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AUTUMN COLLEGE ON PLASMA PHYSICS

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DUST-PLASMA INTERACTIONS IN SPACE AND IN THE LABORATORY

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These are lecture notes, intended for distribution to participants.

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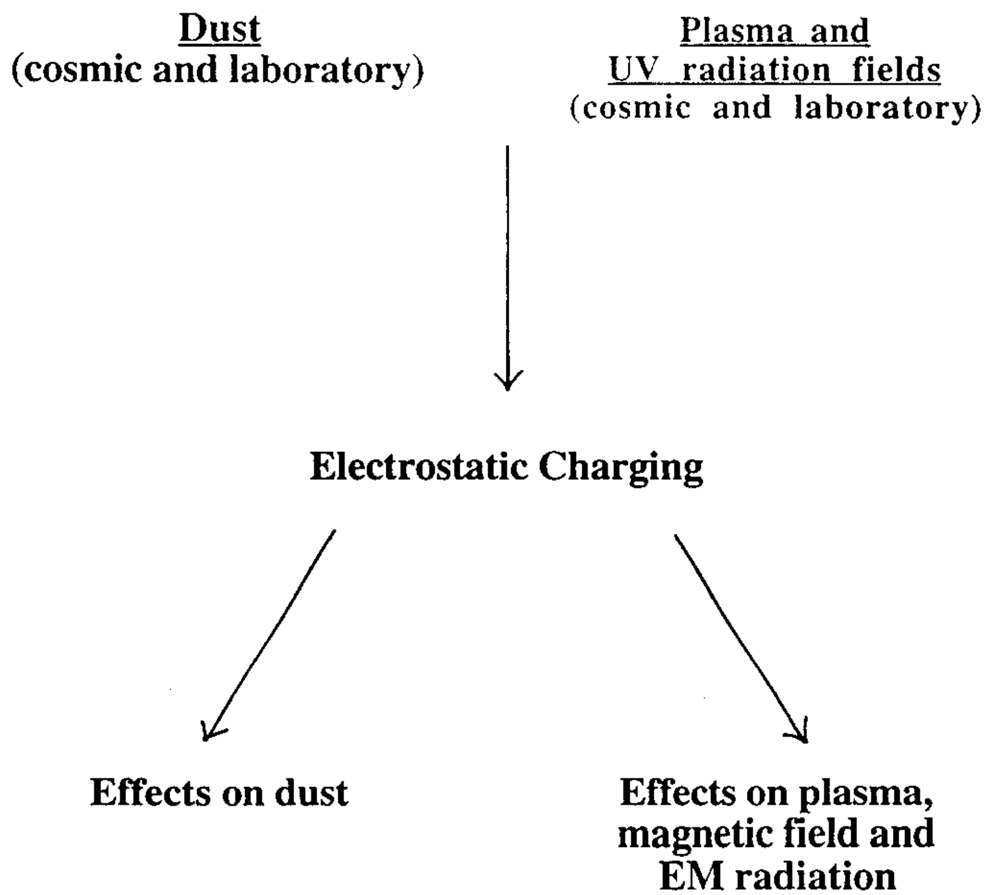
1. Introduction

Ionized gases laden with fine (charged) dust, loosely referred to as dusty plasmas, occur in a wide variety of environments both cosmic and terrestrial with spatial scales and time scales varying by tens of orders of magnitude. They have been investigated by diverse scientific communities ranging all the way from astrophysicists interested in star formation, to industrial engineers involved in the fabrication of microchips for computers. Also, the scope of the processes involved go all the way from the physics of multicomponent plasmas, with varying degrees of collisionality, through surface physics to the physics of condensed matter. This last arises from the most recent development in the field, namely the formation of Coulomb crystals in dusty plasmas in the laboratory.

It is impossible to do justice to such a vast field with a broad overview such as this. However, despite the large disparity between the spatial and time scales of cosmic and laboratory phenomena there is an underlying commonality of the basic physical processes, and my emphasis in these lectures will be on that.

Useful reviews include; Goertz, C. K., *Rev. Geophys.*, **27**, 271, 1989; Mendis, D. A. and Rosenberg, M., *Ann. Rev. Astron. Astrophys.*, **32**, 419, 1994; Sodha, M. S. and Guha, S., *Adv. Plasma Phys.*, **4**, (Ed. A. Simon and W. B. Thompson), Interscience Pub., N.Y., p219, 1971; Bouchoule, A., *Phys. World*, **6**, 47, 1993.


Dust
(cosmic and laboratory)
Plasma and
UV radiation fields
(cosmic and laboratory)
Electrostatic Charging
Effects on dust
Effects on plasma,
magnetic field and
EM radiation

1. Effects on Dust

Physical

- Electrostatic levitation and blow-off
- Electrostatic erosion and disruption
- Nucleation
- Coagulation
- Formation of Coulomb crystals

Dynamical

- Non-Keplerian (Gravito-electrodynamic) orbits
- Orbital evolution
- Transport (laboratory devices)

2. Effects on Plasma

- Change in degree of ionization
- Change in temperature
- Ambipolar E-fields
- New wave modes and instabilities

3. Effect on magnetic field

- Charged dust (ring) currents $\rightarrow \nabla \times \underline{B}$

4. Effect on the EM radiation field

- Enhanced scattering

Definitions

- The nature of the interaction between dust grains and the plasma depend on the ordering of a number of characteristic lengths. They are:

    1. The grain radius, a
    2. The average intergrained distance, $d\left(\sim n_d^{-1/3}\right)$
    3. The plasma Debye length, λ_D
    4. The linear dimensions of the region, L

- In some cases of interest the number density of the background neutrals is quite high. Then the coll.m.f.p of the plasma particles with the neutrals, ℓ , is of importance.

- Generally $\quad a \ll (d, \lambda_D) \ll L$.

- Case 1:

    $a \ll \lambda_D \ll d \rightarrow$ 'Dust - in plasma'

    (Treat dust as a collection of isolated screened particles)

- Case 2:

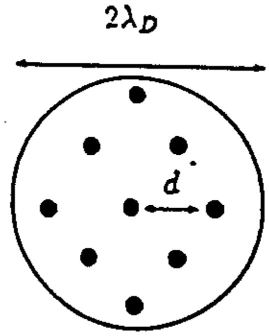
    $a \ll d \ll \lambda_D \rightarrow$ 'Dusty plasma'

    (Charged dust participates in the collective behavior of the ensemble)

- I will use the term 'dust-laden plasma' to include both cases (also colloidal plasma).

- In typical space plasmas,
  grain size $a \ll$ Debye length λ_D

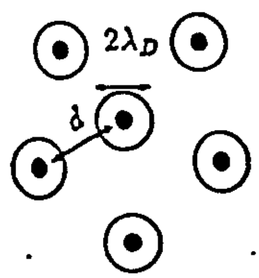
- 'Dusty plasma' — intergrain spacing $d \ll \lambda_D$



  – dust grains treated as massive charged particles, similar to multiply charged negative or positive ions

  – grains can participate in collective behavior (i.e., low frequency modes associated with dust grain motion)

- 'Dust in a plasma' — intergrain spacing $d \gg \lambda_D$ distribution of screened grains → local plasma inhomogeneities



$$d \sim n_d^{-1/3}$$

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

$$= \frac{4\pi n_e e^2}{kT_e} + \frac{4\pi n_i e^2}{kT_i}$$

Table 1. - Typical parameters of dust-laden plasmas (cosmic).

	n_e (cm^{-3})	T(eV)	n_d (cm^{-3})	a(μm)	n_n (cm^{-3})	d/λ_D
Saturn's E-ring	10	10-100	10^{-7}	1	1	0.1
Saturn's F-ring	10	10-100	$\lesssim 10$	1	–	$\lesssim 10^{-3}$
Saturn's spokes	$0.1-10^2$	2	1	1	–	$\lesssim 10^{-2}$
Halley's comet						
Inside ionopause	10^3-10^4	< 0.1	10^{-3}	0.1-10	10^{10}	≥ 1
Outside ionopause	10^2-10^3	~ 1	$10^{-8}-10^{-7}$	0.01-10	–	$\gtrsim 10$
Noctilucent clouds	10^3	0.013	10	0.1	10^{14}	0.2
Interstellar molecular clouds	10^{-3}	0.001	10^{-7}	0.2	10^4	0.3
Zodiacal dust disc (IAU)	5	10	10^{-12}	10	–	5
Solar F-corona	5×10^5	80	10^{-7}	0.3	–	10

Table 2. - Typical parameters of dust-laden plasmas (terrestrial).

	n_e (cm^{-3})	T(eV)	n_d (cm^{-3})	a(μm)	n_n (cm^{-3})	d/λ_D
Rocket Exhausts (near ground)	10^{13}	0.3	3×10^8	0.5	3×10^{18}	5
Flames $(\omega_{pe} < \nu_{en})$	10^{12}	0.2	10^{11}	0.01	5×10^{18}	$\lesssim 1$
Lab-Plasma (DA-wave)	10^8	2-4	10^4	5	5×10^{14}	0.2-0.3
Lab-Plasma (Dust-Ball : $\Gamma_D = 10$)	10^8	2-4	10^3	5	5×10^{14}	0.4-0.6
Process Plasma (Chip manufacture)	3×10^9	2	10^3-10^8	$\lesssim 1$	10^{15}	2×10^{-3} -3
"Plasma Crystal" $(\Gamma_D \gtrsim 10^4)$	10^{10}	2	10^4-10^5	7	10^{16}	2-4
Thermonuclear Fireball (100 Megaton)	10^{14}	1	10^8	1	10^{18}	20

Grain Charging

- **Robert Millikan, 1909:** 'Oil-drop' experiment $\rightarrow$ electron charge.

- $\frac{dQ}{dt} = \frac{d}{dt} c(\phi - \bar{\phi}) = I_{tot}$

- I_{tot} depends on the ratios of several characteristic lengths, grain characteristics, plasma velocity distribution, υ_{rel} and $\Delta\phi$.

- **Contributions to** I_{tot} : electron and ion collection, photoemission, thermoionic emission, secondary emission, electric field emission, etc.

- **<u>Isolated grain</u>:** $d \gg \lambda_D$, $c = a(1 + a/\lambda_D)$, $\bar{\phi} = 0$

  Plasma collection currents $(kn = \ell/a \gg 1)$ first derived by Mott-Smith and Langmuir, 1926 (*Phys. Rev.*, **28**, 727).

  <u>Space plasmas</u>: $a \ll \lambda_D < \ell$: "Orbit limited current" (Max)

  (For detailed review see E. C. Whipple, 1981, *Reports on Prog. in Phys.*, **44**, 1197).

- When $a \ll \ell < \lambda_D$ (lab. plasmas) the current due to the attracted species can be greatly reduced due to collisional energy loss within Debye sheath, leading to ion-trapping. (e.g. see J. Goree, 1992, *Phys. Rev. Letts.*, **69**, 277; in this case $\lambda_D < \ell$.)

- **In the continuum limit:** ($Kn = \ell/a \rightarrow 0$; e.g. charging of aerosols at high pressure), currents are "diffusion-limited" (Fuchs, 1934, . *Phys.*, **89**, 736).

- Gen. currents for <u>finite Kn</u> (Lassen 1961, Chang and Laframboise, 1976, *Phys. Fluids*, **19**, 176).

  $\rightarrow$ continuum currents (Fuchs) as $Kn \rightarrow 0$

  $\rightarrow$ collisionless current as $Kn \rightarrow \infty$ (repelled species)

  $\rightarrow$ $\gtrsim$ collisionless current as $Kn \rightarrow \infty$ (attracted species)

Equilibrium potential (ϕ_s) of an isolated ($d \gg \lambda_D$), small ($\lambda_D \gg a$) grain at rest in a plasma.

(only electron and ion collection currents : $I_e + I_i = 0$)

Maxwellian:

$$\left[\frac{m_i}{m_e}\right]^{1/2} = R_T^{1/2} \left[1 - \frac{e\phi_s}{kT_i}\right] \exp\left[-R_T \frac{e\phi_s}{kT_i}\right]$$

where $R_T = T_i / T_e$

For electron-proton plasma (with $R_T = 1$) $\quad \frac{e\phi_s}{kT} = -2.5$

For electron $-O^+$ plasma $\quad \frac{e\phi_s}{kT} = -3.6$

Generalized Lorentzian (Kappa):

with $R_T = 1$, $\kappa = 2$

$$\frac{e\phi_s}{kT} = \frac{1}{2}\left[1 - \left[\frac{m_i}{m_e}\right]^{1/4}\right]$$

For electron - proton plasma: $\quad \frac{e\phi_s}{kT} = -2.8$

For electron - O^+ plasma $\quad \frac{e\phi_s}{kT} = -6.1$

Charging time:

$$\tau \sim \frac{\lambda_D}{\omega_p} \cdot \frac{1}{a}$$

Orbit limited currents to an isolated grain

$$(a \ll \lambda_D \ll d, \ell).$$

$f(E) \equiv$ isotropic velocity distribution at ∞.

$$\left(E = 1/2\, m\, v^2\right)$$

$J_e \equiv$ electron current density to grain (surface pot = ϕ_s)

$$= -e \iiint f_e(E - e\,\phi_s)\, v_n\, d^3\underline{v}$$

The above integration is performed over all orbits that intersect the grain, i.e. for $E_{tot} = E - e\,\phi_s \geq 0$. Selecting sph. polar coordinates so that $d^3\underline{v} = v^2 \sin\theta\, d\theta\, d\psi\, dv$ and integrating over θ and ψ one gets,

$$J_e = \frac{2\pi e}{m_e^2} \int_{\max(0, e\phi_s)}^{\infty} E\, f_e\,(E - e\phi_s)\, dE$$

Similarly the ion current density, J_i to the grain is given by

$$J_i = \frac{2\pi e}{m_i^2} \int_{\max(0, -e\phi_s)}^{\infty} E\, f_i\,(E + e\phi_s)\, dE$$

If $f_{e,i}$ are <u>Maxwellian</u>, i.e. $f_{e,i} = n_{e,i}\left(\frac{m_{e,i}}{2\pi k T_{e,i}}\right)^{3/2} \exp\left(-E/kT_{e,i}\right)$

then in the case when $\phi_s < 0$, $J_e = -e\,n_e\left(\frac{kT_e}{2\pi\, m_e}\right)^{1/2} \exp\left(e\phi_s/kT_e\right)$

$$J_i = en_i\left(\frac{kT_i}{2\pi\, m_i}\right)^{1/2}\left(1 - e\phi_s/kT_i\right)$$

There are several processes that lead to emission of electrons from dust. These include (1) thermoionic emission (which occurs when grains are hot as in combustion flames), (2) photoemission (when uv radiation is present), (3) secondary emission (when the background plasma is sufficiently hot), and (4) electric field emission (when the surface electric field of a negatively charged grain becomes numerically very large).

These and some of their physical consequences will be discussed in the following pages.

Thermoionic, photoemission and secondary emission currents

$$J_{th} = \frac{4\pi e m_e k^2 T_g^2}{h^3} \exp\left(\frac{-w + \alpha\phi_s}{kT_g} \right)$$

(where w work function, and $\alpha = 1$ if $\phi_s > 0, \alpha = 0$ if $\phi_s \leq 0$)

$$J_{ph} = e \int_0^{\lambda \max} \exp\left(- {\alpha\phi_s}/{kT_{pe}} \right) Q_{abs}(\lambda) Y(\lambda)\, \chi_p(\lambda)\, d\lambda$$

(where $\alpha = 1$, if $\phi_s > 0$, $\alpha = 0$ if $\phi_s \leq 0$) ;

$Q_{abs}(\lambda) = 1$, ${2\pi a}/{\lambda} \geq 1$; $Q_{abs}(\lambda) = {2\pi a}/{\lambda}$, $\frac{2\pi a}{\lambda} \leq 1$.

($\chi_p(\lambda)\, d\lambda$ is the photon flux in $\lambda - \lambda + d\lambda$ and $Y(\lambda)$ is the photoelectron 'yield').

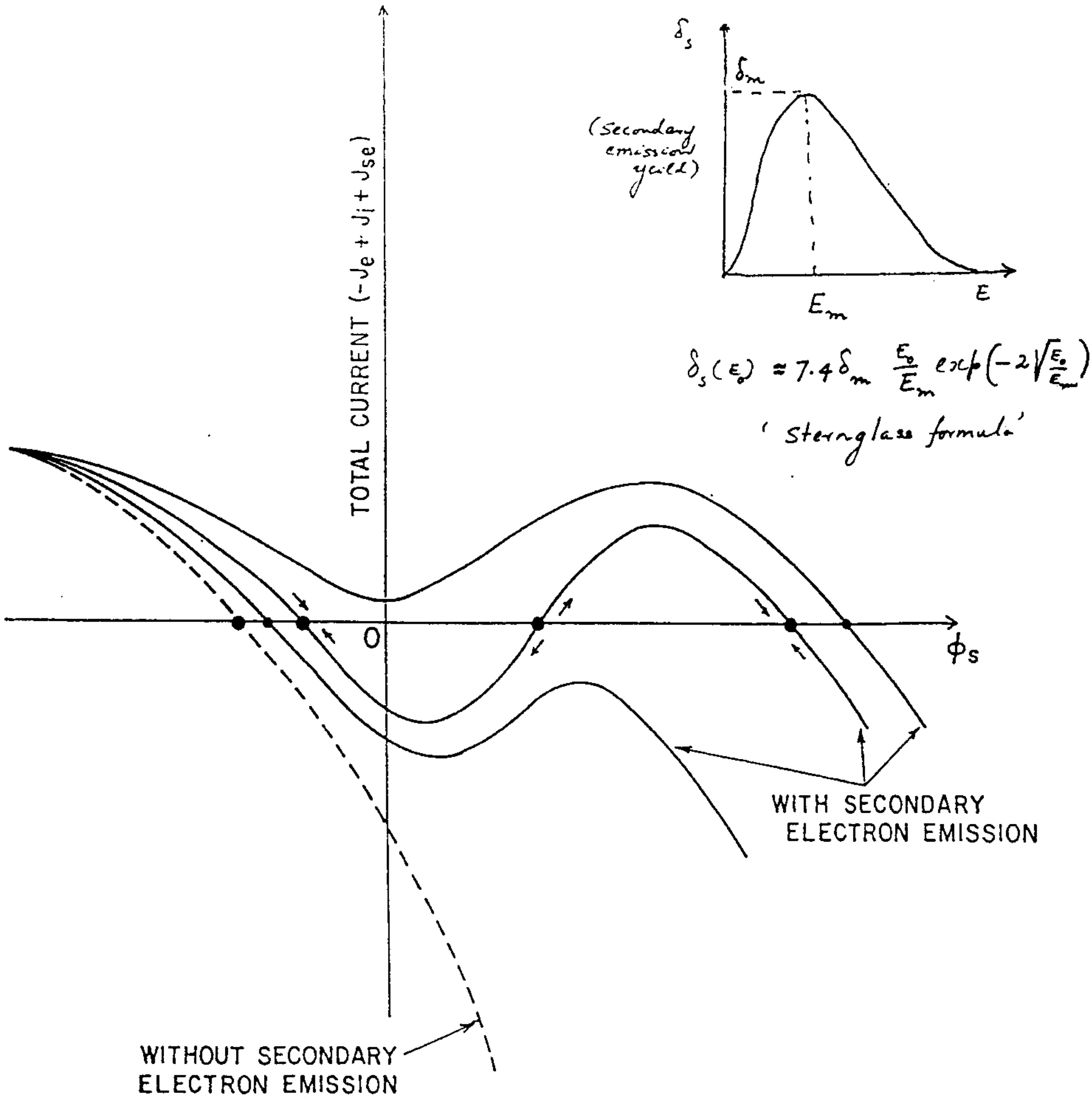
$$J_s = \frac{2\pi e}{m_e^2} \left\{ 1 + \alpha \exp\left(- {e\phi_s}/{kT_s} \right) \left(1 + {e\phi_s}/{kT_s} \right) \right\} \int_{\alpha e\phi_s}^{\infty} E\delta(E) f_e\, (E - e\phi_s) dE$$

(where $\alpha = 1$ if $\phi_s > 0$; $\alpha = 0$ if $\phi_s \leq 0$; and $\delta(E)$ is the secondary emission yield).

(Chow et al., 1993, *J. Geophys. Res.*, **98**, 19065.)

Consequence of secondary emission

Multiple roots for the equilibrium potential (ϕ_s).



E. C. Whipple, 1965, Ph.D. thesis

Lab: M. Horanyi, S. Robertson and B. Walsh, 1996, Physics of Dusty Plasmas, Ed. P.K. Shukla et al., World Sci., Singapore.

Grain Ensemble $(a \ll d \ll \lambda_D)$

We now consider the case of a grain ensemble $(a \ll d \ll \lambda_D)$ with the charging currents being entirely due to electron and ion collection. In this case too, the grains will be negatively charged, as in the 'isolated' grain case, due to the larger mobility of the electrons. However, the grains will acquire a smaller electron charge. This is due to the depletion of the electrons. So the 'driving potential' $(\phi_s - \bar{\phi})$ need not be as negative as in the case of the isolated grain in order for the currents to be equal. So $|Q| = C \left| (\phi_s - \bar{\phi}) \right|$ decreases.

Grain Ensemble — Goertz and Ip, 1984, *Geophys. Res. Lett.*, **11**, 349.

$(a \ll d \ll \lambda_D)$ — Whipple, Northrop and Mendis, 1985 *J. Geophys. Res.*, **90**, 7405.

$$I_e = -e \left[\frac{8\pi k T_e}{m_e} \right]^{1/2} a^2 \, \bar{n}_e \exp \left[(\phi_s - \bar{\phi}) / kT_e \right]$$

$$I_i = e \left[\frac{8\pi k T_i}{m_i} \right]^{1/2} a^2 \, \bar{n}_i \left[1 - e \, (\phi_s - \bar{\phi}) / kT_i \right]$$

where $\bar{n}_e$, $\bar{n}_i$ are the electron and ion densities in the plasma reservoir between the grains.

Charge neutrality : $\bar{n}_e - \bar{n}_i = \eta_d \, Q/e$

where $\eta_d = n_d \left[1 - \frac{4}{3} \pi a^3 n_d \right] \approx n_d$

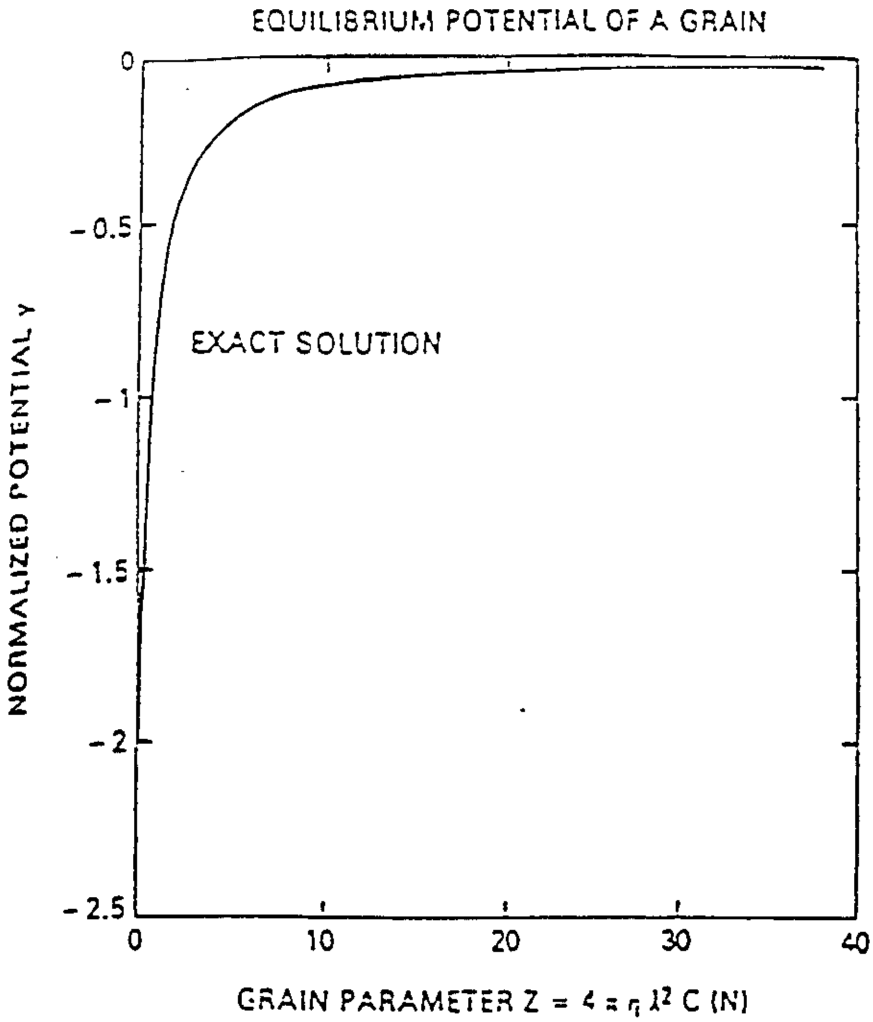
$$I_e + I_i = 0 \quad (\text{with } T_e = T_i = T)$$

$$\Rightarrow \; (1 - y)(1 - yZ) = \left[\frac{m_i}{m_e} \right]^{1/2} (1 + yZ) \exp(y)$$

where $y = e \, (\phi_s - \bar{\phi}) / kT$

$Z = 4\pi \, \lambda_D^2 \, \eta_D \, C(n_d)$; $C(n_d) =$ grain capacitance

$$\lambda_D^2 = kT / \left[4\pi \, (\bar{n}_e + \bar{n}_i) \, e^2 \right]$$



Whipple, Northrop and Mendis, 198

Goertz + Ip, 1984

Xu, D'Angelo + Merlino, 1993. (Lab)

$|Q| = c\,|\phi_s - \bar{\phi}|$ decreases rapidly as Z increases.

$\propto y$

and becomes very small when $Z = \frac{4}{3}\pi\lambda_D^3 n_D \left[3\frac{a}{\lambda_D}\right] \gg 1 \;\rightarrow\; d/\lambda_D \ll (a/\lambda_D)^{1/3}$

Also note:

as $y = e(\phi_s - \bar{\phi})/kT \rightarrow 0$, $\frac{\bar{n}_e}{\bar{n}_i} \rightarrow \sqrt{\frac{m_e}{m_i}}$ (≈ 2.3% for $e - H^+$ plasma)

Expt: Xu, D'Angelo + Merlino (1993).
J. Geophys. Res. 98 7843.

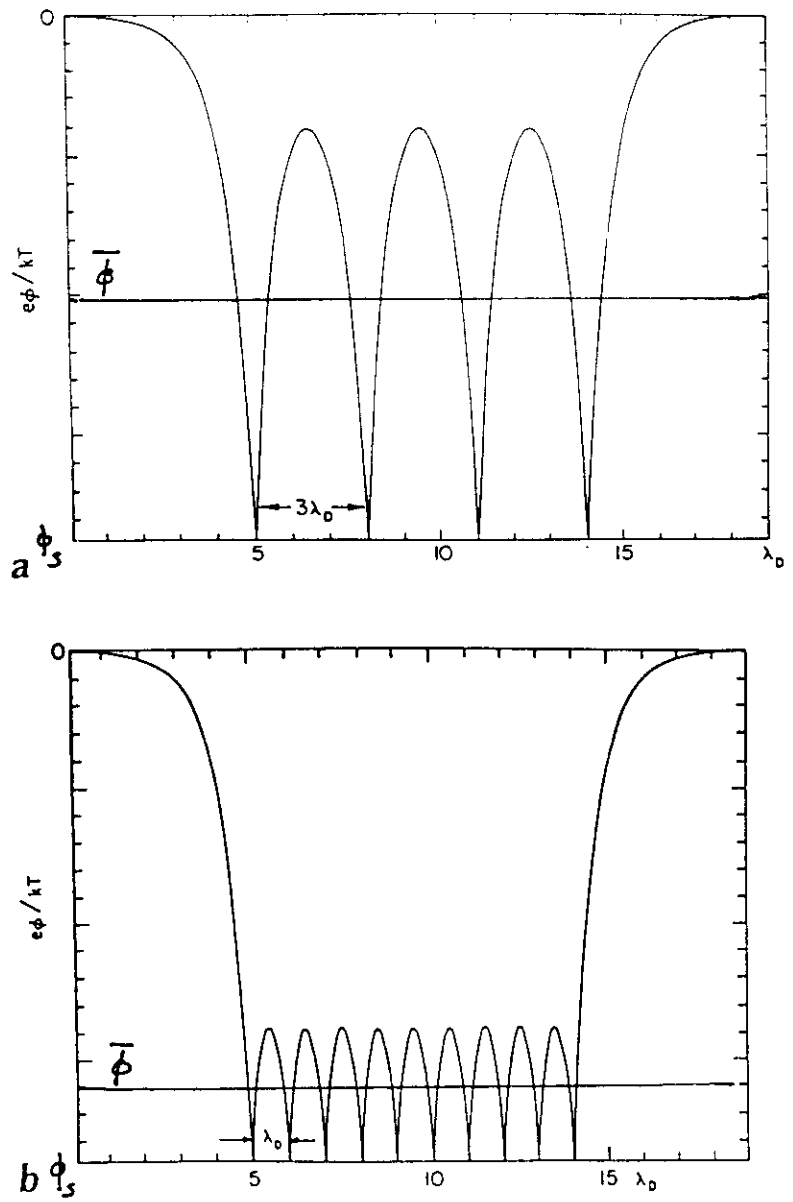


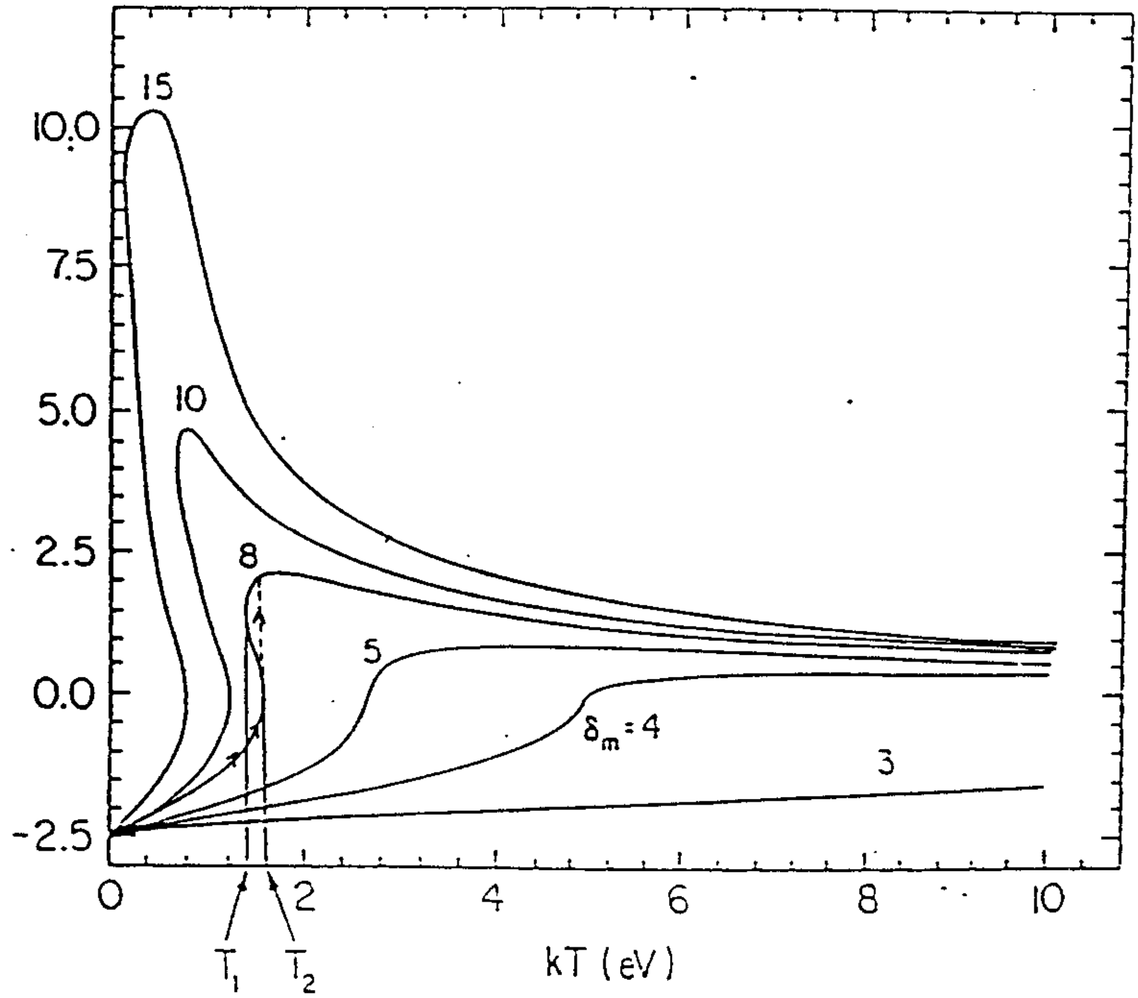
Figure 4. Steady state solution of the one-dimensional Poisson equation for grain sheets placed at regular intervals. The distance between grains is (*a*) $3\lambda_D$ and (*b*) $1\lambda_D$. (From Goertz 1989; Rev. Geophys. 27, 271)

Some physical consequences of dust charging

- Enhanced coagulation
- Electrostatic disruption
- Electrostatic levitation

(for a detailed discussion see pp 430-436, Mendis and Rosenberg, 1994, *Ann. Rev. Astron. and Astrophys.*, **32**, 419).

- Enhanced ionization of molecular clouds in star forming regions.



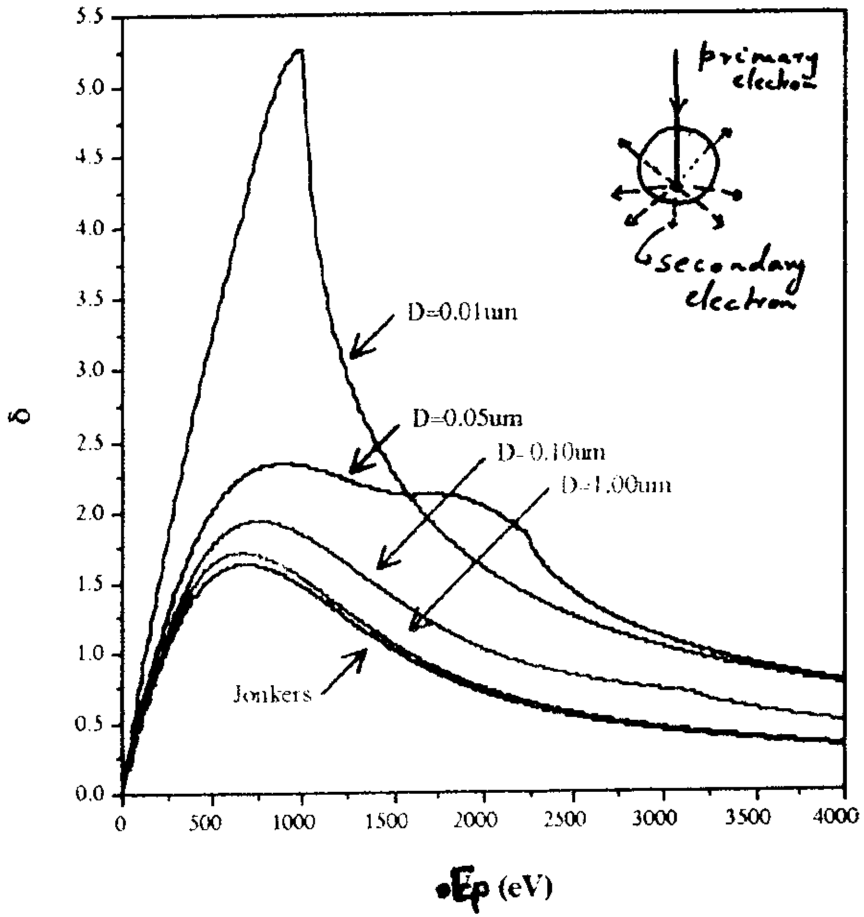
$\tau_{eq} \sim \frac{1}{a}$

Horanyi + Goertz (1990)

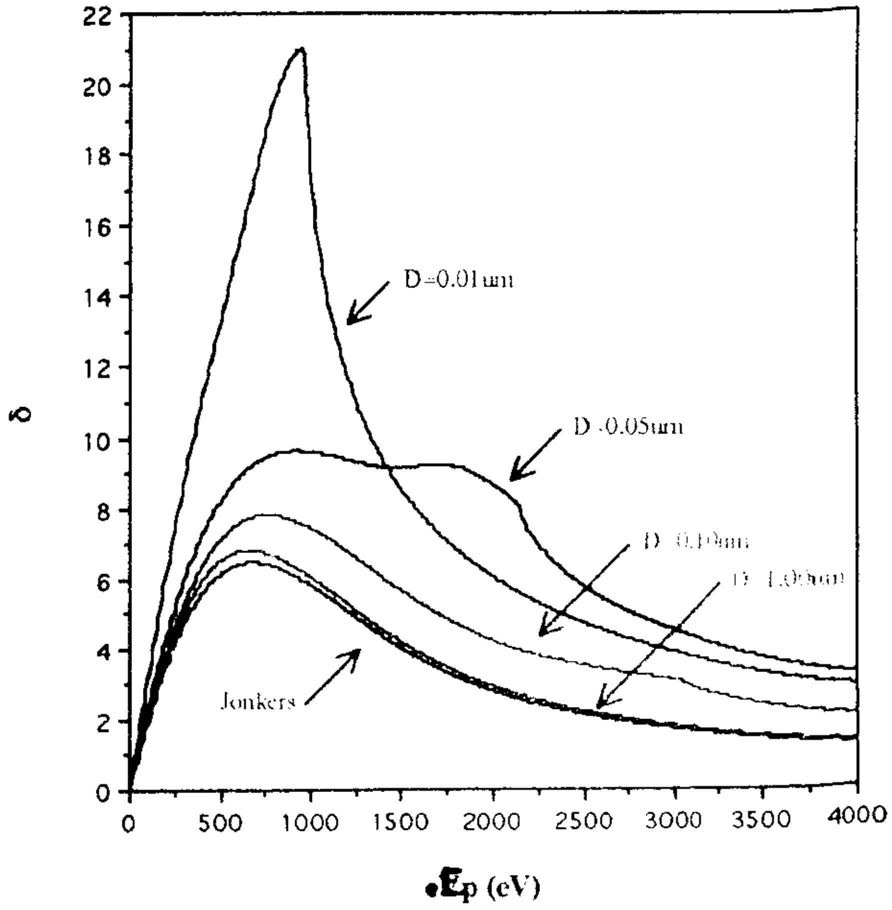
Astrophys. J., 361, 105.

δ from Small Spherical Conductors and Insulators

Conductor (NiO_2)



Insulator (NaCl)



Chow et al, 1993, J. Geophys. Res., 98, 19065.

δ_m, Em (D, α, a, K)

- D: diameter
- α: inverse absorption length of secondaries
- a: Whiddington's const. α (energy loss of primary)^2/distance
- K: efficiency factor for production of secondaries

- Need for similar calculations for photoemission.

ELECTROSTATIC DISRUPTION AND EROSION

1. Electrostatic Disruption

Öpik (1956): *Irish Astron. J., 4, 84*

Sphere of radius R and uniform tensile strength F_t

Electrostatic disruption if

$$F_E = \frac{\phi^2}{8\pi\, R^2} > F_t$$

$$\Rightarrow \quad R(\mu) < R_c = 6.65\, F_t^{-1/2}\ |\,\phi(v)\,|\,.$$

Fechtig et al (1979): (Heos-2)

$10^2 - 10^3$ inc. in micrometeoroid flux in $r \leq 10\, R_\oplus$:

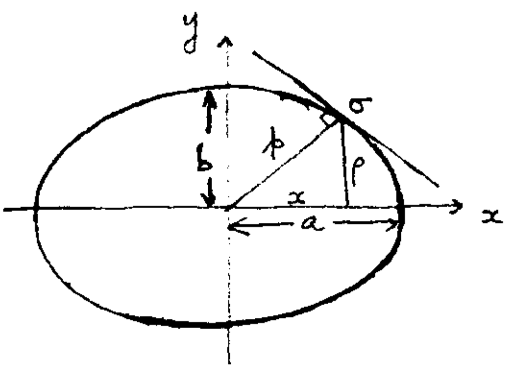
Electrostatic disruption of Type III fireballs, $m_p \sim 10\text{–}10^6$ g .

$m_p = 10$ g ; $|\phi| = 100$ kV $\Rightarrow F_t \leq 2.4\text{x}10^3$ dynes cm^{-2}

$m_p = 10^6$ g ; $|\phi| = 100$ kV $\Rightarrow F_t \leq 2.5\text{x}10^{-2}$ dynes cm^{-2}.

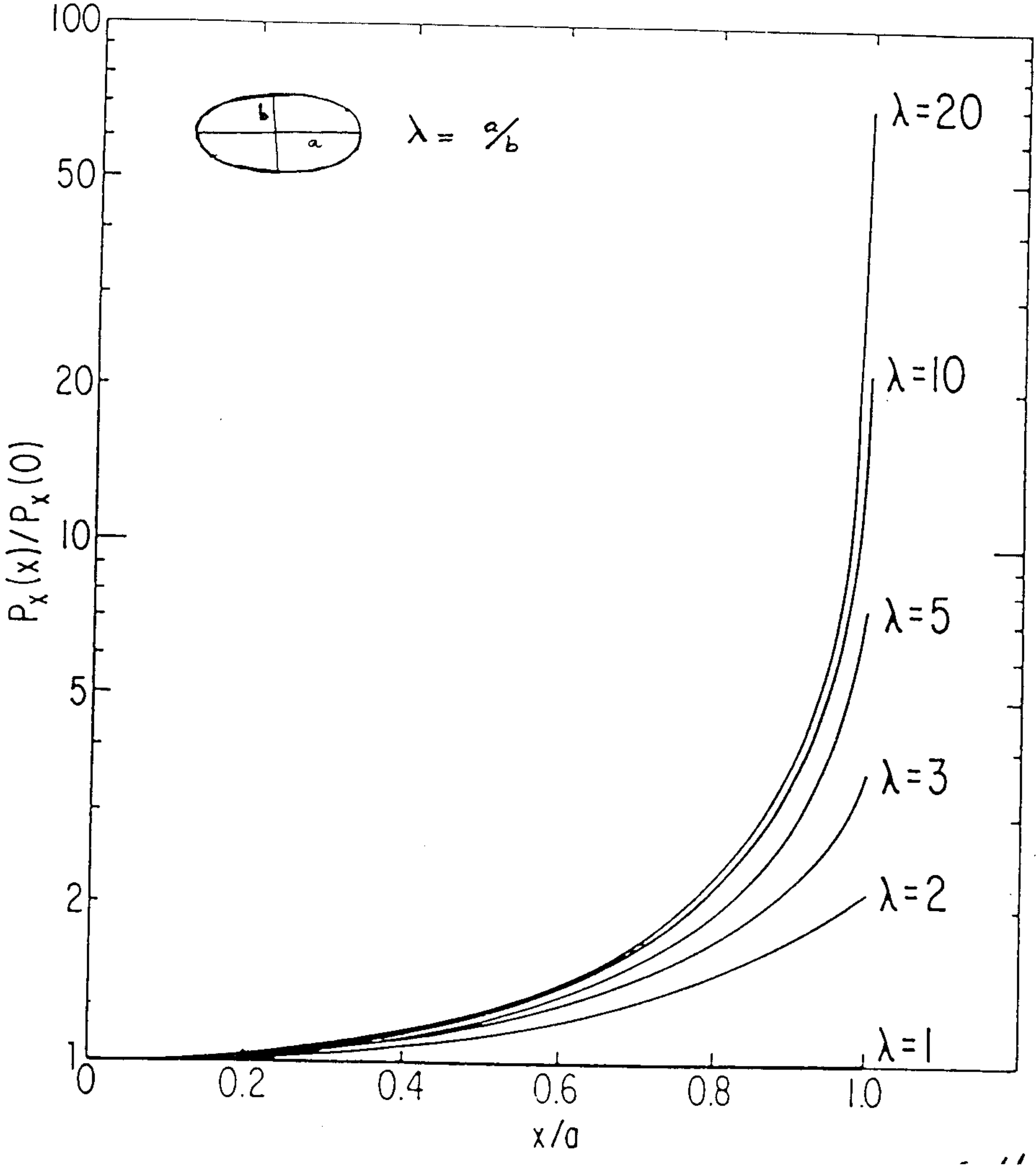
2. Electrostatic Erosion (non-spherical bodies) (Hill and Mendis, 1982)

Can. J. Phys. 59, 877.

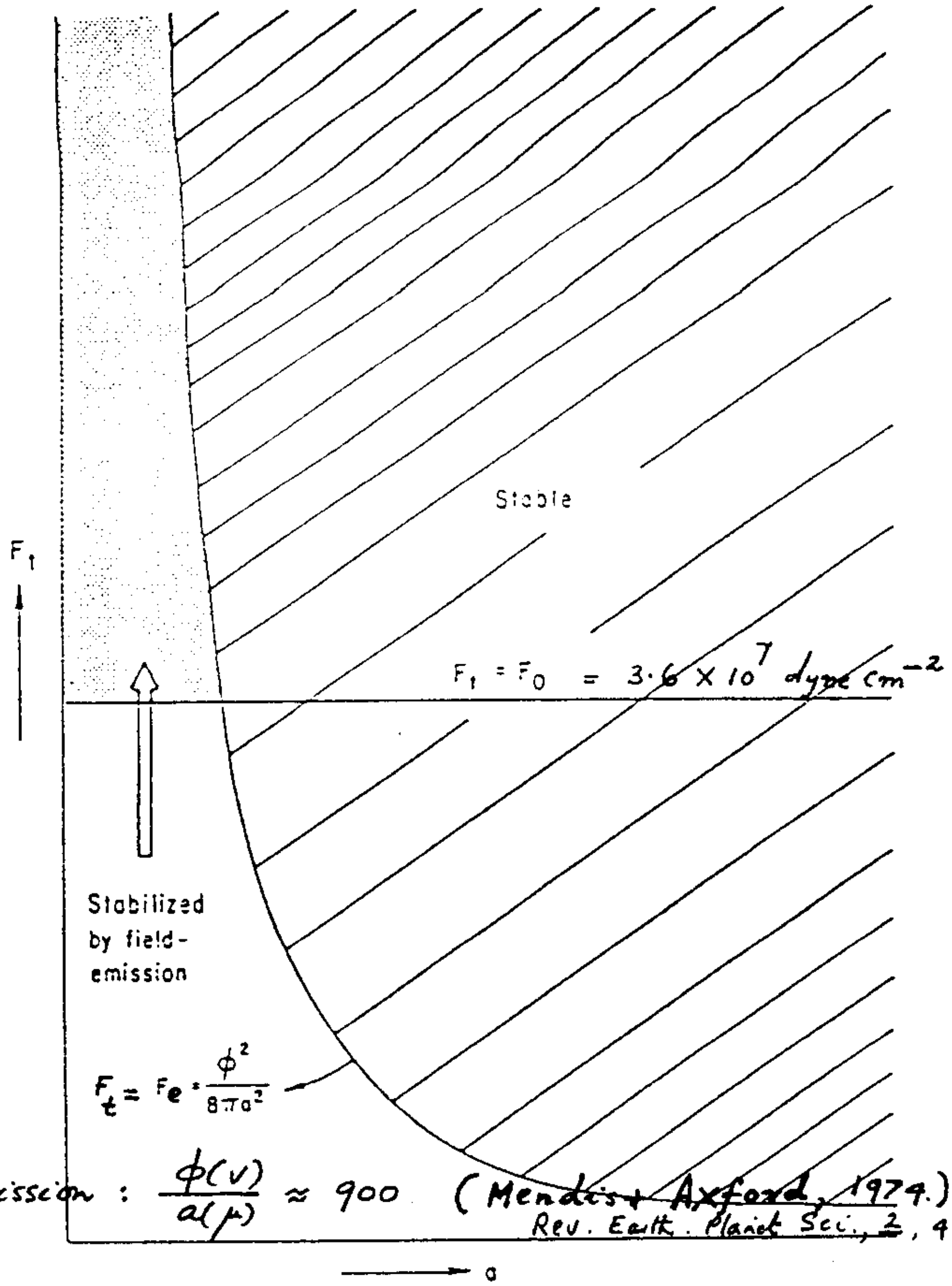


$$\sigma = \frac{pQ\lambda^2}{4\pi a^3}\ ; \ \lambda = \frac{a}{b}$$

$$p_x(x) = \frac{1}{\pi\rho^2}\int_0^{\rho} \frac{E^2}{8\pi}\cdot 2\pi\rho\, d\rho = \frac{Q^2\lambda^4 \ln\left[1 + (\lambda^2 - a)\,(1 - x^2/a^2)\right]}{8\pi a^4(\lambda^2 - 1)\,(1 - x^2/a^2)}.$$



λ = a/b
b
a
λ=20
λ=10
λ=5
λ=3
λ=2
λ=1
100
50
20
10
5
2
1
0
0.2
0.4
0.6
0.8
1.0
x/a
P_x(x)/P_x(0)



Electric field emission : $\frac{\phi(V)}{a(\mu)} \approx 900$ (Mendis + Axford, 1974.) Rev. Earth. Planet Sci., 2, 419

F_t (Iron) $= 2 \times 10^{10}$ dyne cm^{-2}.

F_t (Tektites) $= 7 \times 10^{9}$ dyne cm^{-2}.

Mendis (1991), Astrophys. Space Sci., 176, 163.

Ionization of dusty molecular clouds in star forming regions

Current balance: $(\phi_s > 0)$

$$4\, n_e \left(\frac{k_B\, T_e}{2\pi\, m_e}\right)\left(1+\frac{e\phi_s}{k_B\, T_e}\right) = Q_{abs}\, YJ\, \exp\left(-{}^{e\phi_s}\!\!\big/_{kT_{pe}}\right) \tag{1}$$

Change neutrality:

$$n_e = \int_{a_{min}}^{a_{max}} Z(a)\, \frac{d\, n_d(a)}{da}\, da \tag{2}$$

MNR-distribution (Mathis et al, 1977) :

$$\frac{d\, n_d}{da} = A\, n_H\, a^{-3.5} \quad , \qquad \left(A \approx 1.5\times 10^{-25}\, cm^{2.5}\right) \tag{3}$$

Using (1), (2) and (3), and noting that $Z(a) \approx a\, \phi_s / e$ we get:

$$\frac{4}{\sqrt{2\pi}}\, x\,(1+Bx) = \frac{Q_{abs} Y\, J}{n_H} \sqrt{\frac{m_e}{k_B T_e}} \quad \exp\left(-x\, B\, T_e / T_{pe}\right) \tag{4}$$

where $\qquad x = n_e / n_H \quad , \quad B = 3\, e^2\, a_{min}^{3/2} / 2 k_B\, T_e\, A$

In solving (4) we take, $\quad k_B\, T_{pe} \approx 2e\, V \quad , \quad T_e \approx 100^\circ K \quad$ and $\quad J = \alpha\, G / h\overline{\upsilon} \quad ,$

where $\qquad G(\text{Habing flux}) \approx 1.6\times 10^{-3}\, erg\, cm^{-2}\, s^{-1}$.

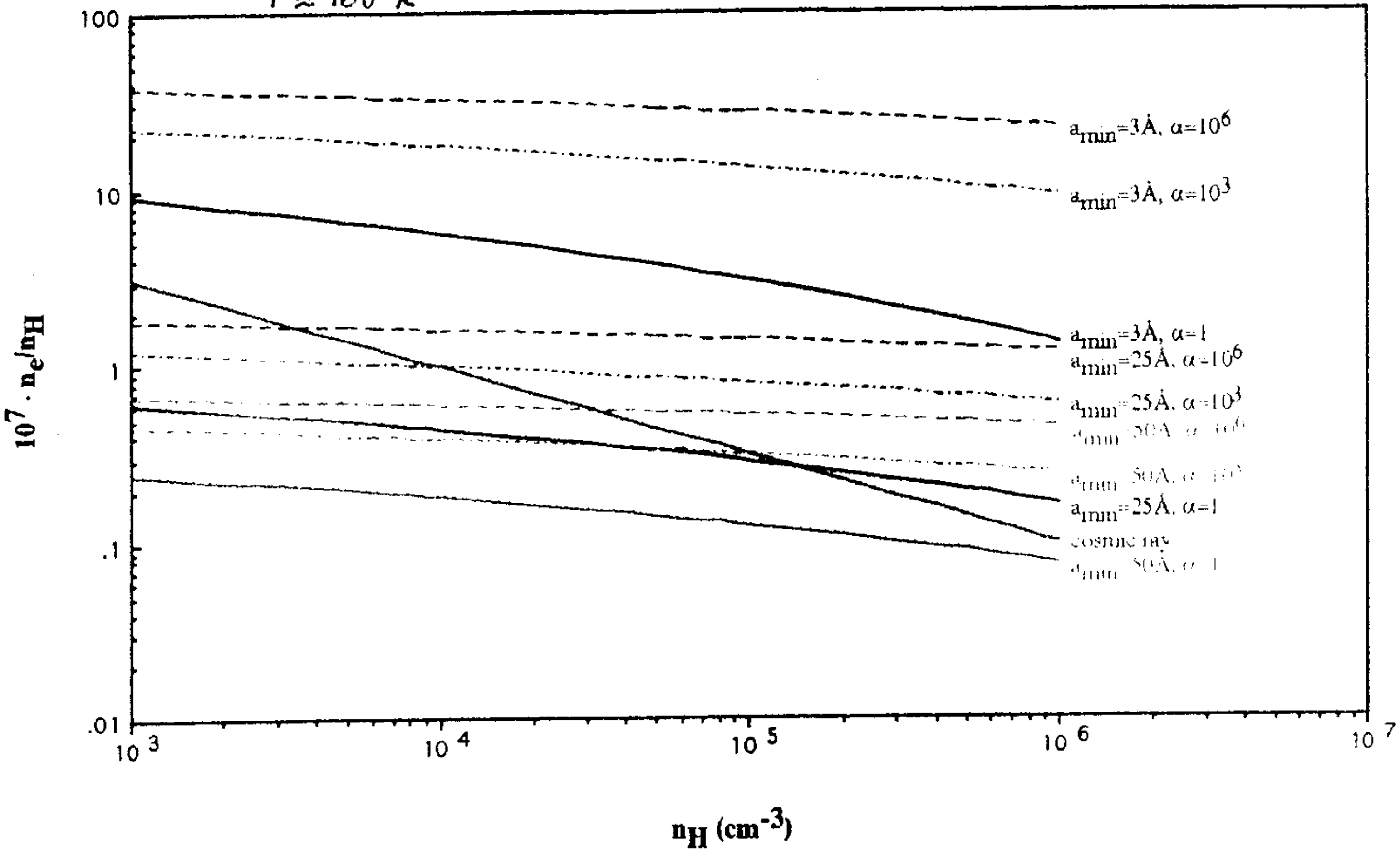
(Rosenberg, Mendis and Chow, 1994)

Astrophys. Space Sci. 222, 247.

Ionization of molecular clouds (Rosenberg et al. 1994)

(Warm photo-dissociation regions, just outside H II regions)

$T \approx 100\,°K$



$a_{min} = 50\,Å, 25\,Å$ (std. MRN)

$a_{min} = 3\,Å$ (Extended MRN — G. Nishi et al 1991).

Dust: MRN distribution: $\frac{dn_d}{da} = A\, n_H\, a^{-3.5}$

FUV (energy flux) = α · Habing flux ($\approx 1.6 \times 10^{-3}$ erg cm^{-2} s^{-1}).

Dynamics

Saturn:

- Evolution of 'radial spokes' (Voyager)
- Wavy F-ring (Voyager)
- Eccentricities of isolated ringlets within the Encke and Cassini divisions (Voyager)

Jupiter:

- 'Gossamer' ring (sync. orbit) (Voyager)
- Lenticular dust distribution around main ring (Voyager)
- High speed streams of fine dust (Ulysses)

Comets:

- (*P/Giacobini-Zinner*) • Overall distribution of dust in the tail (ICE)
- (*P/Halley*) • Distribution of VSG's on the sunward side (Vega)
- (*Ikeya-Seki*) • Waves in dust tail (Ground Obs.)
- (*Donati*) • Skewing of sunward envelopes (Ground Obs.)

Earth:

- Anthropogenic ring at synchronous orbit? ($A\ell_2O_3$ spherules from solid rocket propellant burns)

Proto-planetary nebula:

- Longitudinal focusing of proto-planetary rings

see. Goertz, 1989; Mendis and Rosenberg, 1994.

Gravito - Electrodynamics motion of charged dust in Planetary Magnetospheres

$$\ddot{\underset{\sim}{r}} = \frac{Q(t)}{m}\left[\underset{\sim}{E} + \frac{\dot{\underset{\sim}{r}} \times \underset{\sim}{B}}{c}\right] - \frac{GM_p}{r^3}\underset{\sim}{r} + \underset{\sim}{F}$$

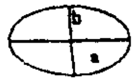
$\underset{\sim}{F}$ = **Forces associated with collisions with photon, particles (neutrals + ions) + other grains.**

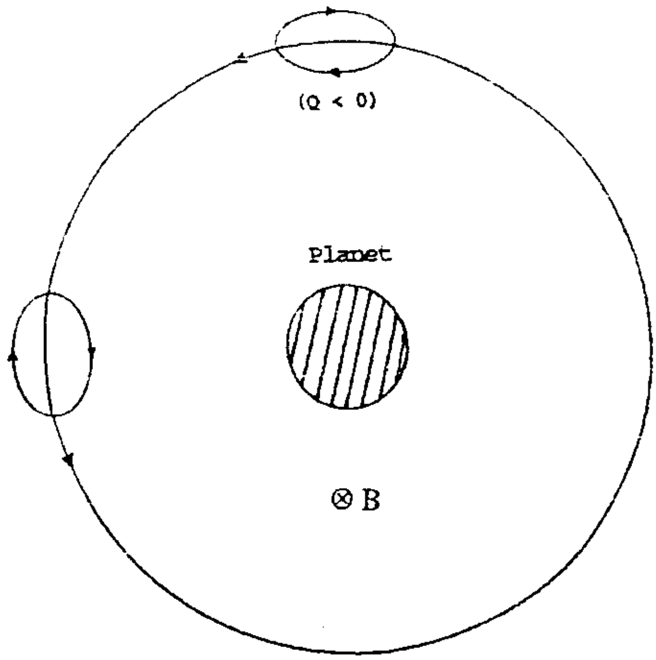
Within the co-rotating regions of the magnetosphere:

$$\underset{\sim}{E} = -(\underset{\sim}{\Omega}_p \times \underset{\sim}{r}) \times \frac{\underset{\sim}{B}}{c}$$

$\underset{\sim}{\Omega}_p$ = **Angular velocity of planetary spin**

Gravitoelectrodynamics





- **Epicyclic motion of a charged dust grain in an almost circular orbit about a magnetized planet.**

Mendis, Houpis and Hill, 1982, *J. Geophys. Res.*, **87**, 3449.

$$\omega_0 = -\frac{QB}{m_d c}, \quad \Omega_k = \left(\frac{GM_p}{r^3}\right)^{1/2}$$

$$\Omega_G^2 - \omega_0 \Omega_G + \omega_0 \Omega_p - \Omega_k^2 = 0$$

$$\omega^2 = \omega_0^2 + 4\omega_0 \Omega_G + \Omega_G^2$$

$$\frac{b}{a} = \frac{\omega}{2\Omega_G + \omega_0}$$

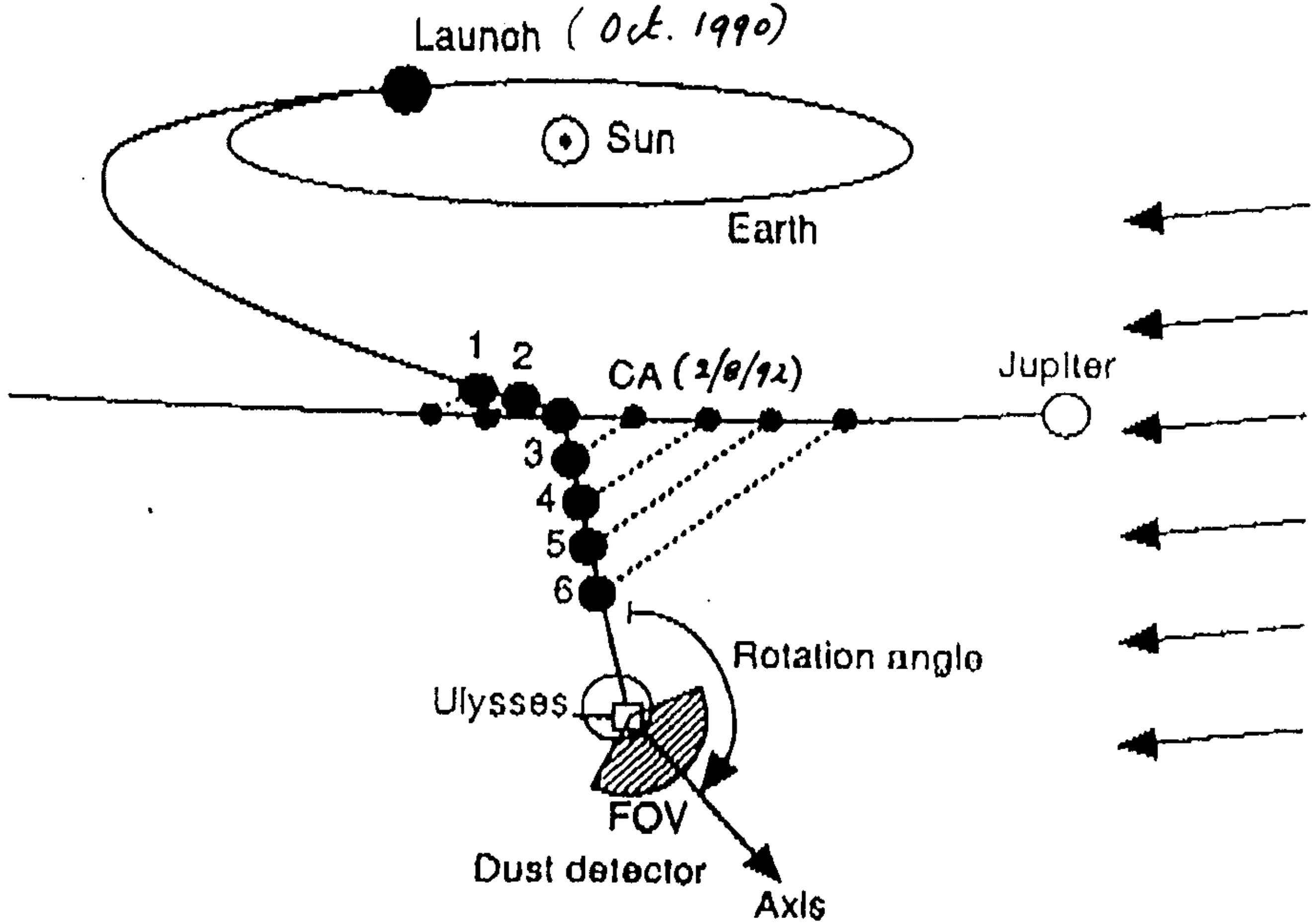
when $Q/m_d \to 0$ $\quad b/a \to 1/2$, $\Omega_G \to \Omega_k$

when $|Q/m_d| \to \infty$ $\quad b/a \to 1$, $\Omega_G \to \Omega_p$

- Periodic variation of the grain charge → new <u>radial</u> drift of the guiding center ("gyrophase drift", T. G. Northrop and J. R. Hill, 1983, *J. Geophys. Res.*, **83**, 1).

(<u>Review</u> T. G. Northrop, 1992, *Physica Scripta*, **19**, 475.)

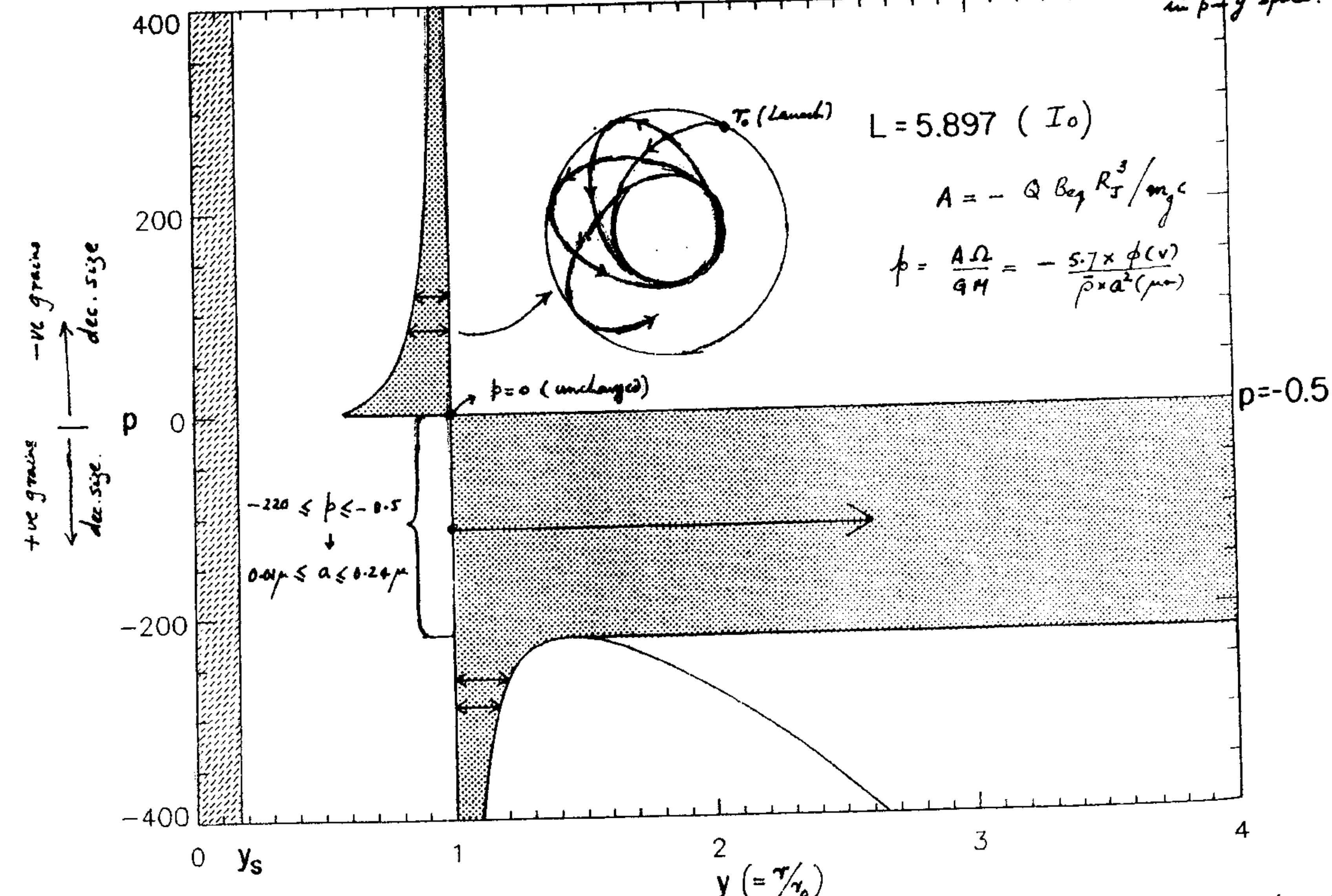
CA = 6.31 R_J



E. Grun et al, 1993, Nature, 362, 428

Numerical Simulation:
"Dusty Ballerina
Skirt"

Jupiter : Centered, aligned dipole ; Q = const. → 2 integrals of the
$v_\perp^2 \geq 0$ → Quadratic in $p(y) = 0$ → regions of confinement in p–y space.



Mendis and Axford (1974), Rev. Earth Planet. Sci., 2, 419.
Horanyi et al., (1995), Astrophys. J, 438, 968.

obs: 1) $0.03 \lesssim a \lesssim 0.2\ \mu m$,
2) $0.005 \lesssim a \lesssim 0.02\ \mu m$

Collective Processes

Much of the work on collective processes in dusty plasmas, as manifested by waves, instabilities and E. M. wave scattering, has been done in recent times. Besides the rapidly developing theory, with possible applications mainly to space, there now exists dedicated laboratory experiments. Here I will discuss some basic aspects of this work. Detailed reviews are given in:

(a) Wave in dusty plasmas, P. K. Shukla

(b) Instabilities in dusty plasmas, M. Rosenberg

(Both in *Physics of Dusty Plasmas*, ed. P. K. Shukla et al., 1996, World Sci. Press, Singapore).

(c) Waves and instabilities in dusty plasmas, F. Verheest, 1996, *Space Sci. Rev.*, 77, 267.

Waves and Instabilities

- $a \ll d \ll \lambda_D$: dust grains considered as pt. particles similar to multiply charged ions in a multi-comp. plasma.
- Significant differences from familiar electron-ion plasmas:

(1) $|q_d|/m_d \,(= z_d\, e/m_d) \ll |q_i|/m_i$.

(2) Typical wave frequencies associated with dust dynamics (e.g. $\omega_{pd} = \left(4\pi\, n_d\, q_d^2/m_d\right)^{1/2}$ and $\Omega_\alpha = |q_d\, B/m_d\, c|$ are very low compared to typical wave frequencies in standard ion-electron plasmas.

(3) Grains are polydisperse : $n(a)\, da \sim a^{-p}\, da$, $p \sim 1 - 4.5$;
$\therefore$ e.g. $\omega_{pd}\,(a) \sim a^{-(p+1)/2}$ is a cts. variable.

(4) q_d is not constant, it fluctuates in response to fluctuations in wave, with phase lag due to finite capacitance of the grains.

(5) Dust grains are more strongly subject to non-electrical forces such as gravity and radiation pressure; new sources of free energy to drive instabilities in a dusty plasma.

- Simple multi-fluid approach : single grain size, neglect grain charge fluctuations (e.g. see Shukla, 1992, *Phys. Scr.*, **45**, 504; D'Angelo, 1990, *Planet Space Sci.*, **38**, 1577).

- System equations :

  (a) Transport equations for each species.

  (b) Maxwell's equations.

  (c) Overall charge neutrality : viz

  $z_i n_i + \varepsilon_d z_d n_d = n_e$

  $(\varepsilon_d = 1 \text{ for } +ve \text{ grains}, \ \varepsilon_d = -1 \text{ for } -ve \text{ grains})$

- The last equation shows that dust can modify usual waves in an electron-ion plasma, by changing their phase velocities, even without participating in the dynamics.

- When dust participates in the dynamics one gets novel modes in the low frequency, low phase velocity regimes.

- Consider 2 linear (perturbed quantities $\sim e^{i(\vec{k}\bullet\vec{x}-wt)}$) electrostatic waves $\left(\vec{B}^{(1)}=\vec{0}\,,\,\vec{E}^{(1)}=-\nabla\phi^{(1)}\right)$ in an unmagnetized $\left(\vec{B}^{(0)}=\vec{0}\right)$ dusty plasma.

Case 1 : Dust considered to be immobile $\left(\vec{\upsilon}_d^{(1)}=\vec{0}\right)$.

Then the dispersion relation for the ion-acoustic mode (modified by the presence of dust via the overall charge neutrality condition) is given, in the phase velocity regime, where electron inertia is negligible
$\left(\upsilon_{ti} \ll \omega/k\right) \ll \upsilon_{te}\,;\ \upsilon_{t\alpha}=\left(kT_\alpha/m_\alpha\right)^{1/2}$, by

$$\omega^2 = k^2\, c_s^2 \left[\delta - \varepsilon_d\, z_d(\delta-1)\frac{m_i}{m_d}\right] \Big/ \left[1+k^2\,\lambda_{De}^2\right]$$

where $c_s =$ ion-acoustic speed $\left(\approx\left(k\,T_e/m_i\right)^{1/2}\right)$ and $\delta = n_{io}/n_{eo}$.

This is now referred to as the dust ion acoustic mode.

when $\quad \varepsilon_d=-1\,,\delta>1$

$$\omega^2 \approx \delta\, k^2 c_s^2 \big/ \left(1+k^2\lambda_{De}^2\right).$$

For long wave-lengths given by $k\,\lambda_{De} \ll 1$

$$\omega/k \approx \left(\delta\, k\, T_e/m_i\right)^{1/2}.$$

- Note in an ordinary plasma $(\delta = 1)$, this mode is heavily damped when $T_e = T_i$ because then $\omega/k \approx (kT_i/m_i)^{1/2} \approx v_{ti}$.

- In a dusty plasma this mode can exist even when $T_e = T_i$ when $\delta \ll 1$.

- As in standard electron-ion plasmas the associated <u>dust ion-acoustic instability</u> can be driven by a small electron drift *w. r. t* ions and dust of the order of a few times the ion thermal speed, (Rosenberg, 1993, *Planet Space Sci.*, **41**, 229).

- Possible role in

  (1) 'inner shock' in dusty cometary ionosphere
  (2) anomalous diffusion of magnetic field in contracting protostellar clouds.
  (e.g. See Mendis and Rosenberg, 1994)

Case 2 : Dust dynamics is included $\left(\vec{v}_d^{(1)} \neq \vec{0}\right)$

$\rightarrow$ novel 'dust-acoustic' mode whose frequency is below the dust plasma frequency and whose phase velocity is in the range $v_{td} \ll v_{ph} \ll v_{ti}$, v_{te}

(see Rao et al., 1990, *Planet Space Sci.*, **38**, 543).

In this case the electrons and ions provide the pressure while the dust provide the inertia, and the dispersion relation is (Rao et al., 1990; Rosenberg, 1993):

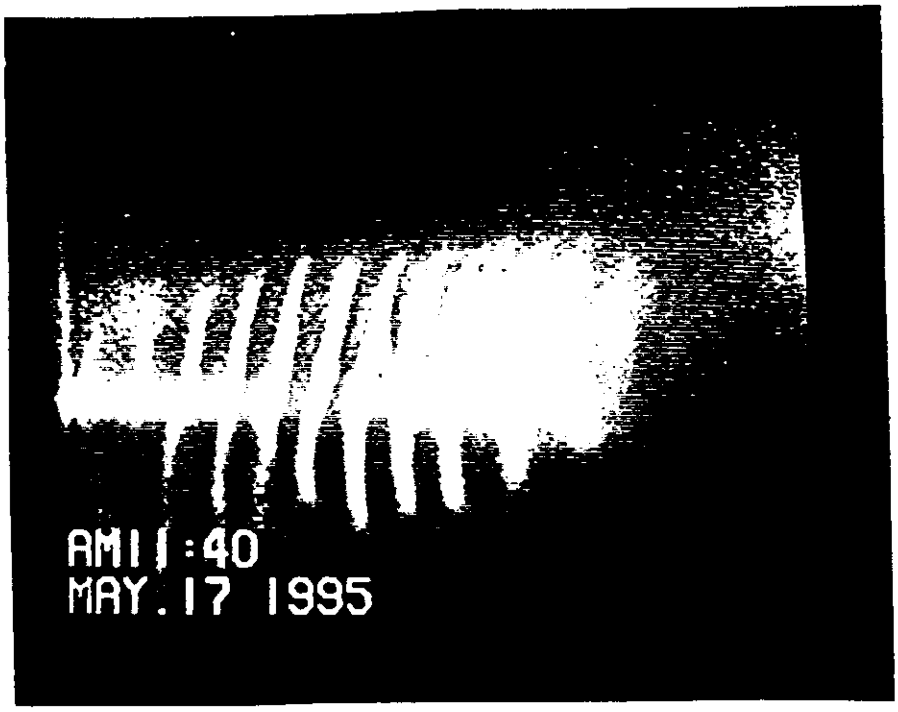
$$\omega^2 = k^2\, c_s^2\, \varepsilon_d\, z_d\, (1-\delta)\frac{m_i}{m_d} \bullet \frac{1}{\left(1+\delta\, T_e/T_i + k^2\, \lambda_{De}^2\right)}$$

- Dust-acoustic instability can be driven by the drifting of dust *w. r. t* electrons and ions with a speed $v_0 > v_{ph}$ (Rosenberg, 1993). Non-linear saturation of this mode $\rightarrow$ ion heating near the E-ring of Saturn (Winske et al., 1995, *Geophys. Res. Letts.*, **22**, 2069).

- Obs. in Laboratory (Barkan et al., 1995, *Phys. Plasmas,* **2**, 3563)

DA wave in a Q-machine plasma column

A. Barkan, R. L. Merlino and N. D'Angelo, 1995, *Phys. Plasmas*, **2**, 3563



- M. N. Rao, P. K. Shukla and M. Y. Yu, 1990, *Planet Space Sci.*, **38**, 543. (wave)
- M. Rosenberg, 1993, *Planet Space Sci.*, **41**, 229. (instability)
- $\lambda \approx 0.6\,\text{cm}.$
  $v_{ph} \approx 9\,\text{cm / sec}.$
  $\nu \approx 15\,\text{Hz}.$
  $\left(A = |\Delta n_d / n_d| \sim 1\right)$
- $T_e \gg T_i, \quad k\lambda_{De} \ll 1$
  $$v_{ph} \to Z_d \left(\frac{k_B T_i}{m_d} \bullet \frac{n_d}{n_i} \right)^{1/2} \sim 10\,\text{cm / sec}.$$
  $n_d / n_i \sim 5 \times 10^{-4}, \quad Z_d \approx 2 \times 10^3, \quad m_d \sim 10^{-12}\,\text{g}$
  $kT_i \sim 0.2\,\text{eV}, \quad kT_e \sim 3\,\text{eV}$

- **Progress:**
  1. Studies of both electrostatic and electromagnetic waves and instabilities in dusty plasmas.
  2. Use both fluid and kinetic approaches.
  3. Linear and non-linear analyses.
  4. Effects of collisionality and strong Coulomb coupling.

- **Drawbacks:**

  Theoretical studies far ahead of observations.

- **Strength:**

  Recent dedicated laboratory experiments. These include (1) the verification of the role of negatively charged dust in the Electrostatic Ion Cyclotron Instability (EICI), Barkan et al., 1996, *Planet Space Sci.*, **44**, 239) and the dust ion acoustic wave and instability (D'Angelo, 1990, *Planet Space Sci.*, **38**, 1143). In addition there is a striking laboratory observation (Barkan et al., 1995, *Phys. Plasmas,*, **2**, 3563) of the Dust Ion Acoustic Wave (DAW) driven unstable by the relative drift between the plasma ions and negatively charged dust. The wave crests of this slowly propagating $\left(\upsilon_{ph} \approx 9 \text{ cm/sec}\right)$ large amplitude $\left(\left|\Delta n_d / n_d\right| \sim 1\right)$ low frequency $(\nu \sim 15 \text{ Hz})$ wave, which are separated by ~ 0.6 cm, are easily seen by light scattering from a laser or even a flash light.

EM wave scattering by charged dust grains

- Thomson scattering by dust : $\alpha \quad q_d^4 / m_d^2 \ll q_e^4 / m_e^2$

- Isolated ($d \gg \lambda_D$) charged grain surrounded by screening cloud of electrons and ions. $\Rightarrow$ Coherent scattering by electrons in screening cloud when wave length of the incident radiation, $\lambda_o > \lambda_D$. $\Rightarrow$ Increase in effective scattering cross section compared to scattering by free electrons or scattering by thermally induced plasma fluctuations. (e.g. Tystovich et al 1989, Tystovich 1992, Bingham et al, 1991, 1992; de Angelis et al 1992, La Hoz 1992, Hagfors 1992).

When $\lambda_o > d \gg \lambda_D \gg a$

$\sigma_{eff} = n_d Z_d^2 \sigma_o$ (σ_o = Thomson cross section for scattering by free electrons)

σ_p = scattering cross section from plasma fluctuations (no dust) $= n_o \sigma_o / 2$

$$\therefore \quad \frac{\sigma_{eff}}{\sigma_p} \approx \frac{n_d Z_d^2}{n_o}$$

- Significantly enhanced scattering $\Rightarrow \dfrac{n_d}{n_o} \gg \dfrac{1}{Z_d^2}$

(i.e.) $n_d \gg \dfrac{2 \times 10^{-6}}{\{\phi\,(v)\, a(\mu m)\}^2}\, n_o$

If $\Phi_s = +3$ V , $a = 0.1\,\mu m$, $n_d \gg 2 \times 10^{-5}\, n_o$

If $n_o = 3 \times 10^3$ cm^{-3} , $n_d \gg 0.06$

- When $\lambda_o > \lambda_D \gg d \gg a$ (grain-grain interaction, plasma depletion) $\Rightarrow$ decrease in σ_{eff} . Possibly no significant enhancement of scattering (La Hoz, 1992, Hagfors, 1992, de Angelis et al 1992). However, there are some disagreements in the theoretical calculations, using various approximations. Need laboratory data.

- It has been suggested that this is the case of the strong radar backscatter observed from the high latitude summer mesopause at certain frequencies (Havnes et al., 1990; *J. Atmos. Terr. Phys.*, **52**, 637).

- Small $(a \leq 0.02\mu m)$ negatively charged dust particles with small negative charge $(z_d = -1)$ and occasionally larger $(a \leq 0.06\mu m)$ positively charged dust $(z_d \sim 80)$ may recently have been observed in this region using rockets launched from Andoya, Norway, in the summer of 1994.

- These charge estimates, while being highly uncertain, appear to be too small to be responsible for the observed radar backscatter as suggested by Havnes et al., (1990).

'Plasma Crystals'

- Formation of Coulomb lattices of negatively charged dust in a plasma (H. Ikezi, 1986, *Phys. Fluids*, **29**, 1764.

- Coulomb Coupling parameter,

$$\Gamma = \frac{\text{Electrostatic P.E.}}{\text{Dust Th.E.}} = \frac{Z_d^2 e^2}{d k_B T_d} \exp(-d/\lambda_D)$$

Coulomb Crystallization $\rightarrow \Gamma > \Gamma_c \approx 170$ (OCP)

- Space applications?: Narrow rings of Uranus (~10-100 km)
  Incomplete Rings of Neptune, (Goertz, 1989).

- Lab. Experiments using RF discharges:
  H. M. Thomas, G. E. Morfill, V. Demmel, J. Goree, B. Feuerbacher, D. Mohlman, 1994; J. H. Chu and Lin I, 1994; Y. Hayashi and K. Tachibana, 1994; J. H. Chu, Ji-Bin Du and Lin I, 1994, Hafiz, U'Rahman, 1996 (private communication). ($\Gamma \gtrsim 500$)
  (Review: H. M. Thomas and G. Morfill, 1996, Physics of Dusty Plasmas, ed P. K. Shukla et al, World Scientific, Singapore).

- Typically $d \sim 160-290\mu m$, $\lambda_D \lesssim 100\mu m$, $a \sim 5-100\mu m$
  $P_n \gtrsim 100$ mTorr ('cool' solid particles, damp out low frequency fluctuations).
  $n_n \sim 10^{16}\ cm^{-3}$, $n_e \sim 10^{10}\ cm^{-3}$, $n_d \sim 10^{6}\ cm^{-3}$, $kT_e \sim 2eV$, $kT_d \sim 0.03eV$

- New material, valuable tool for studying physical processes in condensed matter physics.

- To overcome effects of gravitational compression, micro-g experiments (e.g. shuttle) planned.

- In all these experiments: Electrons, positive ions and negatively charged dust.

- New type of plasma crystal with positively charged dust electrons have also been proposed:
  M. Rosenberg, and D. A. Mendis, 1995, *IEEE Trans. Plasma Sci.*, **23**, 177; M. Rosenberg, D. A. Mendis, D. P. Sheehan, 1996, *IEEE Trans. Plasma Sci.*, in press.

- Dust + Inert gas + UV rad. source (e.g. UV excimer or deuterium lamps). (Work fn. of dust < photon energy < ionization pot. of gas.) Ranges of neutral background pressure where (a) $Kn = \ell/a > 1$ and (b) $Kn < 1$ (atmospheric pressure) have been considered.

- Crystallization over wider range of intergrain spacings.

- Photophoretic force becomes very important at higher pressures (P > 1. Torr). Useful for levitation and overcoming gravitational compression.

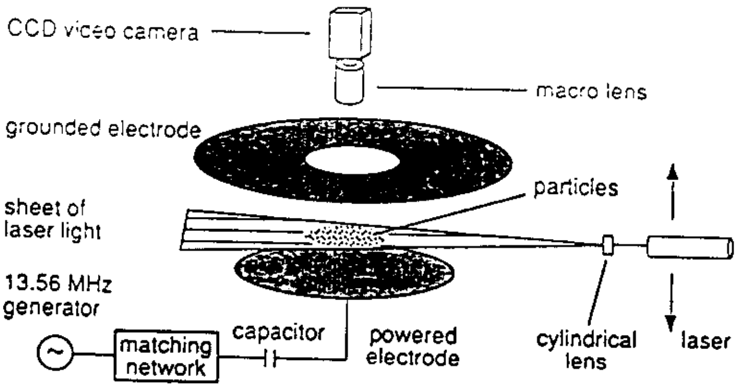


FIG. 1. Schematic of apparatus. A discharge is formed by capacitively coupled rf power applied to the lower electrode. A vacuum vessel, not shown, encloses the electrode assembly. A cylindrical lens produces a laser sheet in a horizontal plane, with an adjustable height. The dust cloud is viewed through the upper ring electrode.

Thomas et al, 1994, Phys. Rev. Lett., 73, 652

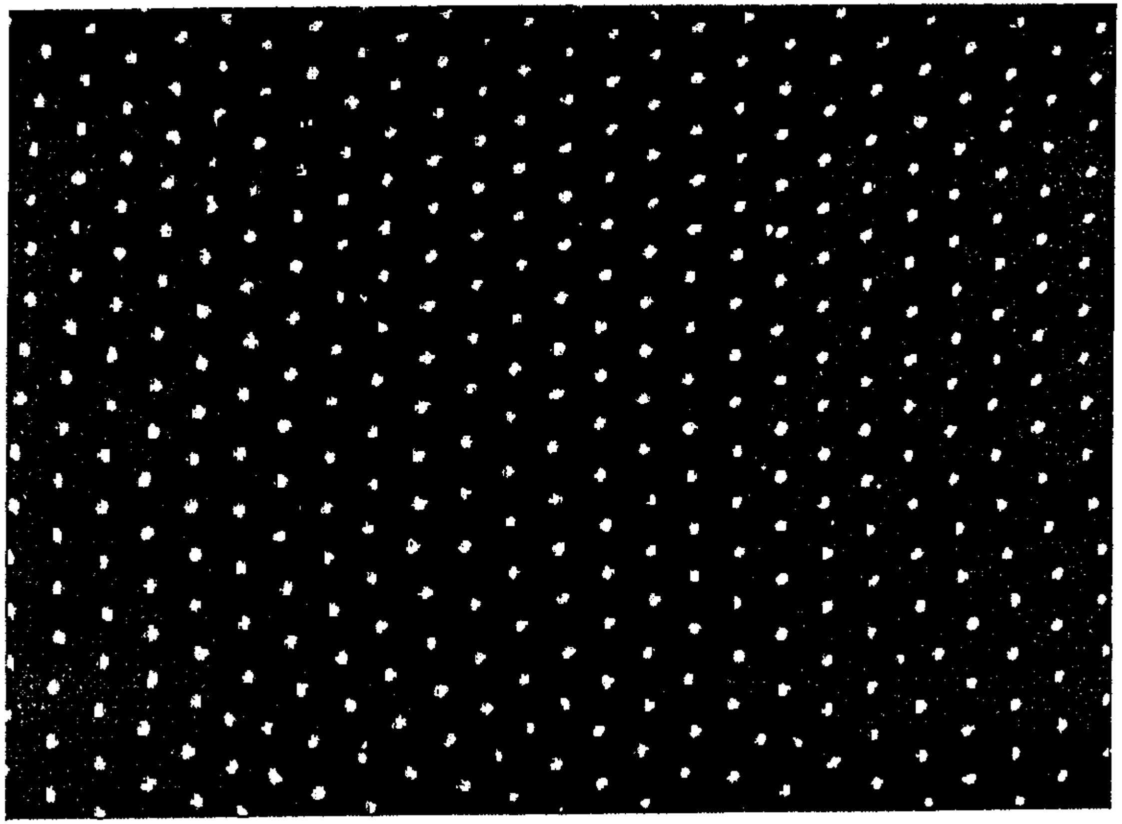


Figure 4: Image of the particle cloud in a plane above the lower electrode. The area shown is $6.1 \times 4.2 mm^2$ and contains 392 particles of $6.9 \mu m$ diameter.

H. M. Thomas and G. E. Morfill, 1996, Phys. Dust Plasmas (ed. P. K. Shukla et al) World Sci press, Singapore.

Coulomb Crystals with positive dust grains

(Rosenberg and Mendis, 1995), IEEE Trans. Plasma Sci, 23, 17
(Low press. $n_n \approx 10^{14}\ cm^{-3}$)

Atm. press: Rosenberg et al, 1996, IEEE Trans. Plasma Sci, 24, 1422.

Dust + inert gas (eg Ar) + UV radiation source;
Work *fn.* of dust $< h\nu <$ Ionization pot. of gas.
$\longrightarrow$ positive grains + electrons

Current balance on grain; and charge neutrality $\longrightarrow$

$$Z_d\left(1+\frac{e^2 Z_d}{aT_e}\right)=\frac{Q_{abs}\,Y\,J}{n_d}\sqrt{\frac{\pi m_e}{8T_e}}\ \exp\left(-\frac{Z_d e^2}{a\,T_{pe}}\right) \qquad (1)$$

$$\Gamma=\frac{Z_d^2 e^2}{d\,T_d}\ \exp\left(-d/\lambda_D\right) \qquad (2)$$

where $d=\left(3/4\pi n_d\right)^{1/3}$ and $\lambda_D=\left(T_e/4\pi e^2 n_e\right)^{1/2}$

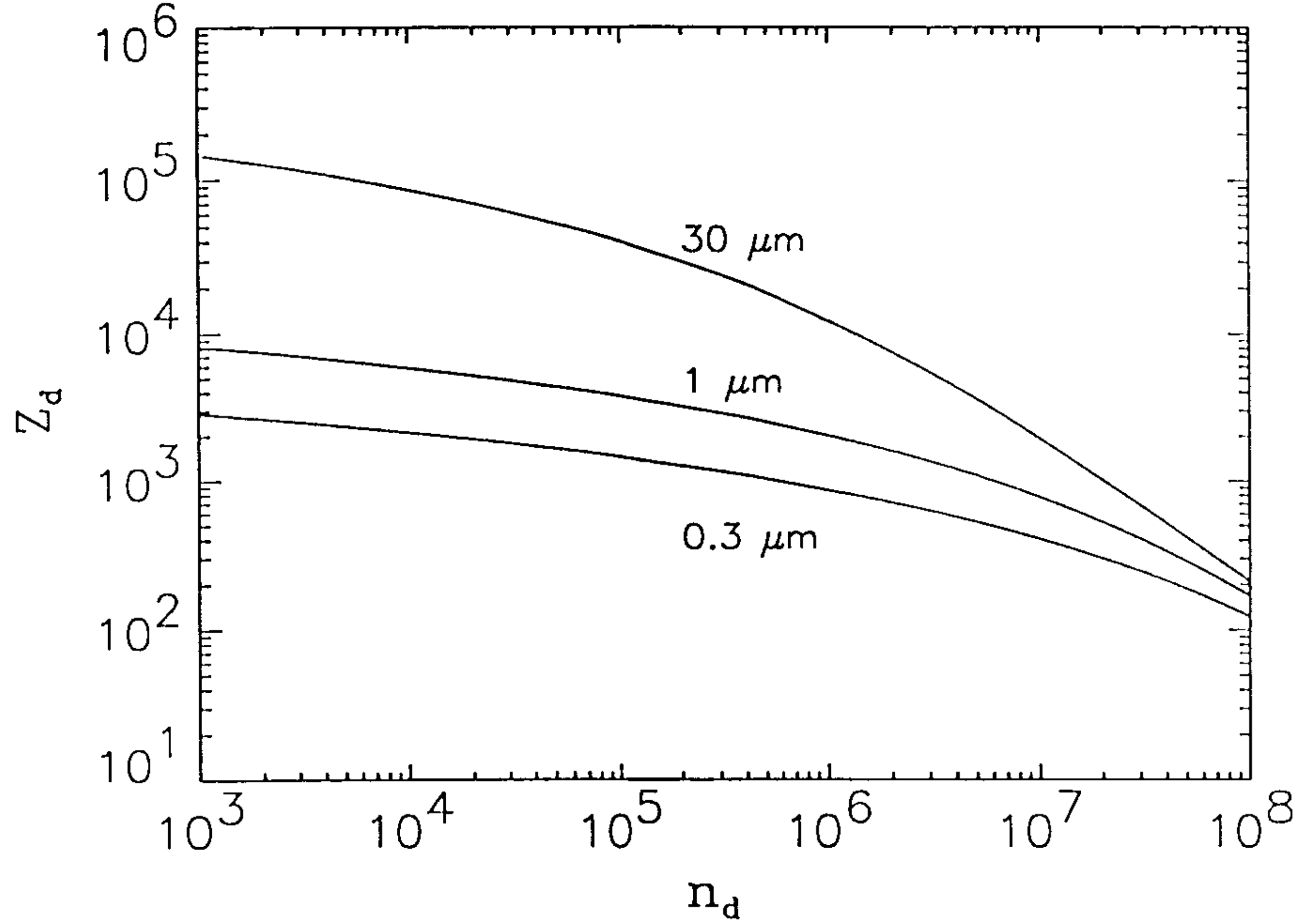
- Use (1) and (2) to show Z_d vs n_d and Γ vs n_d for various values of a (given J, Q_{abs}, Y, T_e and T_{pe}).

- Cts. source of UV photons (eg. Deuterium discharge lamp)
  $J \approx 4x10^{18}$ photons / cm^2 sec, $h\bar{\nu} \sim 8-9\ ev$ (Key and Preston, 1980)

  when $a \approx 1\mu m$, $\frac{2\pi a}{\lambda} >> 1 \quad \rightarrow Q_{abs} \approx 1.$

  $Y \approx 1$ (metals); $Y \approx 0.1$ (dielectrics); Take $Y \approx 0.5$.

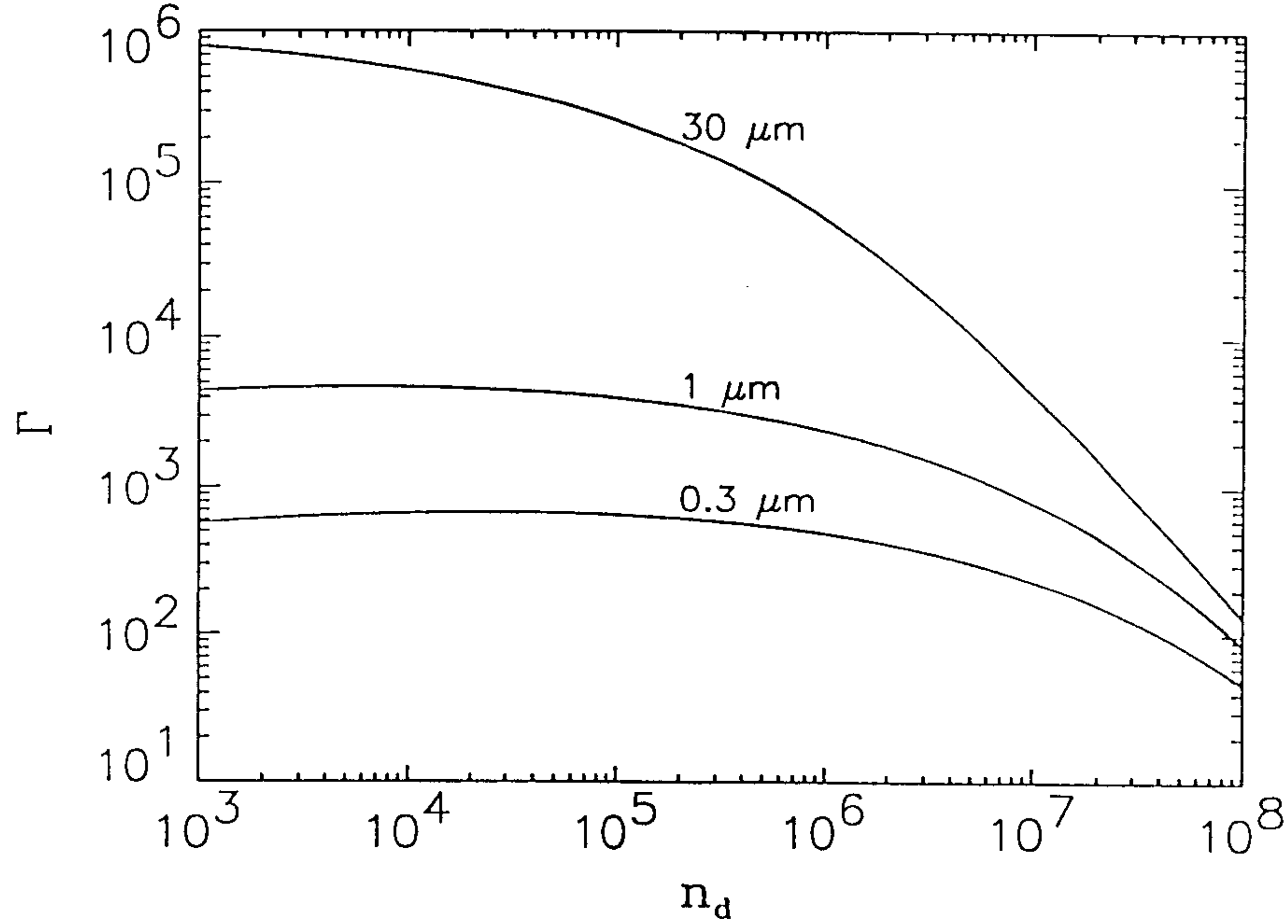
$T_{pe} \approx 2\ ev$, $\nu_{ed} >> \nu_{en}\left(\text{if } n_d / n_n >> 2\times 10^{-12} / a^2(\mu m)\right)$ $\therefore$ $T_e = T_{pe} (\approx 2ev)$.



$J = 4 \times 10^{18}$ photons/cm^2.sec

$Y = 0.5$

$T_e = T_{pe} = 2$ eV.



$T_d = 0.03\,eV$.

For all values of a, $\Gamma > 170$ when $n_d \lesssim 10^7\,cm^{-3}$.

- Gravitational Stability of Crystal Structure

$$m_d\, gh \leq Q^2 / \mathrm{d} \quad \text{(Ikezi, 1986)}$$

$$a = 0.3\mu m, \quad n_d = 10^6\ cm^{-3} \quad \rightarrow Z_d \approx 10^3.$$

$$\text{with } \rho = 1 \left(\text{i.e. } m_d \approx 10^{-13} g\right), \quad h \leq 0.4\ \text{cm}.$$

Since $d \sim 60\mu m$ # of Layers ≥ 60.

- Thermalization <u>rate</u> of grains on neutrals

$$\sim \pi a^2\, n_n\, v_n \left(\frac{m_n}{m_d}\right) \sim \frac{1}{a} \quad .$$

- Recoil effect due to photoemission of electrons >> radiation pressure effect.

$\rightarrow \mathrm{v}_d$, terminal $\approx 160\ cm/s$, when $n_n \approx 10^{14}\ cm^{-3}$.

$\left(\mathrm{v}_d \sim 1/n_n\right)$

- Recoil effect balanced by gravity when $a(\mu m) \sim 3 \times 10^{-19} YJ \sim 0.6$.

- UV heating of the grain : not significant.

* Atm. pressure : Photophoretic force is important.

** Recently strongly coupled ($\Gamma \sim 50$) dusty plasmas with positively charged grains (produced by thermoionic emission) has been observed in the lab. (Fortov et al. 1996. Phys Rev E54 1