conditions regardless of the form of the sheath potential, the shape of the probe, nonuniformities in the probe surface potential, or the presence of magnetic fields. Some resulting consequences have been explored by Laframboise and Parker (1973), Laframboise and Rubinstein (1976), Parker and Laframboise (1978), and Rubinstein and Laframboise (1978, 1982, 1983). In the two-dimensional case, the same requirement applies to particles having positive total transverse energy $[E_\perp = \frac{1}{2}m(v_x^2 + v_y^2) + q\phi > 0]$; this case would apply to a cylindrical probe oriented parallel to the $z$ axis. Under nonmagnetic conditions, this requirement is usually fulfilled if the probe radius is smaller than about one Debye length (Laframboise, 1966). For a radially-symmetric potential, the orbit-limited condition reduces to a requirement that the dependence of potential on radius be less steep at every radius than a local inverse-square potential; this requirement was first derived by Mott-Smith and Langmuir (1926). For prolate and oblate spheroidal probes in the Laplace limit, the same condition gives values of major-to-minor axis ratio beyond which orbit-limitation breaks down (Laframboise and Parker, 1973); such probes may be a useful model for some nonspherical dust particles. If the charged particles have a nonnegligible drift, then their ambient velocity distribution is no longer isotropic, and the treatment given in this paper becomes inapplicable; a review of available theories for this situation has been given by Godard and Laframboise (1983).

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# CHARGING OF A DUST PARTICLE BY PLASMA CURRENTS

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ABSTRACT

In a recent paper (Gargano et al. (1989)) various models for determining the potential distribution around a dust grain in a plasma have been compared. It is assumed that the grain charging is entirely due to plasma currents in each case.

A single dust particle in a plasma has many similarities with a plasma probe at floating potential. To study the charging of a stationary dust grain having a high potential ($e\phi/T >> 1$) one grain is considered. It is assumed that the grain has a negative potential on its surface and that the mean grain separation is much greater than the electron Debye length. Using the stationary condition of zero total plasma current at the grain surface it is possible to determine $\phi_0$, the potential on the surface of the grain. It is known that far from the grain the potential approaches the Debye-Huckel potential. Using these boundary conditions Poisson's equation has been solved numerically using the shooting method for various values of grain radius and ion to electron temperature ratio. The results of these calculations may be used to evaluate the effective charge of the dust grain (de Angelis et al. ( 1989)).

There are four models currently under investigation. Each model results in different expressions for the particle densities, $n_e, n_i$, which are substituted into Poisson's equation:

$$\frac{d^2\Phi}{dx^2} + \frac{2}{x}\frac{d\Phi}{dx} = \frac{n_i(\Phi)}{n_0} - \frac{n_e(\Phi)}{n_0}$$

where $x = \lambda_{Di}^{-1} r$; $\Phi = |e\phi|/T_i$. $\lambda_{Di}$ is the ion Debye length and $\phi$ the plasma potential.

In the simplest model the electrons have a Maxwell-Boltzmann distribution and the ions a Maxwellian distribution. There are no ions with negative energy. In the second model the first model is modified to take into account the absorbing radius of the grain. The third model takes into account ions performing bound motion, which were excluded in the first two cases. Preliminary results indicate that the bound ions do not have a significant effect on the potential distribution. In the fourth case we assume Maxwellian electrons and cold ions. The calculations for the last case differ from the other cases and are similar to those carried out previously by Allen et al. (1957), when examining the collection of positive ions by a probe, with the condition that the probe radius was much larger than the electron Debye length. Here the equations are solved in the opposite limit in which the grain (or probe) radius is much smaller than the electron Debye length.

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## Dust Plasma Interaction in the Solar System

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Dust particles in planetary rings, cometary tails, interplanetary or interstellar medium are immersed in a radiative,fields and plasma environment. The grains will necessarily collect electrostatic charges, consequently their dynamics will be changed as they will experience the Lorentz force in addition to the gravitational and Poynting–Robertson forces. If the intergrain distance is smaller or comparable with the Debye shielding distance of the plasma, the intergrain Coulomb forces will become important leading to possible collective dust behavior. The dust grains also act as plasma source and/or sink, changing the density, temperature and flow field of the plasma environment. In this presentation we will consider only low dust densities, so the change in the dynamics of the dust is important but the fields and plasma environment is not coupled to the dust. This is the standard "dust in the plasma" approach of "gravito-electrodynamics" as opposed to the full "dusty plasma" description (Mendis, 1987). The gravitational force is proportional to the cube of the particle size, the Poynting–Robertson force is proportional to the square and finally the Lorentz force is proportional to the size of the grain itself, resulting a transition with decreasing particle sizes from gravity dominated to Lorentz force dominated dynamics. Typically for micron sized grains the Lorentz force becomes a non negligible perturbation (Parker, 1964).

We will shortly review the physics of charging and point out that for most cases the electron and ion thermal fluxes, photoelectron and secondary electron fluxes are the major charging currents (Whipple, 1981), and discuss the possible multiple solution of the current equilibrium equation (Meyer–Vernet, 1981).

Based on the existence of the multiple solution case for the equilibrium potential we will demonstrate the effect of "charging hysteresis" on the size distribution of coagulating particles. We will point out that the standard power law distribution can be severly distorted as the result of reduced (increased ) collision probability between particles with the same (opposite) charge polarity (Horanyi and Goertz, 1988).

As specific examples we will discuss the evolution of the spatial distribution of small dust grains in the cometary environment (Horanyi and Mendis, 1987) around Mars (Horanyi and Luhmann, 1989), Earth (Horanyi et al., 1988) and Jupiter (Shaffer and Burns, 1987) and point out the importance of charging effects around Saturn (Mendis et al., 1983) and Uranus.

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# Orbit evolution of dust in planetary magnetospheres

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We have studied the orbit evolutions of dust particles in Saturns magnetospheres. The orbits of micron sized dust particles will under normal physical conditions be close to the Kepler orbit, where the magnetic force and force from drag between dust particles and plasma, will act as perturbating forces. To calculate the charge on the dust particles, we considered a plasma with Maxwellian velocity distribution and with a relative velocity between the dust and the plasma [1]. The magnetic force will give rise to a gyro phase drift [2,3,4] if there is a significant delay in charging of the dust particles. The drag force includes direct particle drag (direct collisions) and Coulomb drag [5]. Since these two forces are small compared to the central force we solved the perturbation equations from celestial mechanics, which give the rate of change of the elliptical elements in the orbit. The changes of the major axis $a$ and the eccentricity $\epsilon$ are calculated for different values of density $n$ and temperature $T$ in the plasma and for different initial values of $a$ and $\epsilon$. Orbital evolutions are also calculated with gradients in $T$ and $n$ and with values for $T$ and $n$ from Pioneer and Voyager measurements. In the last case we also considered secondary electron effects.

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## DUSTY PLASMAS IN PLANETARY RINGS

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Voyager observations (Smith et al., 1981, 1982) of the rings of Saturn have revealed that they are not smooth disks but show large radial variations of optical depth at scale lengths ranging from less than a few tens of kilometers to several thousand kilometers. These are not related to any known resonances with Saturn's moons and associated density waves, and there is no universally accepted explanation of the structure. Voyager has also revealed the existence of radially elongated thin (in azimuth) structures (spokes) which appear dark in backward scattered but bright in forward scattered light. This suggests that they contain small micron size or submicron size grains. We discuss the only detailed spoke formation mechanisms published so far (Goertz and Morfill, 1983; Morfill and Goertz, 1983; Goertz, 1984). We also show that the radial displacement of the dust grains contained in the spokes causes a significant transport of angular momentum which can lead to the exponential growth of perturbations in the ring surface mass density.

The spoke model is based on the assumption that the spokes contain electrostatically levitated small dust particles (radius less than 1 μm) and that the thin radial elongation is due to rapid radial motion of dense plasma clouds whose radii are of the order of several thousand kilometers. The small dust particles coexist with large ring particles (centimeter to meter size). They either reside on the large particles, move between the ring particles, or are lifted off the ring particles above the ring plane. Because of the presence of such plasma clouds the ring charges to a surface potential of the order of -6 V. The electric field at the ring surface may be strong enough to lift negatively charged dust particles.

After a dust grain escapes from the Debye sheath into the charge neutral plasma above (or below) the ring plane, it will quickly charge to a surface potential of -6 V and thus carry a negative charge of several 100 electrons. However, because Q/m is still small, the grains will move on nearly Keplerian orbits. The plasma cloud, on the other hand, corotates with Saturn. Thus there is an azimuthal current which causes an azimuthal charge separation field. The magnitude of this azimuthal field has been calculated by Goertz and Morfill (1983) by balancing the current carried by the relative motion between the negative dust particles and the plasma with the field aligned current which eventually closes by a Pedersen current in Saturn's ionosphere.

The plasma cloud will ExB drift in the radial direction with a speed $V_R=E/B$ where $B(B=B_oL^3)$ is the magnetic field of Saturn at the distance $LR_s$. Goertz and Morfill (1983) have shown that this velocity ranges from zero exactly at synchronous orbit ($L_s$=1.866) to several tens of kilometers per second inside L=1.8 and outside L=1.9. The plasma cloud moves away from synchronous orbit if Q is negative. As it does, it leaves behind a radial trail of elevated dust particles, the spoke.

Small dust particles elevated above the ring plane at a radial distance r are subject to electromagnetic forces which tend to force them into corotation with the planetary magnetic field. Dust particles residing on the big ring particles or moving on Kepler orbits between the big ring particles in the ring plane have a very small charge to mass ratio and are not significantly affected by electromagnetic forces. Inside synchronous orbit the elevated dust particles lose angular momentum to Saturn, and outside of it they gain angular momentum. For $Q < 0$ the dust particles elevated at a radial distance r move toward synchronous orbit by an amount $\Delta r$ and will settle back onto the ring at a radial distance $r+\Delta r$. Since the specific angular momentum (angular momentum per mass) of the dust settling down at $r+\Delta r$ is different from the Keplerian specific angular momentum of the absorbing ring particles, these big ring particles will experience a torque when the dust is absorbed and hence change their angular momentum. The magnitude of this torque is proportional to the flux of dust onto the ring material and the radial hopping distance $\Delta r$. The big ring particles absorbing the dust will move onto a new circular Keplerian orbit corresponding to their new angular momentum. Averaged over many episodes of dust absorption, this yields a radial velocity of the ring material which was given by Goertz et al. (1986) and Goertz and Morfill (1988).

Goertz et al. (1986) show that in the B ring at L=1.8, for example, the effective velocity is $7\times10^{12}(Q/e)^2$ cm $s^{-1}$ which for Q/e = 200 becomes $3\times10^{-7}$ cm $s^{-1}$. The effective diffusive transport velocity for a typical ring viscosity of 20 $cm^2$ $s^{-1}$ is only $2\times10^{-9}$ $cm^2$ $s^{-1}$. Clearly, electromagnetic angular momentum transport is, at least, equal in importance to viscous transport. Since the electromagnetic transport is away from synchronous orbit, one expects a minimum of the optical depth there. This is, indeed, observed.

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# Nonlinear Transition Scattering Of Waves On Charged Dust Particles In a Plasma

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## Abstract

We consider the scattering of waves on charged dust particles surrounded by screening clouds of plasma particles in a dusty plasma. For wavelengths such that the electron cloud can oscillate coherently in the field of the incident wave, the scattered power is found to be much larger than usual scattering on free particles, and for highly charged grains the scattered power strongly depends on the sign of the charge on the grain.

Charged dust grains in a plasma are screened by plasma particles and can be considered, usually, as infinitely massive with respect to the ion mass. In is known that transition scattering can occur even on a particle of infinite mass, due to the oscillations of the screening electron cloud (Ginzburg and Tsytovich 1984), and wavelengths larger than the Debye length will scatter coherently.

For a grain of charge $Z_g e$, since the scattering charge is of the same order, we would then expect a scattering cross section of order

$$\sigma \cong (Z_g e)^2 \sigma_0 >> \sigma_0 \qquad (1)$$

where $\sigma_0$ is the usual cross section for Thomson scattering on free electrons.

In a recent paper (Tsytovich, de Angelis and Bingham 1989) the processes of transition scattering in dusty plasmas have been considered both in the linear region ($e\phi_0/T << 1$), where $\phi_0$ is the grain potential in the plasma, and for the non linear case $e\phi_o/T >> 1$ when the structure of the shielding cloud has to be calculated numerically using the results of Laframboise and Parker (1973) if the grain can be assimilated to a small spherical probe at floating potential.

The result for the scattered power can be written in the form:

$$Q = \frac{E_o^2}{m_e^2} \int \frac{(\mathbf{k}.\mathbf{k_o})^2}{k^2 k_o^2 \omega_o^3 \left.\frac{\partial \varepsilon}{\partial \omega}\right|_{\omega_o}} |Z_{eff}(\mathbf{k} - \mathbf{k_o})|^2 d\mathbf{k} \tag{2}$$

for the particular case of longitudinal into longitudinal wave scattering.

In (2) $E_o$ is the amplitude of the incident wave (of wave number $k_o$ and frequency $\omega(k_o)$), $\varepsilon(k,\omega)$ is the plasma dispersion function and $Z_{eff}(k)$ is a wave-number dependent effective charge for scattering.

The expression for $Z_{eff}$ is different in the two regimes. In the linear regime it is found that

$$Z^L_{eff} = \frac{Z_g e}{1+T_e/T_i+k^2d^2} \tag{3}$$

where $T_{e,\,i}$ is the electron (ion) temperature and d is the Debye length. Eq. (3) is given for the particular case of a single grain: for a distribution of grains the structure factor of the grains also appears in $Z_{eff}$. In the non-linear regime:

$$Z^{NL}_{eff} = (2\pi)^3 \int (n_e(r) - n_o) e^{i\mathbf{k}.\mathbf{r}} d\mathbf{r} \tag{4}$$

where $n_o = n_e\ (r \to \infty\ )$ and the electron density $n_e(r)$ is given by:

$$n_e(r) = \begin{cases} n_o e^{-\varphi(r)} & Z_g < 0 \\ n_o\{e^{\varphi(r)}(1 - \Psi(\varphi^{1/2}) + \frac{2}{\sqrt{\pi}}\varphi^{1/2}(r)\} & Z_g > 0 \end{cases} \tag{5}$$

where $\varphi(r) = |\, e\, \phi(r)\, | / T_e$, $\Psi\ (x)$ is the error function and $\phi(r)$ is the potential distribution around the grain to be determined from numerical solutions of Poisson's equation.

The results of the numerical calculations ($\sigma >> \sigma_o$ , $\sigma$ ($Z_g > 0$) >> $\sigma$ ($Z_g < 0$)) can be understood from the expressions reported here. Eq. (3) shows that the cross-section will depend on $Z_g^2$, as anticipated in (1), thus increasing over $\sigma_o$ for $Z_g >> 1$.

Eq. (5) shows the difference in the electron density for positive and negative grain: the electron cloud is enhanced around a positive grain leading to a larger $Z_{eff}$ and hence increased scattering. These large changes in the scattering cross-section could possibly produce charge separation in a system of positive and negative grains and could also be of help for diagnosis the presence of charged grains in a plasma from the level of scattered power.

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# Physics of Plasma with Disperse Condensed Phase

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## Abstract

Plasma with disperse condensed phase (CDP) is a low-temperature plasma with suspended charged liquid or solid particles. The particles may be either purposedly introduced in a plasma or produced, as a result of volume condensation under gas outlow, in the ablation products from surfaces affected by intensive energy fluxes. Appearance of particles results in new important plasma properties [1-4].

Emitting or absorbing electrons, the condensed particles may change the plasma electron number density and composition of plasma charges. In the given review the classification is given of states of plasma with CDP under the local thermodynamic equilibrium conditions (T = 1500-3000 K, $N_e=10^3$-$10^{14}$ $sm^{-3}$). The equation of ionizational equilibrium are written down for ideal and non-ideal plasmas with monodisperse and polydisperse system of CDP-particles [5]. The plasma with particles of large radii is non-homogeneous in the vicinities of strongly screaned particles. So one must distinguish the total and renormalized charges of particles [3,5]. The renormalized charge displays itself in the static conductivity values. The total charge influences the plasma emissivity.

The electron density is defined by thermoionic emission and by background gas ionization. At high value of ionizational atomic potentials (or low value of electron work function) the plasma electrophysical properties are defined by the CDP particles. On the opposite case all electrons are given by ionization of a gas [2,5].

Because of high particle charges plasma with CDP can be strongly non-ideal due to the electrostatic interaction. A strong interparticle correlation gives rise to a lattice like structure of the particle system. Relaxation processes are reviewed and the time is estimated which is required for the formation of space ordered structure [6,7].

The influence of particles is discussed on the electron mobility and on the energy exchange rate plasmas with CDP [1, 2, 8, 9].

The formulae are obtained for the calculation of the high-frequency $10^{11}$-$10^{14}$ $c^{-1}$) plasma emissivity. Bremsstrahlung from the CDP particles, the electron transition radiation and polarization radiation of particles are considered. At the case of large particle potential the radiation of orbital and suborbital electrons predominates [10,11].

In the review are presented the experimental results in solid fuels combustion plasmas [12, 13], in plasma with injected particles [14, 15], in near-surface laser generated plasma [16].

The formation and evolution of particles distribution over the charges and radii are discussed for magneto-hydrodynamic energy conversion installations [17].

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# Electric Antennae in Dusty Plasmas

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## 1 Dust as antennae or antennae in dust?

The above title has two aspects: the dust grains themselves might behave as antennae or actual electric antennae can be immersed in dusty plasmas.

How can one build an antenna with a dust grain? A trivial answer is: put it in an electromagnetic field. Another possibility is to design a natural flip-flop, using the non-unicity of the grain potential [9] [10] when secondary electron emission is present [17]. The corresponding antenna frequency, however, would be of the order of the inverse of the charging time, and thus usually very low, unless the "grains" were meter-sized or larger.

Another possibility is to take into account the grain spin. The spin frequency at equilibrium (which is not necessarily realized) is generally larger than the ambient plasma frequency. Since the grain charge has a dipolar component, rotating grains behave as small antennae whose (damped) plasma wave emission can be important in the grain energy balance [11]. If the spinning grains have also a translation velocity larger than the ion thermal velocity, one gets an antenna instability, which spins-up the grains and may break them by centrifugal disruption [11].

I shall not discuss these effects here, but restrict to actual electric antennae, for which the theory has been confirmed by many experiments and is surely not a mere physicist's dream.

What happens when one puts an electric antenna in a dusty plasma? First, the antenna acts as a voltmeter, detecting the charged particles passing by it; second, it is a target for particles and especially grain impacts. These properties have been used for electron and dust diagnosis in the solar wind, comets and planetary rings.

## 2 Antennae as plasma wave detectors

The conventional use of electric antennae is for remote sensing by electromagnetic wave detection. But they can also be used for in-situ diagnosis, by detecting local sources, i.e. electrostatic waves produced by moving ambient plasma particles. The corresponding voltage power spectrum is (in the absence of static magnetic field) (see [19] and refs. in [15])

$$V^2 = \frac{2}{(2\pi)^3} \int \mathbf{dk} \frac{2\pi m \omega_p^2 \left|\mathbf{k.J}(\mathbf{k})\right|^2}{\epsilon_0 k^4 \left|\epsilon_L\right|^2} \int d^3v \quad f(\mathbf{v})\, \delta(\omega - \mathbf{k.v})$$

where $\mathbf{J}$ is the current distribution along the antenna, $\epsilon_L$ the plasma longitudinal permittivity, and $f(\mathbf{v})$ the electron velocity distribution. (For realistic dusty plasmas and antennae working at frequencies of the order of the plasma frequency $\omega_p$, the motion of the other plasma components can be neglected).

Therefore, a mere spectroscopy of the measured voltage spectrum yields an electron diagnosis. For the method to be efficient, the antennae must be properly designed [15] and be wire dipoles of size a few Debye lengths. Broadly speaking, at frequencies $\omega < \omega_p$, the antenna only sees the electrons at a distance smaller than the Debye length $L_D$, so that a passing-by electron is seen as a short potential impulse, whose Fourier transform yields a white spectrum which is a simple function of the temperature. For $\omega \geq \omega_p$, the antenna of length $L$ sees mostly the Langmuir wave $k_p \sim \sqrt{\omega^2/\omega_p^2 - 1}/\sqrt{3}L_D$ satisfying $k \sim 1/L$, so that the spectrum has a cut-off at $\omega_p$ and a peak just above. When $\omega \to \omega_p$, then $k_p \to 0$, the phase velocity $\omega/k \to \infty$, so that the wave interacts with the high energy electrons; the fine structure of the peak therefore yields hot electron parameters: in particular, a hot Maxwellian or a power-law velocity distribution produce rather different peak fine structures [3]. Finally, for $\omega \gg \omega_p$, one gets a $\omega^{-3}$ power-law proportional to the total electron pressure [3].

This method, which requires a sensitive and well-calibrated receiver, has been tested (see refs. in [15]) in the solar wind whenever the electron velocity distribution was measured independently by conventional methods. Since it senses a much larger plasma volume (because $1/k_p \to \infty$ for $\omega \to \omega_p$), it is much less sensitive to the spacecraft perturbations and to the secondary and photoelectrons, which hamper the usual electron analyzers at low plasma temperatures. Figure 1 shows an example of the spectrum detected during the encounter of the spacecraft ICE with comet Giacobini-Zinner, where this method provided the profile of electron density and temperature in the cold plasma tail and coma [13].

## 3 Antennae as targets for impacts

The above formulation implicitely assumes that the antenna is a mere high-frequency voltmeter, transparent to particles and at zero dc-potential. In other words, I have neglected the dc inhomogeneity surrounding the antenna (see [8]) and the particle impacts and emission on its surface. This problem is very difficult even with simple geometries [2], and I will assume that the medium is homogeneous, with the partial justification that I apply the results to wire antennae of radius smaller than $10^{-3}$ Debye length, and at a dc potential of order the photoelectron temperature, i.e. generally smaller than the plasma electron one.

Now, what is the effect of the particle impacts or emission? Let us consider one electron impact on a wire antenna: it produces a step of potential, with a rise time of order $1/\omega_p$ and a much larger decay time $\tau_d$ which is the recovery time of the system; for $\tau_d^{-1} \ll \omega \ll \omega_p$, one gets a $\omega^{-2}$ power spectrum, which can be calculated from the dc electron flux. This can be generalized to other plasma particles, and it can be shown (see refs. in [15]- this has been verified in practice [14]) that this process yields a negligible contribution to the spectrum detected by a long wire dipole antenna for $\omega$ of the order of $\omega_p$.

Now what about the dust grain impacts? If the velocity is sufficient, the impacting grain is vaporized and ionized, together with a fraction of the target material. This produces an expanding plasma cloud in which there is a charge separation, and a fraction of this charge is recollected by the antenna. This recollected charge is a function of the grain mass $m$ and velocity, and of the nature of the materials, and has been studied in the frame of conventional in-situ dust detectors (see [4] [5]). Typically, each impact of a micron-sized grain produces a transient of potential of amplitude $\propto m^{0.8}$ with a rise time $\tau_r$ of order $2 \times 10^{-5}$seconds$\ll \tau_d$. Therefore, this process produces a power spectrum $\propto \omega^{-2}$ if $\tau_d^{-1} \ll \omega \ll \tau_r^{-1}$ and $\propto \omega^{-4}$ if $\omega \gg \tau_r^{-1}$ [14]. The measured level yields a diagnosis of the grain mass distribution $dn/dm$ as

$$V^2(\omega) \;\propto\; \int^{m_{max}} dm \;\; m^{1.6} \;\; dn/dm$$

where $m_{max}$ is the mass of the largest grains collected during the measurement time span.

This has been applied in particular to dust detection in Saturn [1][6] and Uranus [12][7] ring planes (see Figure 2) aboard Voyager which did not carry conventional dust detectors.

## 4 Future

This method is a good alternative to conventional plasma analyzers for electron diagnosis in cold plasmas: it can be very precise, senses a much larger plasma scale and, with long antennae, is much less sensitive to spacecraft perturbations.

On the theoretical side, it should be generalized to different realistic electron velocity distributions (this point is under study), and to anisotropic plasmas (see [18]). One should also assess the precise validity of neglecting the dc-inhomogeneity surrounding the antenna. Finally, the use of rf antennae for dust diagnosis, which is still in its infancy, deserves further analysis.

In the immediate future, this method might provide a grain diagnosis aboard Voyager-2 near Neptune. After the year 2000, it will be used (at least for plasma detection) in the CRAF project (Fig. 3) [16] which will explore comet Kopff; it is also proposed to be used in the joint project "Cassini" in Saturn environment.

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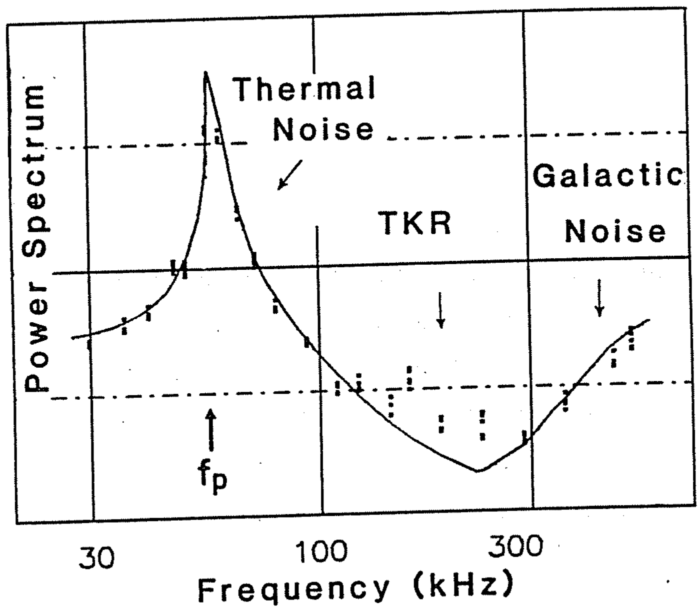


Fig. 1: Example of voltage power spectrum detected by the radio experiment aboard ICE in comet Giacobini-Zinner. A spectroscopy of all the spectra acquired gave the profile of electron density and temperature (and parameters of the hot electrons) (from [14]).

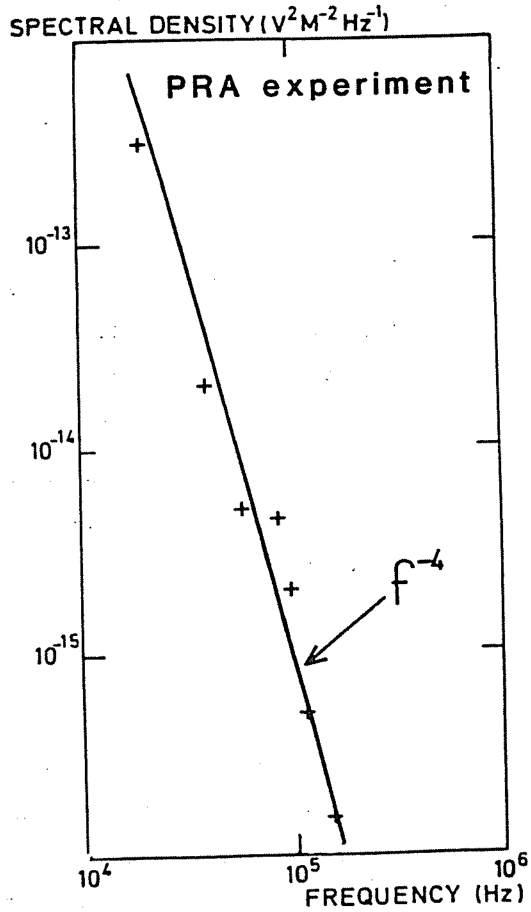


Fig. 2: Power spectrum detected by the Planetary Radio astronomy Instrument aboard Voyager 2 at Uranus ring plane crossing. This provided dust parameters (from [12]).

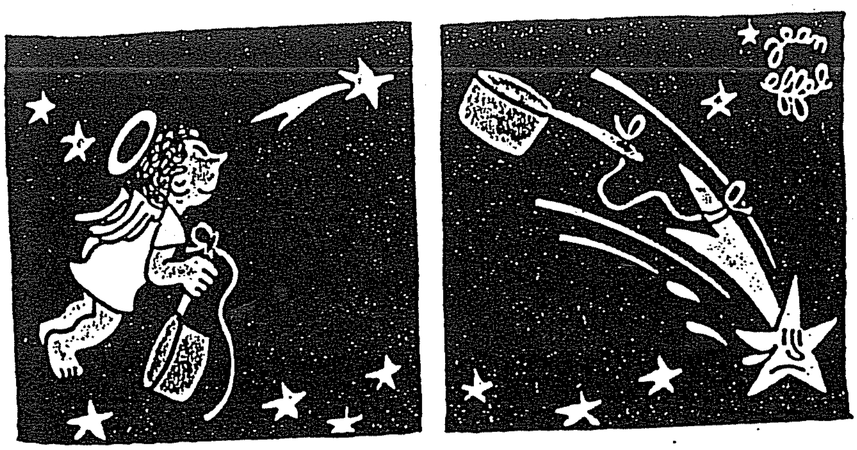

Fig. 3: A poet's view of the "Cometary **Rendez-vous Asteroid Fly-by**" mission, by Jean Effel ("Le Petit Ange", 1976).

# Dispersion Properties of Dusty Plasmas

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**Abstract**

The presence of charged dust particles in a plasma can change its dispersion properties. From the linear response of an equilibrium dusty plasma to the propagation of small perturbations we find an average dielectric function $\varepsilon(\omega, k)$ for the system in the case when the grain space distribution is random, and ensemble averages are taken over the random variables. For the case of high frequency plasma waves, when $\varepsilon \cong 1 - \omega_p^2/\omega^2$ for the unperturbed case (cold plasma) we find that e becomes complex in the presence of the dust, leading to possible damping in a domain where Landau damping is usually negligible ($\omega >> kV_T$).

Dust particles in space can be charged due to plasma currents and other effects (see e.g. references 1,2). If the plasma and grains system is neutral the ion and electron densities are different and the average potential in the system (see references 3, 4) is given by:

$$\bar{\phi}_o = \frac{1}{V}\int \phi_o(r)\, d^3r = \frac{3Q}{\lambda_D}(\lambda_D/r_o)^3 \qquad (1)$$

where $Q$ is the charge of grains (assumed all equal), $\lambda_D$ is the Debye length and $r_o$ the average separation between grains:

$$\frac{4}{3}\pi r_o^3 = N_g^{-1} \qquad (2)$$

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The potential $\phi_o(r)$ is solution of the Vlasov equilibrium system:

$$(\mathbf{v}\cdot\nabla)f_{o\alpha}(\mathbf{r},\mathbf{v}) - \frac{q_\alpha}{m_\alpha}\nabla\phi_o(\mathbf{r})\cdot\frac{\partial f_{o\alpha}(\mathbf{r},\mathbf{v})}{\partial \mathbf{v}} = 0 \tag{3}$$

$$\nabla^2\phi_o(\mathbf{r}) = -4\pi[\rho_g(\mathbf{r}) + \sum_\alpha q_\alpha \int f_{o\alpha}(\mathbf{r},\mathbf{v})\, d^3v] \tag{4}$$

where $\rho_g(\mathbf{r})$ is the charge density distribution of grains.

The dispersion properties of this system (i.e. the response to the propagation of small perturbation to the equilibrium solutions) have been recently found (ref. 5) for the case when the grains are assumed to be infinitely massive and randomly distributed (the results are also valid on a timescale short compared to a grain response to the perturbation). The calculation of ref. 5 are based on the usual linear perturbation theory of the Vlasov system i.e.

$$f_\alpha = f_{o\alpha} + \delta f_\alpha \,;\; |\delta f_\alpha| << f_{o\alpha} \tag{5}$$

$$\frac{\partial}{\partial t}\delta f_\alpha + (\mathbf{v}\cdot\nabla)\delta f_\alpha - \frac{q_\alpha}{m_\alpha}\nabla\phi_o\cdot\frac{\partial}{\partial \mathbf{v}}\delta f_\alpha + \frac{q_\alpha}{m_\alpha}\mathbf{E}\cdot\frac{\partial}{\partial \mathbf{v}}f_{o\alpha} = 0 \tag{6}$$

$$\nabla\cdot\mathbf{E} = 4\pi\sum_\alpha q_\alpha \int f_{o\alpha}(\mathbf{r},\mathbf{v},t)\, d^3v \tag{7}$$

This system can be solved via the Fourier-Laplace transforms method taking into account the dependence of $\phi_o$ and $f_{\alpha o}$ on position, due to the inhomogeneity introduced by the presence of the grains.

A dispersion relation obtains upon averaging the result on the ensemble of random distributions of grains, assuming a correlation function

$$B(\mathbf{r} - \mathbf{r}') = \langle\sigma(\mathbf{r})\,\sigma(\mathbf{r}')\rangle \tag{8}$$

where the brackets denote the ensemble average and $\sigma(r)$ is a (dimensionless) stationary random function related to the (random) potential energy of a plasma particle of type $\alpha$ at position r:

$$U_\alpha(r) = q_\alpha\,\phi_o(r) \equiv u_\alpha\,\sigma(r) \tag{9}$$

where

$$u_\alpha = q_\alpha \bar{\phi}_o \; ; \qquad \langle \sigma(r) \rangle = 1 \tag{10}$$

and the equilibrium distribution function $f_{\alpha o}(\mathbf{r},\mathbf{v}) = f_{\alpha o}(U_\alpha + \varepsilon_\alpha)$, where $\varepsilon_\alpha = \frac{1}{2} m_\alpha v^2$ is expanded to second order in $u_\alpha$.

The result for the dielectric function is given for the case of longitudinal, high frequency electron oscillations (cold plasma limit) as:

$$\varepsilon(\omega, \mathbf{k}) = 1 - \frac{\omega_{pe}^2}{\omega^2}\left(1 + \frac{1}{2}\mu_e^2\right) + \mu_e^2\, \chi(\omega,\mathbf{k}) \tag{11}$$

where $\mu_e = u_e/T_e$ is the perturbation parameter and the generalized susceptibility $\chi$ is given by:

$$\chi(\omega,\mathbf{k}) = \frac{\omega_{pe}^2}{n_o \omega^2} V_{Te}^2 \int \frac{(\mathbf{k}\cdot\mathbf{q})\mathbf{k}\cdot(\mathbf{k}-\mathbf{q})}{k^2} S(q) \int \frac{f_{eo}(v)}{[\omega - (\mathbf{k}-\mathbf{q})\cdot\mathbf{v}]^2} d^3v \; +$$

$$- \int \frac{2}{\omega}(\mathbf{k}\cdot\mathbf{q}) S(q) \int \frac{f_{eo}(v)}{[\omega - (\mathbf{k}-\mathbf{q})\cdot\mathbf{v}]} d^3v \tag{12}$$

where $V_{Te}$ is the electron thermal velocity, $f_{eo}(v)$ the distribution function of the electrons at infinite distance from the grains and $S(q)$ is the spectral density of the correlations (the Fourier transform of the correlation function $B(r)$).

In this region ($\omega >> KV_{Te}$) Landau damping is negligible but the susceptibility can still have an imaginary part due to the pole in the integrals [12] , leading to wave damping in the presence of charged dust particles. Physically this can be interpreted as similar to non-linear Landau damping due to resonant particles.

$$\omega = (\mathbf{k} - \mathbf{q}) \cdot \mathbf{v} \qquad |\mathbf{k} - \mathbf{q}| > k \tag{13}$$

in the beat of the wave $E(\omega, \mathbf{k})$ with a zero frequency wave of wave number $\underline{q}$ ($\sim r_o^{-1}$) due to the plasma imhomogeneity in the presence of a distribution of charged grains.

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# Nonlinear Effects In Dusty Plasmas

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**Abstract**

Several suggestions are made for studying various kinds of nonlinear effects in dusty plasmas.

Dusty plasmas are common in space and astrophysical environments. As is well known, the dusty plasma is characterized by several species including the electrons, the protons, the negative ions, highly charged dust particles, as well as neutrals. In fact, dust particles are negatively charged micron size heavy objects which are much heavier than the ions. Clearly, multi-species dusty plasmas can support a great variety of new normal modes which have not yet been explored. The nonlinear effects associated with collective oscillations in dusty plasmas could, henceforth, be very rich.

In order to have a clear understanding of nonlinear effects in dusty plasmas, it would be necessary to have a complete knowledge of the collective modes and their dampings. For example, we suggest to consider high-frequency plasma waves as well as low-frequency ion-acoustic and hydromagnetic (Alfvén or magnetosonic) waves in a three or four component dusty plasmas. Having acquired a complete knowledge of the wave characteristics, we shall be in a position to incorporate such nonlinear effects as the harmonic generation which can give rise to wave steepening. When the dispersive effects are taken into consideration, the wave may assume a localized structure so that it may propagate over long distances and could be observed in situ. For illustrative purposes, we would like to propose to study the formation of solitary wave solutions in dusty plasmas with Boltzman distributed electrons and ions and a fluid of dust particles whose dynamics is governed by the continuity and momentum equations. Since dust particles are very heavy, the linear and nonlinear inertial forces are balanced by the electric force. In the presence of the external magnetic field or the electromagnetic fluctuations, the Lorentz force must also be included in the momentum equation. The work on this line is in progress and the results shall be reported in due course of time.

The scattering of electromagnetic waves off normal or quasimodes in dusty plasmas is another area of research which is worth persuing. Here, it is possible to derive equations which could be similar to Karpman or Zakharov's equations. One can then investigate various kinds of scattering instabilities and the formation of envelope solitons. The latter can accelerate charged particles in dusty plasmas. The stimulated Compton scattering of hydromagnetic waves in dusty plasmas could be considered as a possible nonlinear damping mechanism in astrophysical and cometary plasmas.

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# Stochastic Particle Acceleration in dusty plasmas

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**Abstract**

The interaction of plasma particles with charged dust grains is characterized by an effective exchange of energy between the plasma particles and the much more massive and highly charged dust grains, which can have negative charges of the order of $10^3$ - $10^4$ electrons, leading to an energization of the plasma particles. The process has similarities to the Fermi acceleration mechanism in which particles are accelerated stochastically during collisions with moving magnetic clouds. In the present case plasma particles gain energy in a collision with a head on component of velocity and loses energy in an over-taking collision. The momentum gain or loss is equal to $mu\cos\phi$ where m is the mass of the plasma particle and u is the velocity of the dust grain and $\phi$ is the angle between the dust and plasma trajectories. Assuming an inverse square law for the force between the dust grain and the plasma particle the net change in velocity is found to be proportional to $1/u^4$. A Monte-Carlo code has been developed[1] to study the effects of electrons interacting with a moving charged dust cloud. For a collision operator where electrons gain or lose the same amount of energy per collision irrespective of their energy the whole spectrum heats up producing an electron distribution with a higher temperature. For collision operators where the velocity change is proportional to $1/u^4$ then it is possible to accelerate the low energy particles producing a beam like distribution function, there is also a systematic increase in velocity of the higher energy particles.

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# Streaming Instability In a Cold Dusty Plasma

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The two stream instability[1], in space plasma/dust systems, has been considered by Havnes[2,3] in connection with the motion of charged grains in interstellar clouds (ref.2) and the interaction between the solar wind and the cometary dust (ref.3). In this contribution I present some preliminary considerations on streaming instabilities in a cold dusty plasma, in the perspective of a general investigation of the changes introduced in a plasma by the presence of charged dust. Here the effects of electron depletion is considered.

Consider a charged dust beam, number density $n_{og}$, consisting of grains, with mass $M$ and charge $Q = -Z_g e$, moving with the same speed $V_o$ inside a cold plasma at rest, charactherized by equilibrium values $n_{oi}$, $n_{oe}$ of the ion and electron density. Then the dispersion relation, if we take the reference sistem fixed in the plasma, is given in the linear theory by [4]:

$$1-\frac{\omega_p^2}{\omega^2}-\frac{\omega_g^2}{\left(\omega-k_{\parallel}V_o\right)^2}=0, \qquad k_{\parallel}=\frac{\mathbf{k}\cdot\mathbf{V_o}}{V_o} \tag{1}$$

where k and $\omega$ are, respectively, the wave number and the frequency of the electrostatic perturbation, while :

$$\omega_p^2=\omega_{oi}^2+\omega_{oe}^2, \quad \omega_{oi}^2=\left(\frac{4\pi e^2 n_{oi}}{m_i}\right), \quad \omega_{oe}^2=\left(\frac{4\pi e^2 n_{oe}}{m_e}\right),$$
$$\omega_g^2=\left(\frac{4\pi Q^2 n_{og}}{M}\right) \tag{2}$$

are the plasma frequency and the "grain plasma" frequency.

If the grains are negatively charged due only to plasma currents, each grain collects, on average, $Z_g$ electrons more than ions and overall electrical neutrality requires:

$$e n_{oi} - e n_{oe} = e Z_g n_{og} \tag{3}$$

this means that, at the equilibrium, $n_{oi} \neq n_{oe}$ and that $Z_g$ and $n_{og}$ are not indipendent parameters. Using (3) it is possible to reexpress the frequencies $\omega_p$ and $\omega_g$ in terms of $\omega_{oi}$ with coefficients depending on the fractions, relative to the ions, of "free electrons" and dust grains present :

$$\omega_p^2 = \alpha \omega_{oi}^2, \qquad \text{where} \quad \alpha = 1 + \frac{n_{oe}}{n_{oi}} \frac{m_i}{m_e}$$

$$\omega_g^2 = \beta \omega_{oi}^2, \qquad \text{where} \quad \beta = \frac{m_i}{M} \frac{\left(1 - \frac{n_{oe}}{n_{oi}}\right)^2}{\frac{n_{og}}{n_{oi}}} \tag{4}$$

Note how in a plasma strongly depleted of electrons ($n_{oe}/n_{oi} << 1$,which is possible if only plasma currents contribute to the grain charging) we can have $\omega_{oi} \approx \omega_{oe}$. Equation (1) has two imaginary solutions[4], one of which with positive imaginary part corrisponding to the instability, when :

$$k_{\parallel} < k_{cr} = \frac{\omega_{oi}}{V_o} \alpha^{\frac{1}{2}} \left(1 + \left(\frac{\beta}{\alpha}\right)^{\frac{1}{3}}\right)^{\frac{3}{2}} \tag{5}$$

Then the relative non-resonant growth rate can approximatively stimated as[4] :

$$\gamma = \beta^{\frac{1}{2}} \frac{\omega_{oi}}{\left(\frac{\alpha \omega_{oi}^2}{\left(k_{\parallel} V_o\right)^2} - 1\right)^{\frac{1}{2}}} \tag{6}$$

Equations (5) and (6) constitute a "new" regime for a streaming instability in a cold dusty plasma and the effects are presently being investigated.

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# Vertical structure of planetary rings with dust size distributions.

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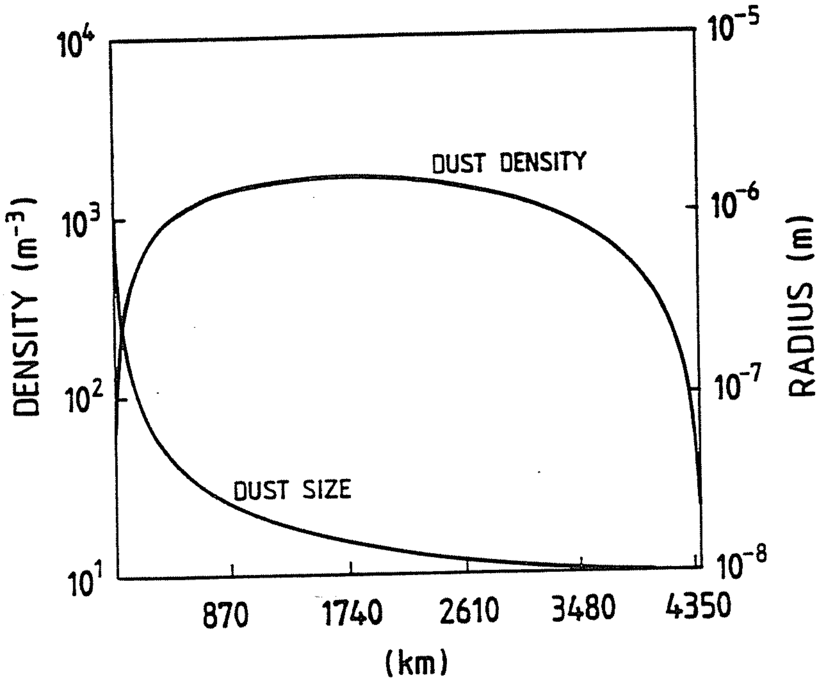
In a situation with a gradient in the charge density due to dustparticles, there will also be a gradient in the cloud potential. In a planetary ring the resulting electrostatic force opposes the component of the gravitational force pointing towards the central plane. Vertical ring structures resulting from an equilibrium between these two forces have earlier been calculated for cases with one dust size only[1,2]. We have repeated those calculations including a dust size distribution. Since the electrostatic force is proportional to $r_d$, the dust radius, and the gravitational force is proportional to $r_d^3$, we get a seperation of particles with different charge to mass ratio. In our calculations we have not included any random motion of the dustparticles, and this results in a perfect separation of dustparticles with different charge to mass ratios.



The figure shows an example of the change in dust density and dust size as a function of altitude above the central plane. The dust size distribution is here choosen to be $n(r_d) = Ar_d^{-3.5}$.

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# Dust and the Polar Mesospheric Summer Echoes

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Very strong radar echoes, which apparently cannot be explained by incoherent scatter theory, have been observed in the summer polar mesopause during the season for noctilucent clouds.[1,2] The backscatter signals and clouds are generally observed from late May to early August at a height between 80 and 90 km.[3] The thickness of the radar scattering layers are of the order of km with considerable structure down to the range resolution ($\gtrsim$ 150 m). Rocket experiments have observed a phenomenon called electronic "bite-out" with an apparent sudden reduction in the electron density near or in the backscatter region.[4]

We have discussed if dust can be the cause of both the "bite-out" and the radar backscatter. During the summer the mesopause temperature may drop to $\lesssim 140°K$ and water vapour (and other gases?) may condense, f.ex. on already existing small dust (smoke) particles from meteorites. The condensed particles are observed visually as noctilucent clouds.[3] The density $N_d$ of "large" dust of radius $> 0.05\mu m$ may possibly be up to 10 particles/cm$^3$.[5] Most of the solar radiation at energies above $\sim 7$ eV is absorbed above the mesopause but even so, if the dust which is formed have a photoelectric work-function in the 3 to 4 eV range, the photoelectric effect may possibly produce a positive surface potential on the larger dust particles. Amorphous ice have a work-function of 8.7 eV and would not be influenced much by a photoelectric effect. However, the larger grains which are formed in the summer mesopause are probably "dirty" as a result of a combined condensation of vapour and accretion of small meteoritic dust, and may therefore have properties very different from amorphous ice.

If dust of radius $\sim .1\mu m$ have a surface potential of $U_D \leq 4$ Volt, which corresponds to $Z_d \leq 280$ unit charges, this adds up to a possible charge density of dust $N_d Z_d \lesssim 2.8 \times 10^3$ cm$^{-3}$ which is very close to the values observed in the electronic "bite-outs". We propose that the "bite-out" is due to the rocket probe sampling both the electron and dust current whence the measured electron density is really the difference between the true electron density and $N_d Z_d$. The low positive potential on a rocket electron probe, sufficient to deflect the low-energy ions, is not able to deflect the massive dust.

Further, a presence of dust particles with considerable surface potentials will cause inhomogeneities in the plasma which to some extent can be pictured as dust particles of charge $Z_d e$ each with a surrounding electron cloud numbering $\sim Z_d$ electrons. Preliminary calculations[6] indicate that the scattering cross-section of one such cloud may be $\sim Z_d^2 \sigma_T$ where $\sigma_T$ is the Thompson scattering cross-section from one single electron. The total "effective" electron density for scattering due to such clouds may then be $N_d Z_d^2 \lesssim 8 \times 10^5$ cm$^{-3}$ compared to the true electron density $\lesssim 10^4$ cm$^{-3}$ measured in the scattering layers.

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# Shocks In Dusty Interstellar Clouds

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The friction due to the drift between neutrals and charged particles in shocks propagating perpendicular to the magnetic field in interstellar clouds with low fractional ionization allows a continuous transition of all fluid variables if the Mach number is below a critical value even if no other dissipation processes are taken into account (Mullan, 1971; Draine, 1980; Draine, Roberge, Dalgarno, 1983; Chernoff, 1987). In previous investigations of such shocks (so called C-type shocks) based on multifluid models for the plasma the effect od dust has been neglected (Mullan, 1971; Chernoff, 1987) or has been taken into account under approximations which are valid if the charge density on the dust grains is small compared to the charge density of the ions and the electrostatic polarization field along the direction of shock propagation can be neglected for the motion of dust particles (Draine, 1980; Draine, Roberge, Dalgarno, 1983).

Recently, work has been done to investigate the ionization structure, the dust grain charge and dynamics in C-type shocks in dense molecular clouds treating the dust as a separate fluid (Pilipp, Hartquist and Havnes, 1989). Here the grain dynamics have been treated in a manner analogous to that which was employed by Nakano and Umebayashi (1980) in their study of grain drag in molecular material. We consider the plasma to consist of four fluids: 1) neutral fluid (about 80% $H_2$ molecules, about 20% He atoms, and small amounts of O, Mg, CO, $H_2O$ and OH), 2) ion fluid (mainly $H^+{}_3$, $HCO^+$, $H_3O^+$, $Mg^+$ and $MgH^+$ produced by cosmic rays and succeeding chemical reactions), 3) electron fluid and 4) dust grain fluid (for which all dust grains are assumed to be spherical with radius $10^{-5}$ cm and to carry the average charge $q_g e$ per dust grain with $e$ = elementary charge). The shocks are considered to be one dimensional and steady and all variables are assumed to depend on the space coordinate $z$ with respect to a cartesian coordinate system $(x, y, z)$. In the distant upstream region (for $z \rightarrow -\infty$) the flow velocity $\mathbf{v}_S$ (with $v_s = |\mathbf{v}_S| = 15\ \mathrm{kms}^{-1}$) is assumed to be aligned along the $z$ axis and a homogeneous magnetic field $\mathbf{B}_0$ (with $B_0$ =

$|\mathbf{B}_0| = 4.74 \times 10^{-3}$ G) to be aligned along the $x$ axis (perpendicular shock). In addition, in the distant upstream region the number density $n_n$ of the neutrals is $10^7$ $cm^{-3}$, the gas temperature 20 K, the particle number density $n_g$ of the dust grains $\approx 10^{-4}$ $cm^{-3}$, the ion number density $n_i \approx 3 \times 10^{-9} n_n$ , and the average charge on the dust grains $q_g e \approx -0.5e$.

We find from our calculations that in the center of the shock the dust carries most of the negative charge, i.e. we have there

$$|q_g n_g| \approx n_i \tag{1}$$

Then the condition of quasineutrality and charge conservation (together with vanishing current at $z \to -\infty$ ) requires that the negatively charged dust particles move approximately with the ions in the $z$ direction. These requirements are effected by the $z$ component $E_z$ of the electric field (polarization field) which is given by

$$E_z \approx \frac{m_g \nu_{gn} \left( v_{nz} - v_{gz} \right)}{|q_g e|} \tag{2}$$

$m_g$ is the mass per dust grain, $\nu_{gn}$ the damping frequency of the grains due to collisions with neutrals, and $v_{nz}$ ,$v_{gz}$ are the $z$ components of the neutral and dust grain bulk velocities. We find that the fractional ionization $n_i/n_n$ drops suddenly in the shock by more than an order of magnitude. As the gas moves from the preshock region into the shock the relative speed $v_{nz} - v_{gz}$ increases and thus $E_z$ increases. Since the ions and electrons move nearly with the **E** x **B** drift (in contrast to the dust grains), their speed relative to the neutrals and to the dust grains increases leading to increased frictional ion and electron heating. Both the increased ion temperature and increased relative ion grain speed leads to faster recombination onto grains which results in decreases in the ion density $n_i$ and $|q_g|$. As $|q_g|$ falls, $E_z$ increases and a runaway is possible.

For the parameter regime considered our treatment of dust grain dynamics provides stronger coupling of the neutrals to the charged particles and thus to the magnetic field and a much stronger polarization electric field in the shock as compared to previously used approximations.

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# Dust charge and plasma potential in a dusty plasma

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It is now known that charges on dust in dust collections can be very different from those of single isolated dust particles.[1,2,3,4] Goertz and Ip[2] considered homogeneous dust plasmas where the intergrain distance was large compared to the dust size. Whipple et al.[5] and Houpis and Whipple[6] extented these calculations into regimes of very closely packed grains but found significant differences from earlier results only for such high dust densities that plasma absorption and plasma transport must be major processes if a plasma is to be maintained. Such processes were not taken into account. Havnes, Morfill and Goertz[3] considered dust charges and dust cloud potentials of a dust cloud of given structure embedded in a plasma. As the dust density increases, the charge on each dust particle decreases relative to the charge on a single isolated dust particle in the same plasma environment, while the local cloud potential increases relative to that of the plasma, i.e. the cloud shields itself electrostatically and $n_i \neq n_e$. The local cloud potential $V$ determines the local ion and electron density. Havnes[4] included a photo-electric effect in the dust charging while Havnes, Aanesen and Melandsø[8] have found analytical approximations for the dust charge and dust cloud potential as a function of dust density and plasma parameters. The effects of a dust size distribution and photo-electrons are also considered. Earlier linearized solutions for the dust surface potential $U$ and cloud plasma potential $V$ were applicable only for dense or tenuous clouds[9] and did not represent the solution well in the important region where $U \sim V$.

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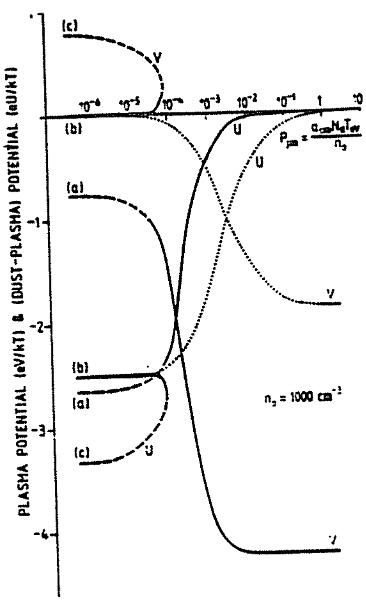


The relative cloud plasma potential eV/kT and dust–plasma potential eU/kT. in terms of the plasma kinetic energy kT. as a function of a parameter $P_{\mu m}$. This parameter is proportional to the dust density $N_d$ if we consider dust size $a_{\mu m}$ (in micrometers). plasma temperature $T_{eV}$ (in eV) and cloud ambient plasma density $n_0$ (cm$^{-3}$) as fixed quantities.

The dotted line curves correspond to the results when the plasma is thermalized.[2] The full (and broken) lines are for the non-Maxwellian plasma considered in Havnes et al.[7] The branches corresponding to the same set of the multivalued solutions for the last case are numbered with identical letters. The physically most relevant parts of the solutions are drawn with a solid line.

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