15th Topical Conference on RF Power in Plasmas
May 20 –22, 2003   Jackson Hole, Wyoming

Waves and Instabilities in Dusty Plasmas

Bob Merlino

University of Iowa

Outline

- What is a dusty plasma?
- Where are dusty plasmas?
- Charging of dust particles
- Waves in dusty plasmas

Dusty Plasmas

- Dust represents much of the solid matter in the universe and this component often coexists with the ionized matter forming a <u>dusty plasma</u>.

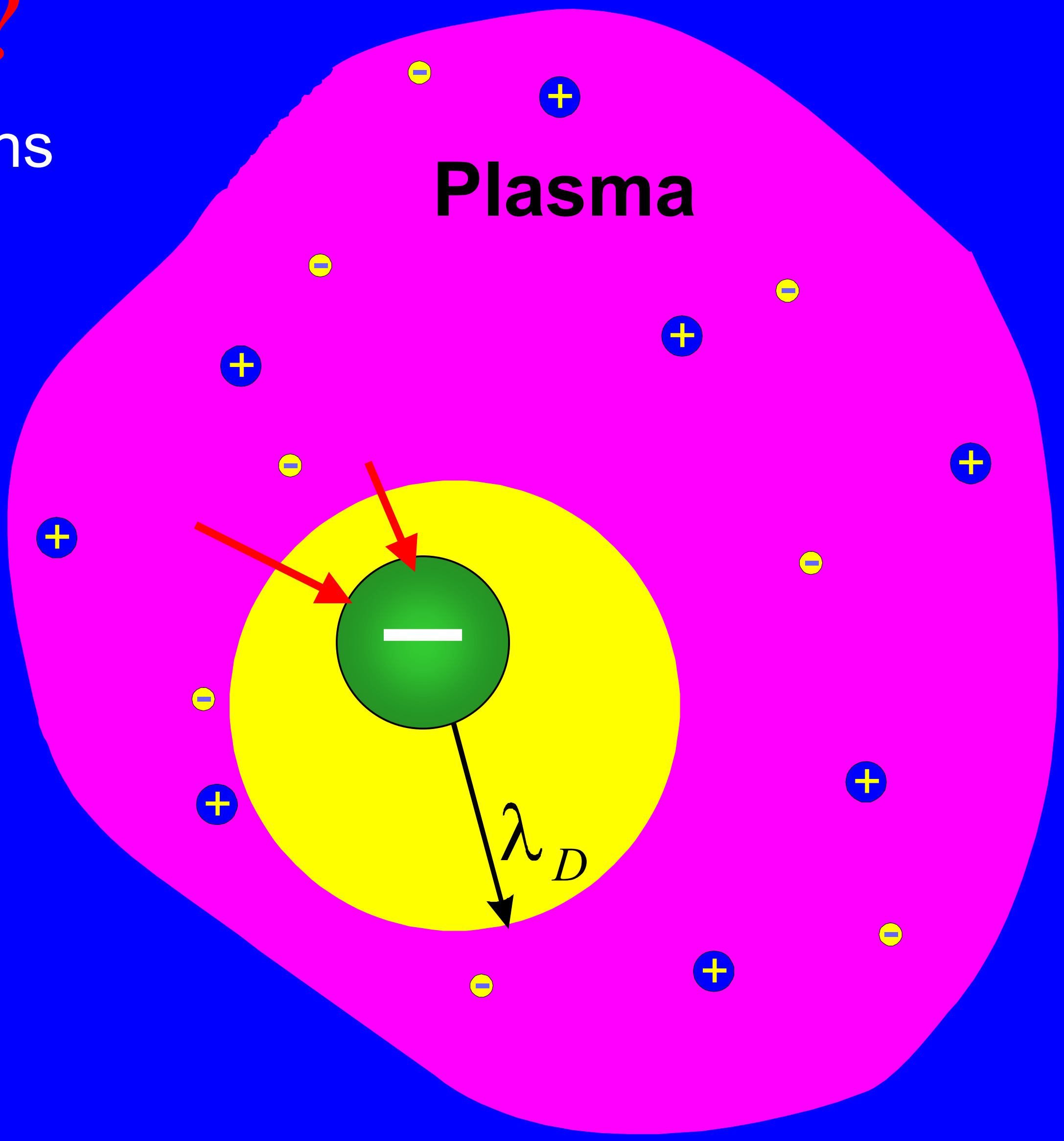
- Dust is often present in laboratory plasmas as well either by choice or circumstance.

What is a dusty plasma?

plasma = electrons + ions

small particle
of solid matter

- absorbs electrons and ions
- becomes negatively charged
- Debye shielding



Importance of Charged Dust

- the dust acquires an electrical charge and thus is subject to electromagnetic *as well as* gravitational forces

- the charged dust particles participate in the <u>collective plasma processes</u>

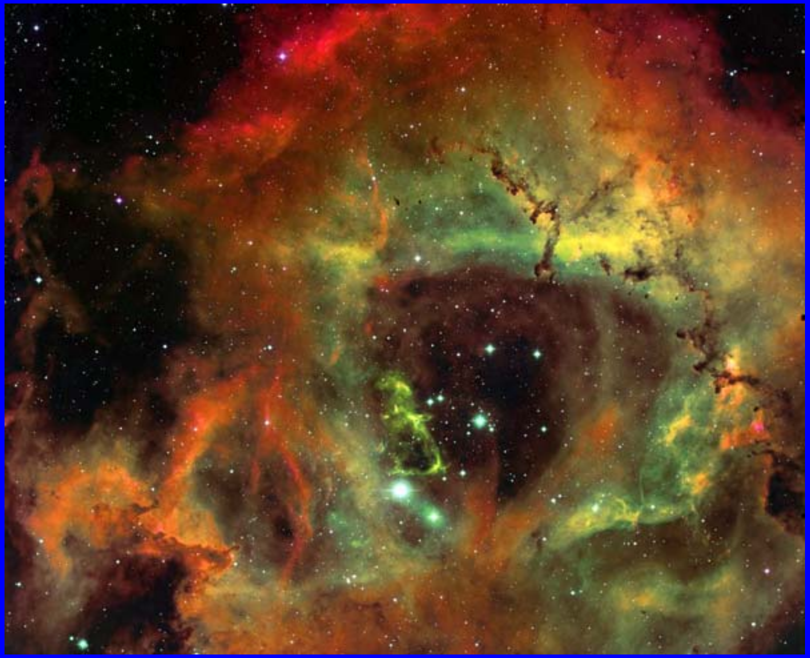
DUSTY PLASMAS

Natural

1. Solar nebula
2. planetary rings
3. interstellar medium
4. comet tails
5. noctilucent clouds
6. Lightning
7. snow

Man-made

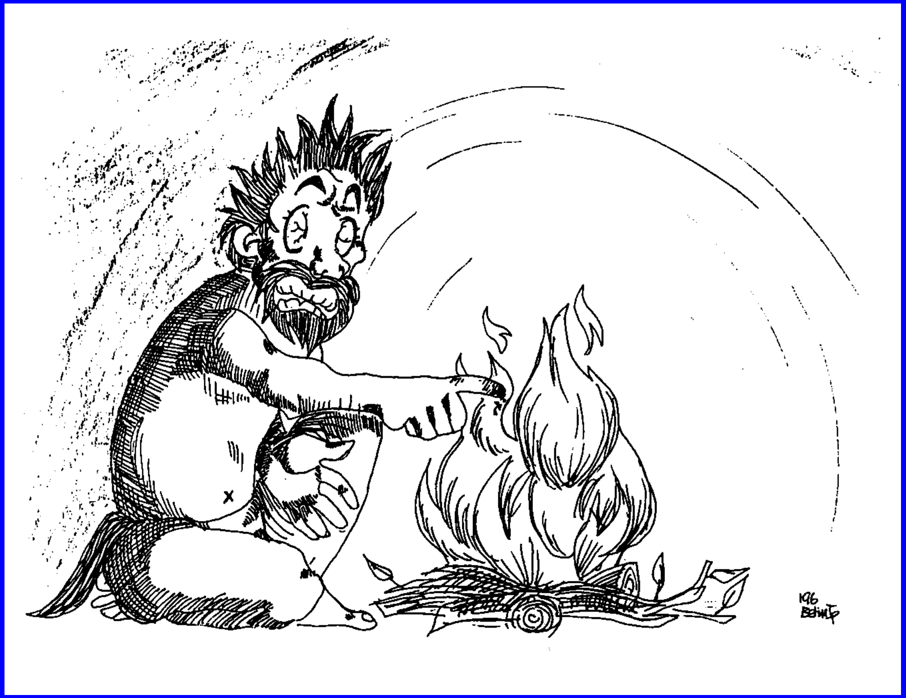
1. Microelectronic processing
2. rocket exhaust
3. flames
4. fusion devices
5. H bomb



Rosette Nebula

Our solar system accumulated out of a dense cloud of gas and dust, forming everything that is now part of our world.

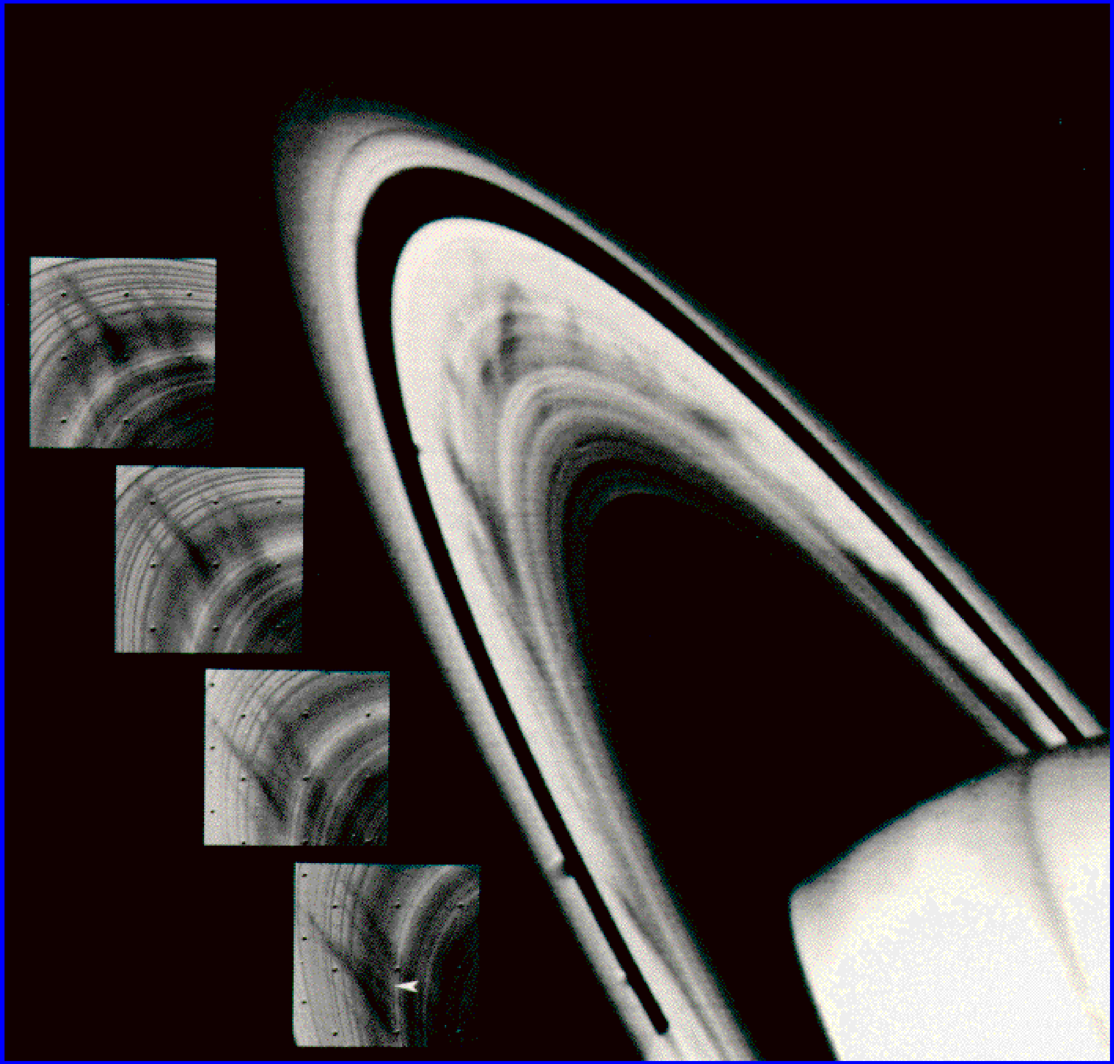
A flame is a very weakly ionized plasma that contains soot particles.



An early temperature measurement in a dusty plasma.

Comet Hale-Bopp

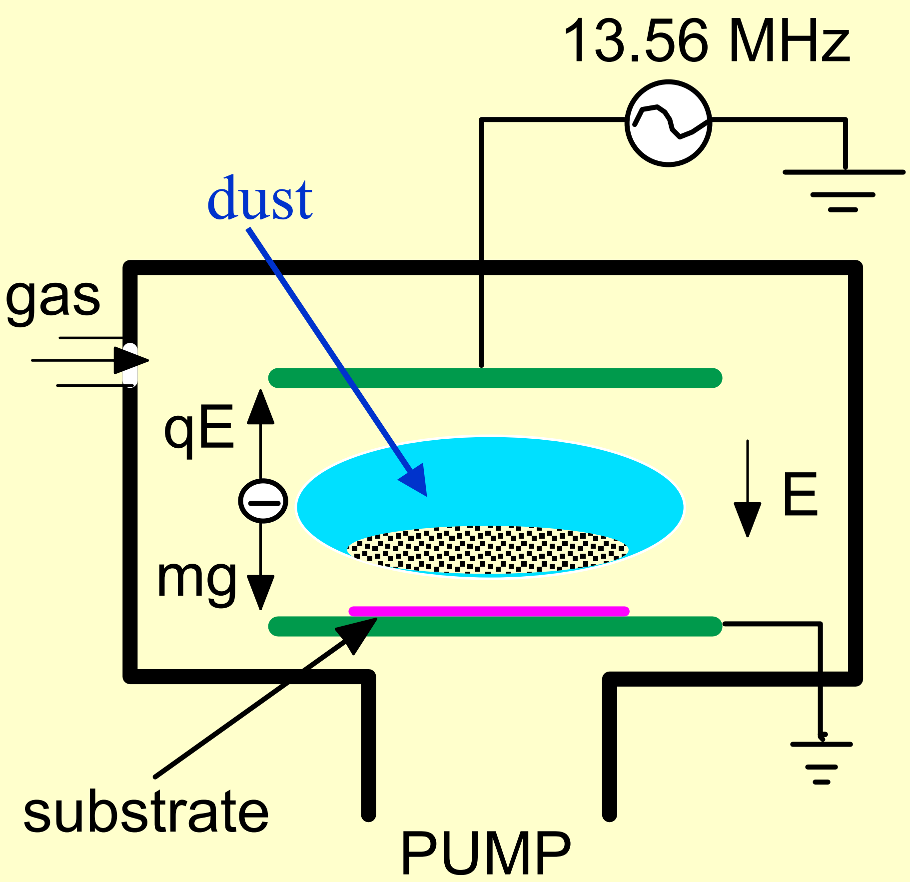
Spokes in Saturn’s B Ring

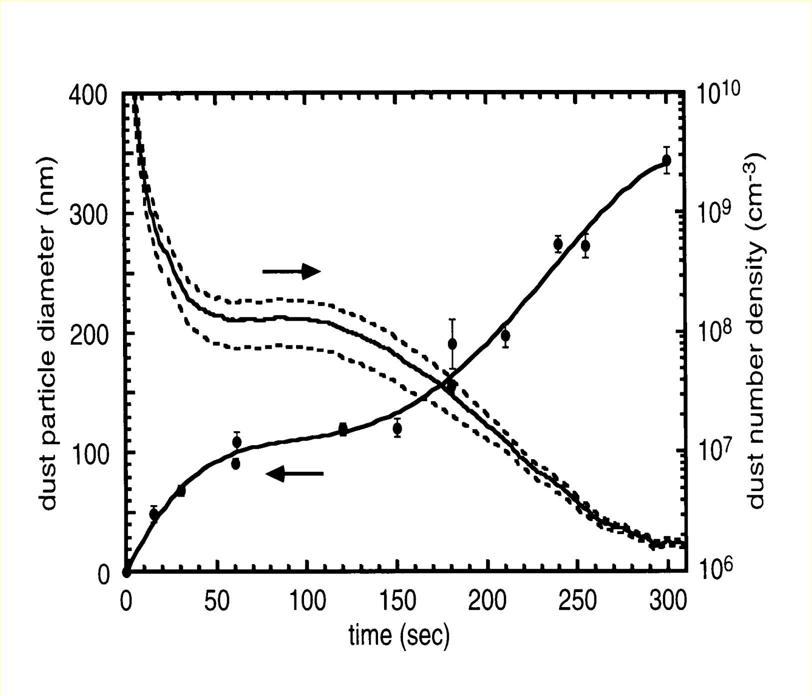


Voyager 2
Nov. 1980

Cassini-
Huygens
July 2004

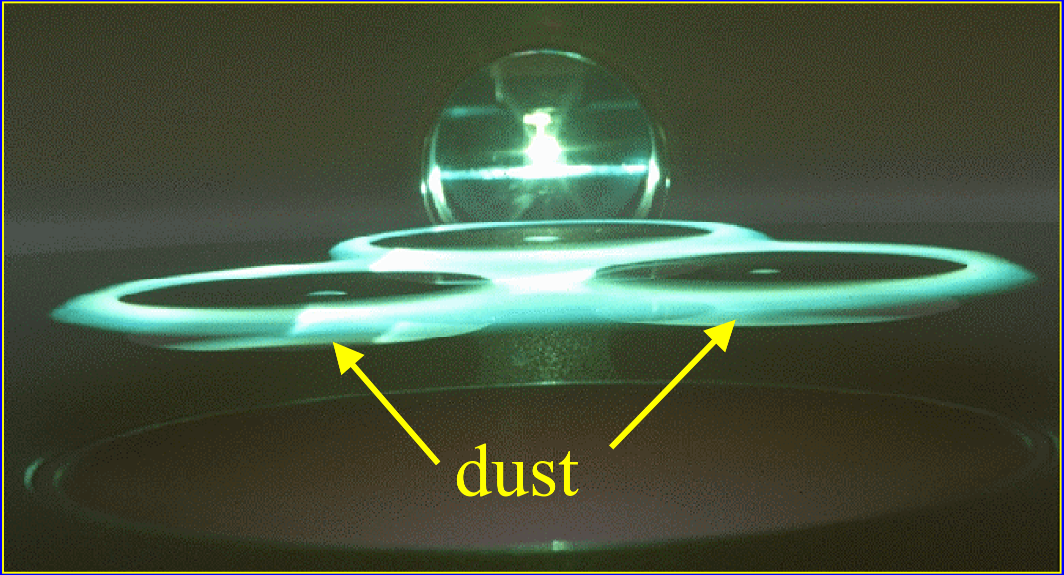
Semiconductor Processing System





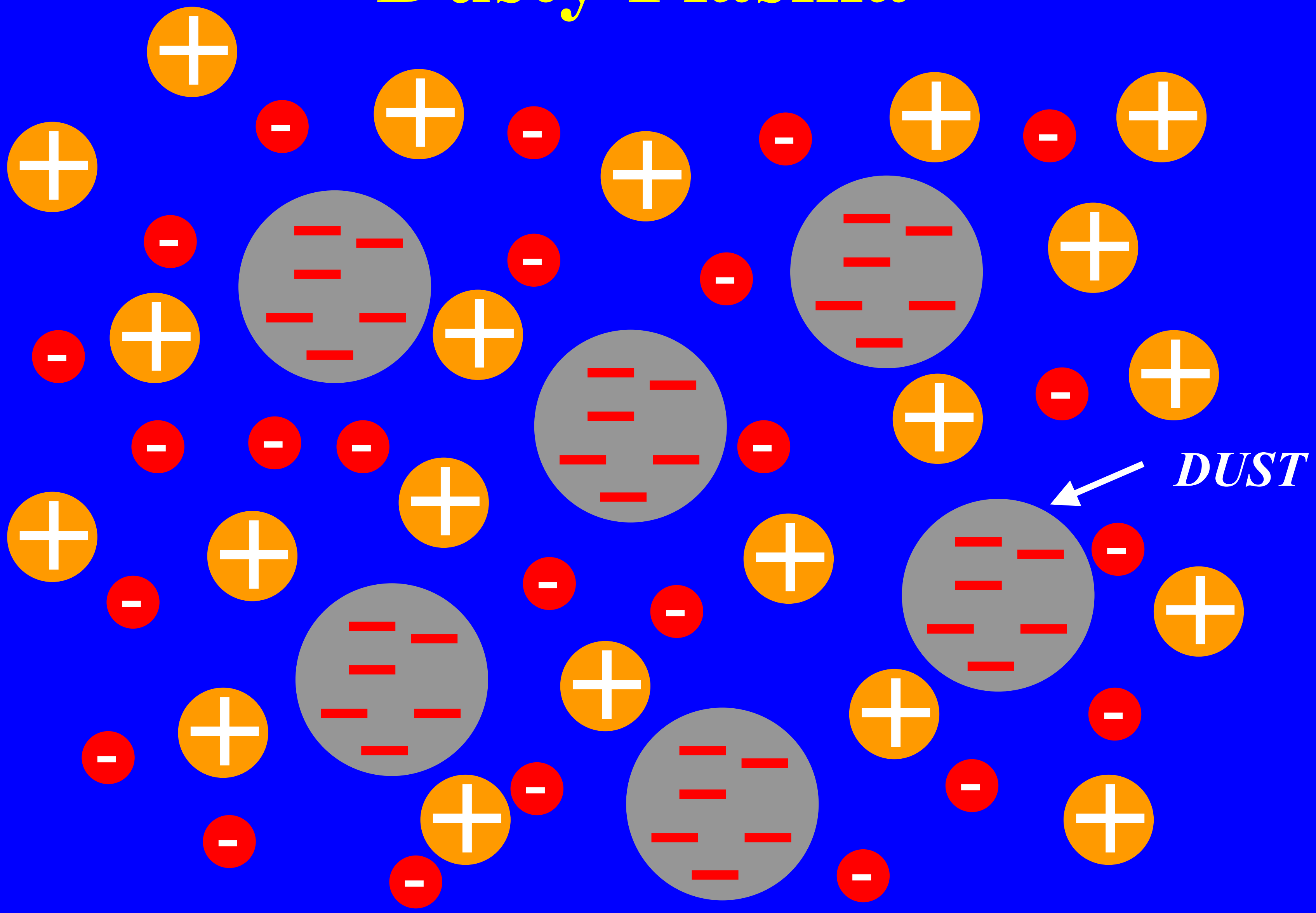
silane (SiH_4) + Ar + O_2 $\rightarrow$ SiO_2 particles

Semiconductor Manufacturing



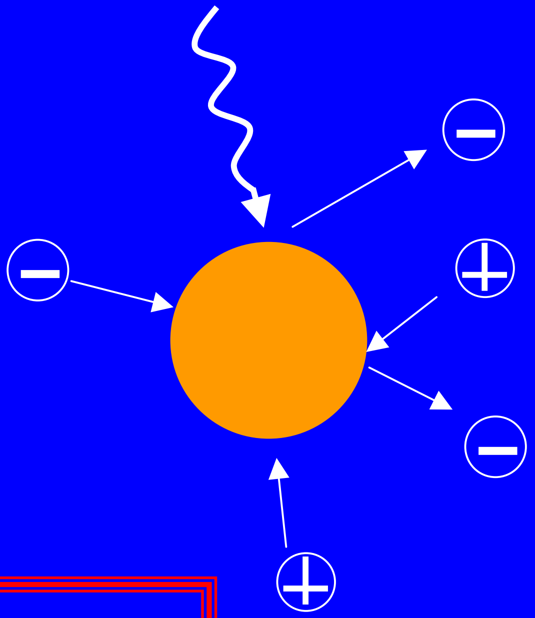
Physics Today
August 1994

Dusty Plasma



Dust Charging Processes

- electron and ion collection
- secondary emission
- UV induced photoelectron emission



Total current to a grain = 0

$$\Sigma I = I_e + I_i + I_{sec} + I_{pe} = 0$$

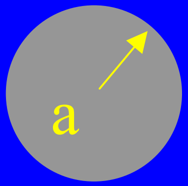
The Charge on a Dust Grain

In typical lab plasmas $I_{sec} = I_{pe} = 0$

Electron thermal speed >> ion thermal speed so the grains charge to a negative potential V_S relative to the plasma, until the condition $I_e = I_i$ is achieved.

electron repulsion

$$I_e = en_e\sqrt{\frac{kT_e}{m_e}}\ \exp\left(\frac{eV_S}{kT_e}\right)\ \pi a^2$$



$$I_i = en_i\sqrt{\frac{kT_i}{m_i}}\ \left(1-\frac{eV_S}{kT_i}\right)\ \pi a^2$$

$Q = (4\pi\varepsilon_o a)\ V_S$

ion enhancement

Typical Lab Plasma

- For $T_e = T_i = T$ in a hydrogen plasma

$$V_S = -\,2.5\ (kT/e)$$

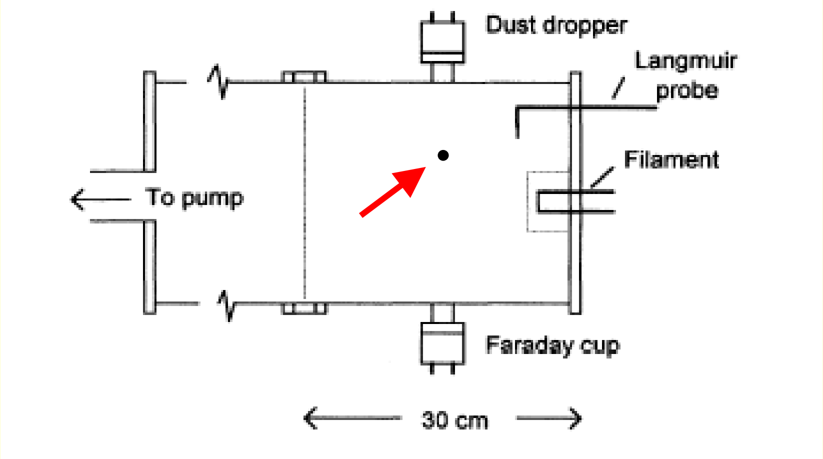
- If $T \approx 1$ eV and $a = 1\ \mu$m,

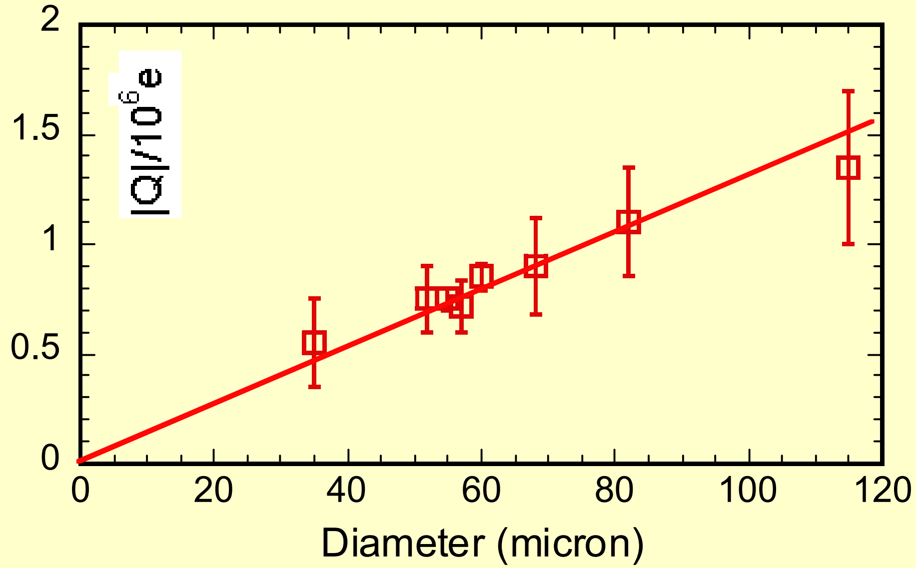
$$Q \approx -\,2000\ e$$

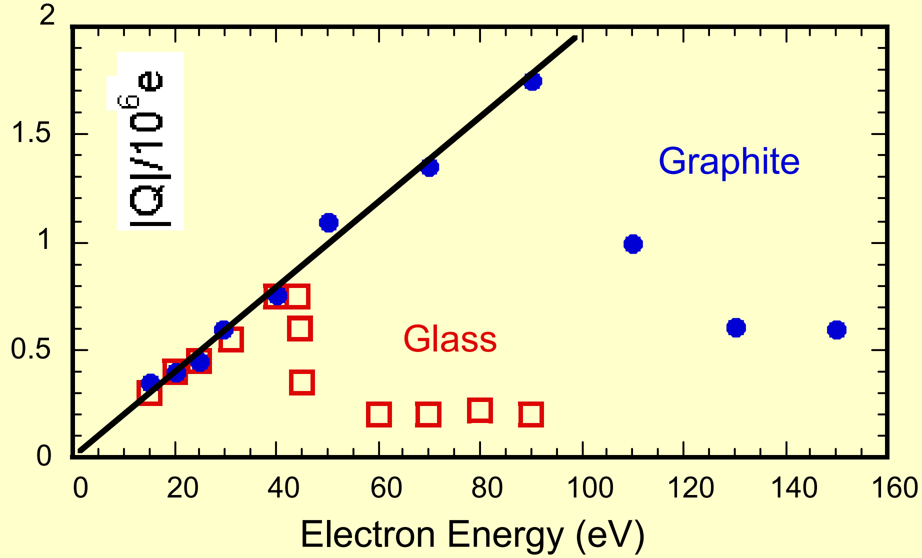
- Mass: $m \approx 5 \times 10^{12}\ m_p$

Dust Charge Measurements

Walch, Horanyi, & Robertson,
Phys. Rev. Lett. 75, 838 (1995)







Waves in dusty plasmas

- electrostatic dust ion-cyclotron waves (EDIC)
- dust ion acoustic waves (DIA)
- dust ion acoustic shocks (DIAS)
- dust acoustic waves (DA)
- Dust cyclotron mode
- Strongly coupled dusty plasmas

Effect of dust on plasma waves

- the presence of dust modifies the characteristics of the usual plasma modes, even at frequencies where the dust does not participate in the wave motion
- the dust provides an immobile charge neutralizing background

$$n_i = n_e + Z_d n_d$$

Dust Modes

- new, low frequency (~ few Hz) modes in which the dust grains participate in the wave motion appear in the dispersion relations
- the dust dynamics can be observed visually since the dust motion can be imaged and recorded on tape

Quasineutrality in dusty plasmas

- For low frequency waves the condition $n_i = n_e + Z_d n_d$ holds in both zero and first order

- defining: $\varepsilon = n_{do} / n_{io}$ we characterize the dusty plasma using the quantity εZ_d which is the fraction of negative charge on the dust grains

Fluid theory of Low frequency electrostatic waves in dusty plasmas

Three component plasma: electrons, ions, negative dust

$$I. \quad \frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha v_\alpha) = 0$$

$$II. \quad n_\alpha m_\alpha \frac{\partial v_\alpha}{\partial t} + n_\alpha m_\alpha (v_\alpha \cdot \nabla) v_\alpha + q_\alpha n_\alpha \nabla \varphi$$

$$- q_\alpha n_\alpha (\vec{v}_\alpha \times \vec{B}) = 0$$

$$III. \quad n_i = n_e + Z_d n_d$$

New Phenomena in Dusty Plasmas

- Unlike ordinary plasma, or plasmas containing negative ions, the *charge on a dust grain is not constant*, but fluctuates with the local plasma potential.
- This leads to new damping effects and new mechanisms for wave growth.

Fluid theory: mode frequencies

- for ion and electron modes we treat the dust as an immobile negative background
- for dust modes we can neglect the electron and ion inertia terms

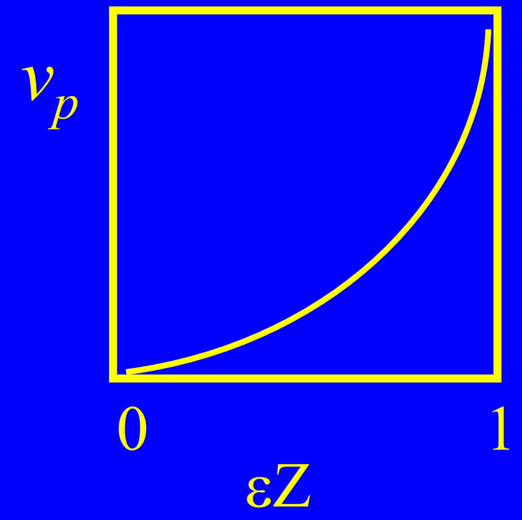
- For excitation conditions (growth rates, critical drifts, etc.) we must use kinetic theory

Dust Ion Acoustic Mode

- DIA: ion-acoustic wave modified by dust
- Dispersion relation:

$$v_p = \frac{\omega}{K_{\|}} = \left[\frac{kT_i}{m_i} + \frac{kT_e}{m_i\left(1 - \varepsilon Z_d\right)} \right]^{\frac{1}{2}}$$

$$= C_{DIA}$$

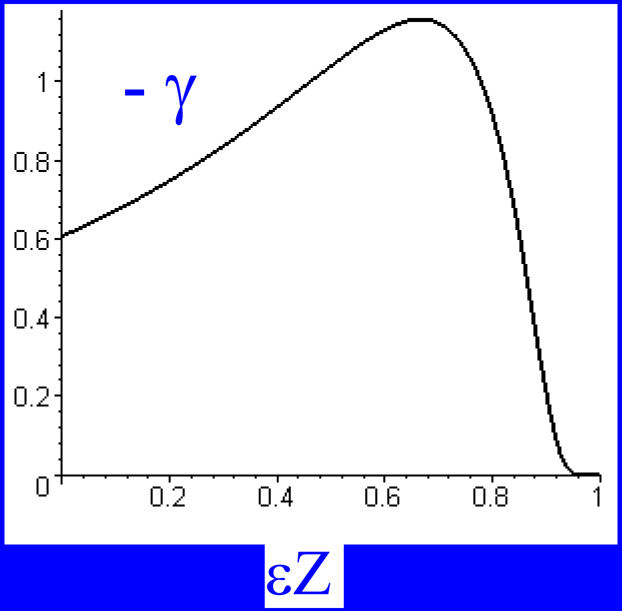


DIA – Kinetic Theory

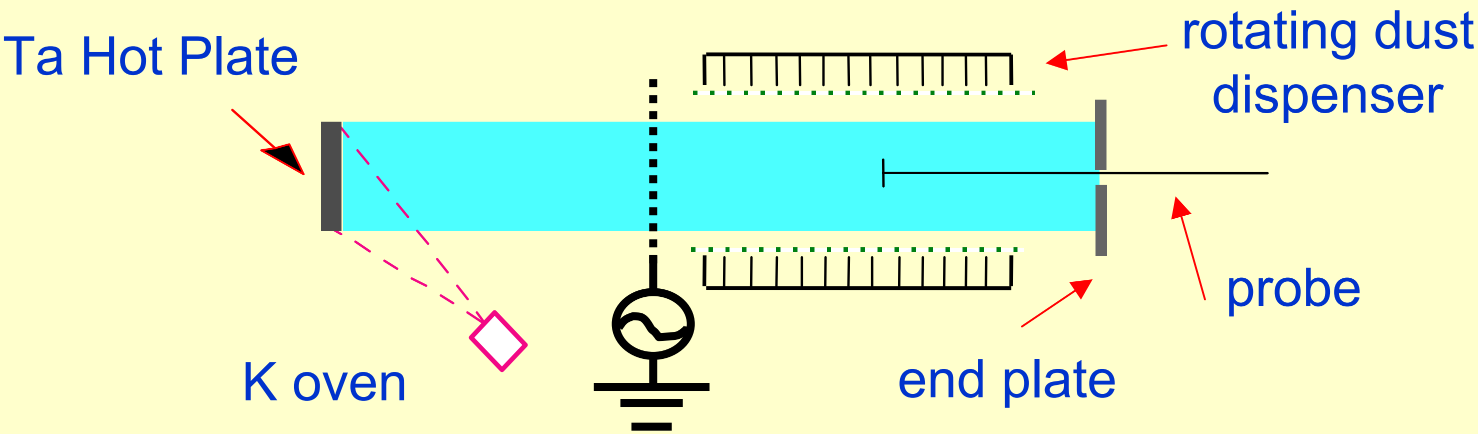
Dust acoustic waves are normally heavily Landau damped in a plasma with $T_e = T_i$. However the presence of negatively charged dust can drastically reduce the damping.

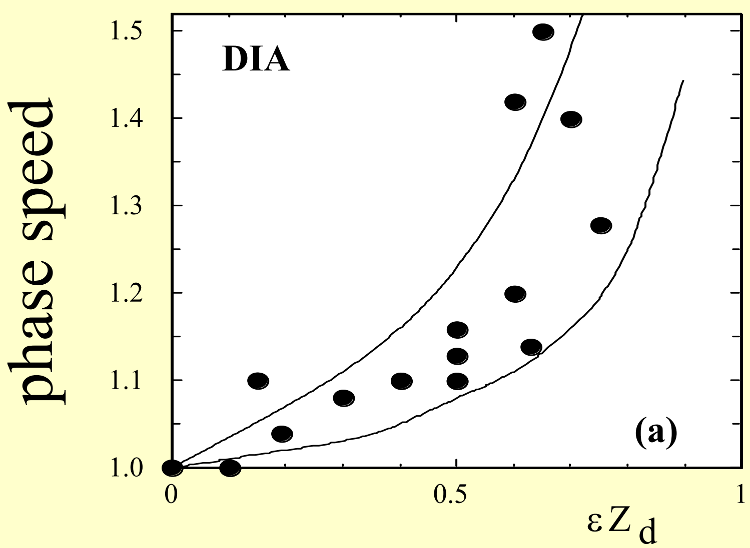
$$\gamma = -\omega_r \left(\frac{\pi}{8}\right)^{\frac{1}{2}} \left[\left(\delta \frac{m_e}{m_i}\right)^{\frac{1}{2}} + \left(\delta \frac{T_e}{T_i}\right)^{\frac{3}{2}} e^{-\delta \frac{T_e}{2T_i}} \right]$$

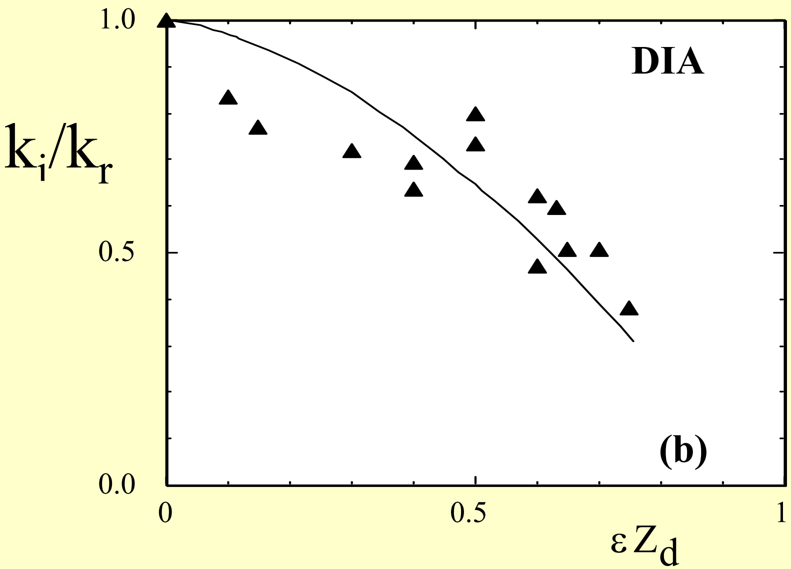
$$\delta = \frac{1}{1 = \varepsilon Z_d}$$



Dust Ion Acoustic Wave Experiment



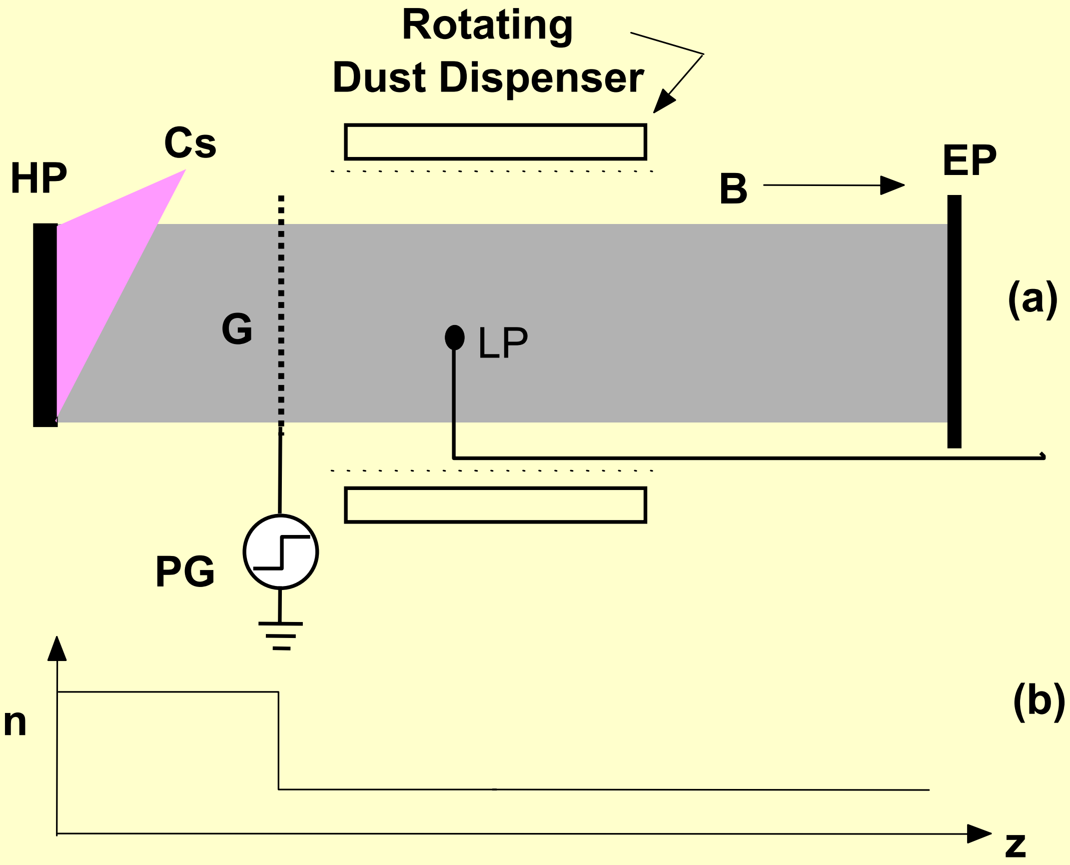




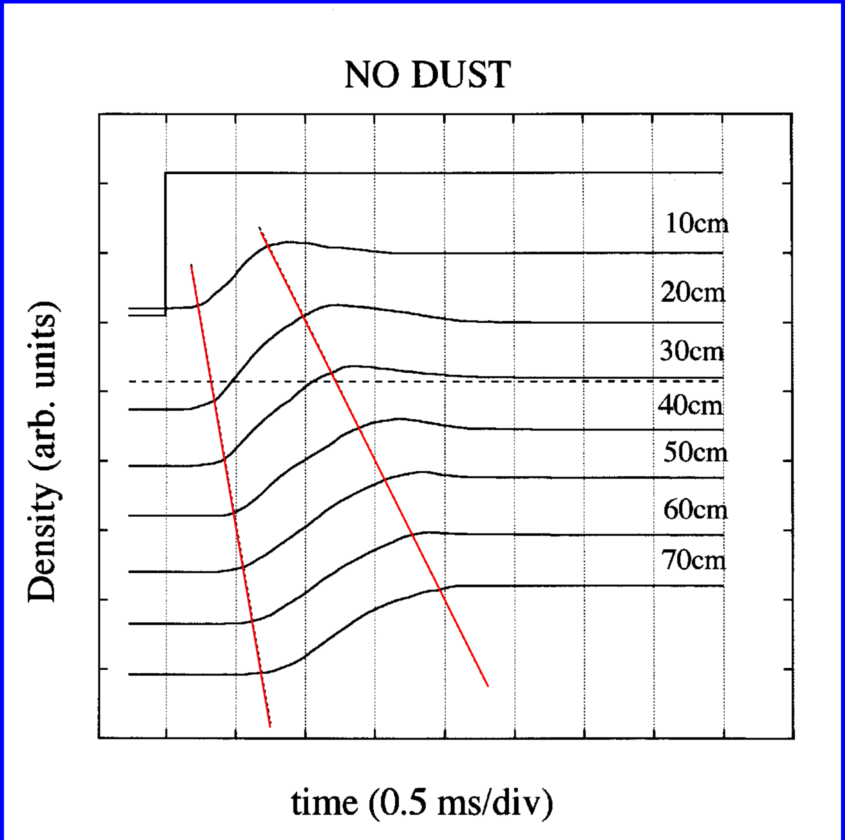
DIA - Conclusion

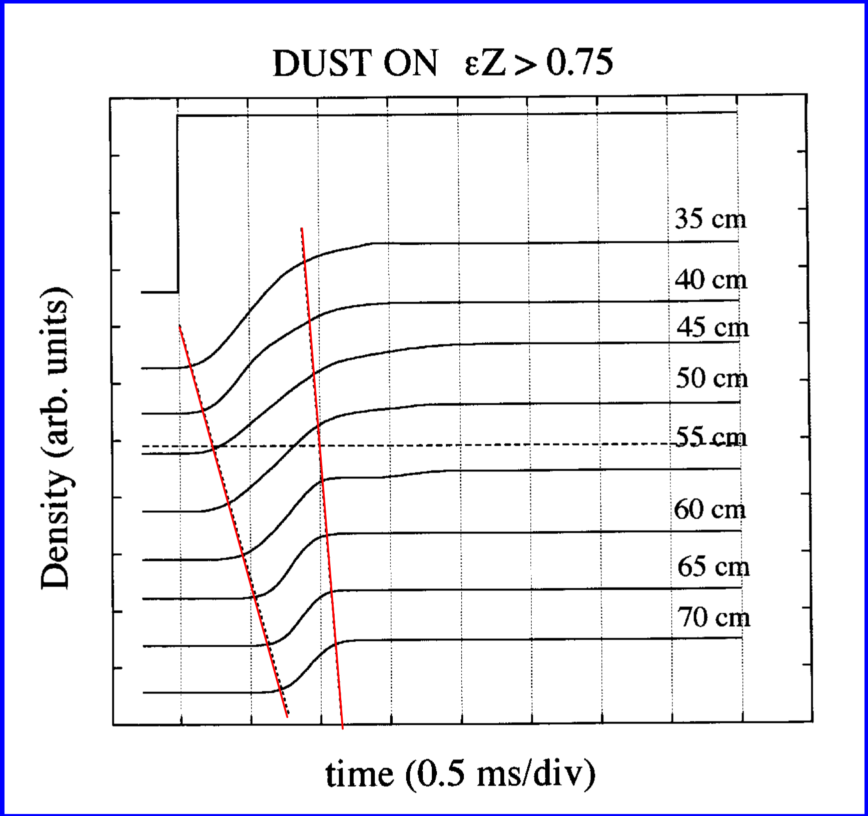
- Ion acoustic waves which would otherwise not propagate in a plasma with $T_e = T_i$ can propagate in a plasma with a sufficient amount of negatively charged dust.
- In the presence of negative dust, the wave phase velocity increases, decreasing the effect of ion Landau damping.

Experimental setup

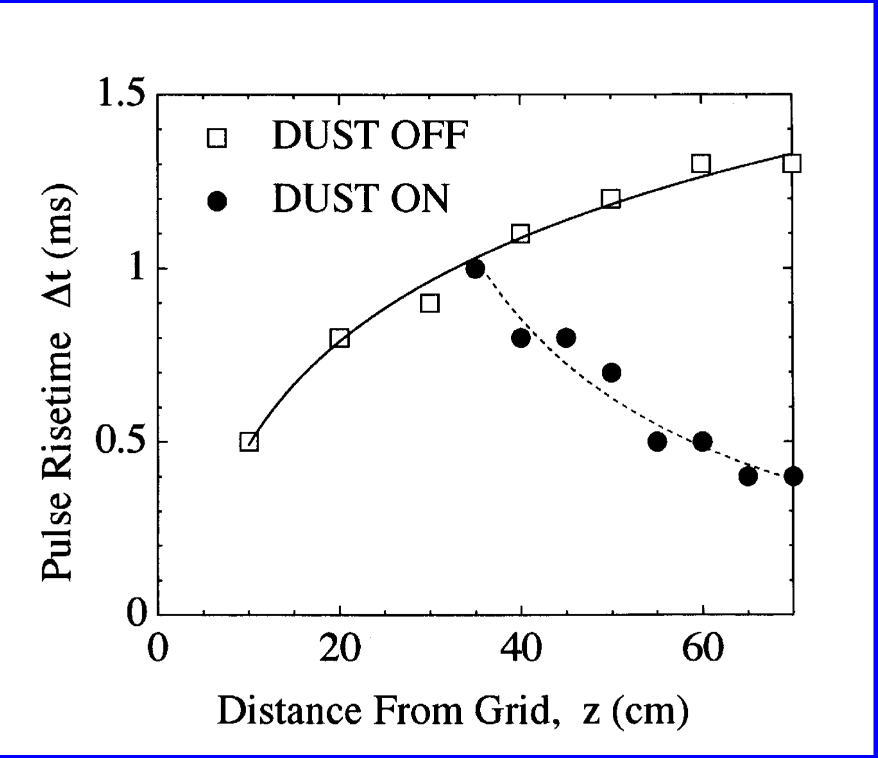


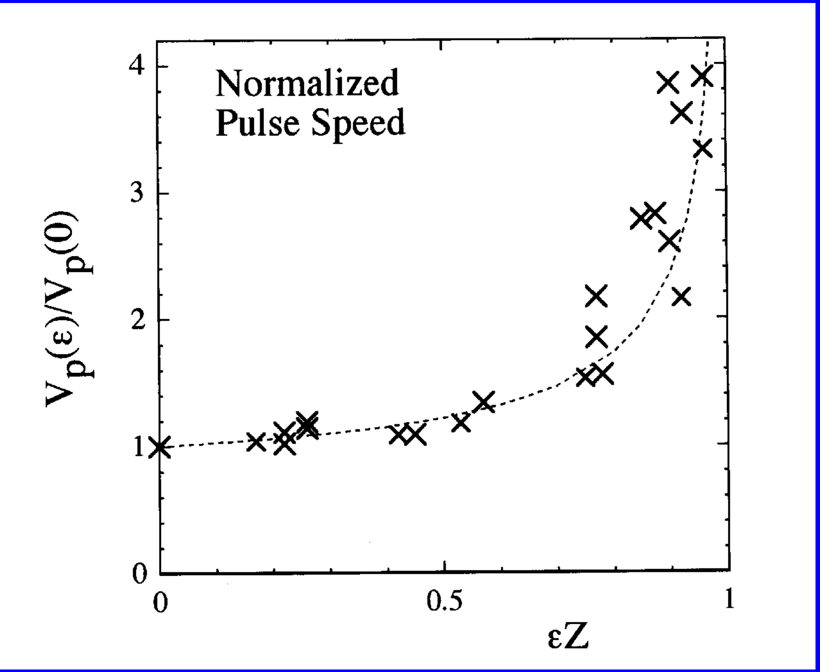
DIA Shocks – results





DIA Shocks – results





EDIC: fluid theory

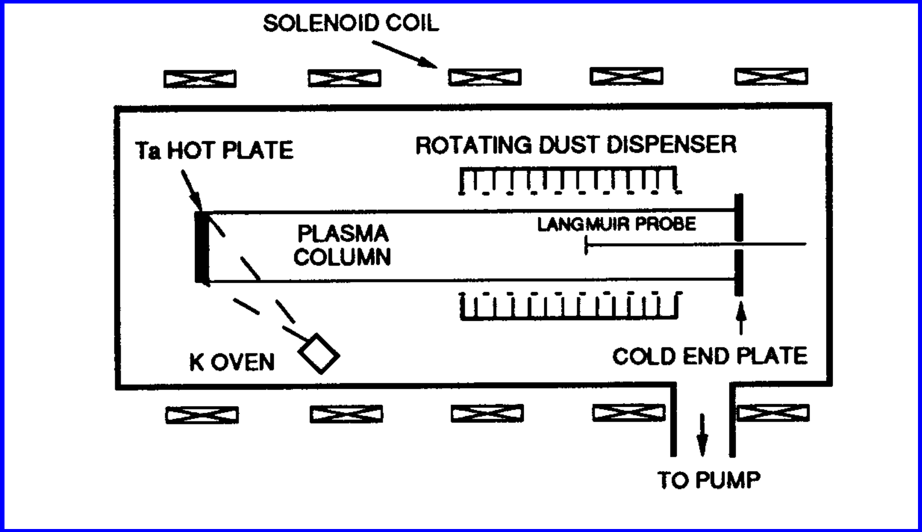
- Electrostatic ion-cyclotron waves excited by electron current along the magnetic field

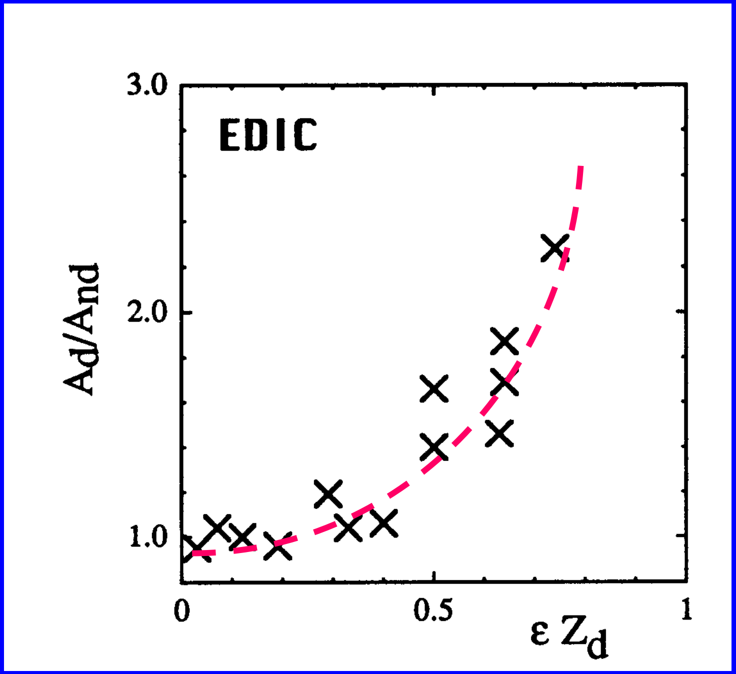
- Propagate at large angle to B

$$\omega^2 = \Omega_{ci}^2 + K_\perp^2 \left(\frac{kT_i}{m_i} + \frac{kT_e}{m_i (1 - \varepsilon Z_d} \right)$$

$$= \Omega_{ci}^2 + K_\perp^2 C_{DIA}^2$$

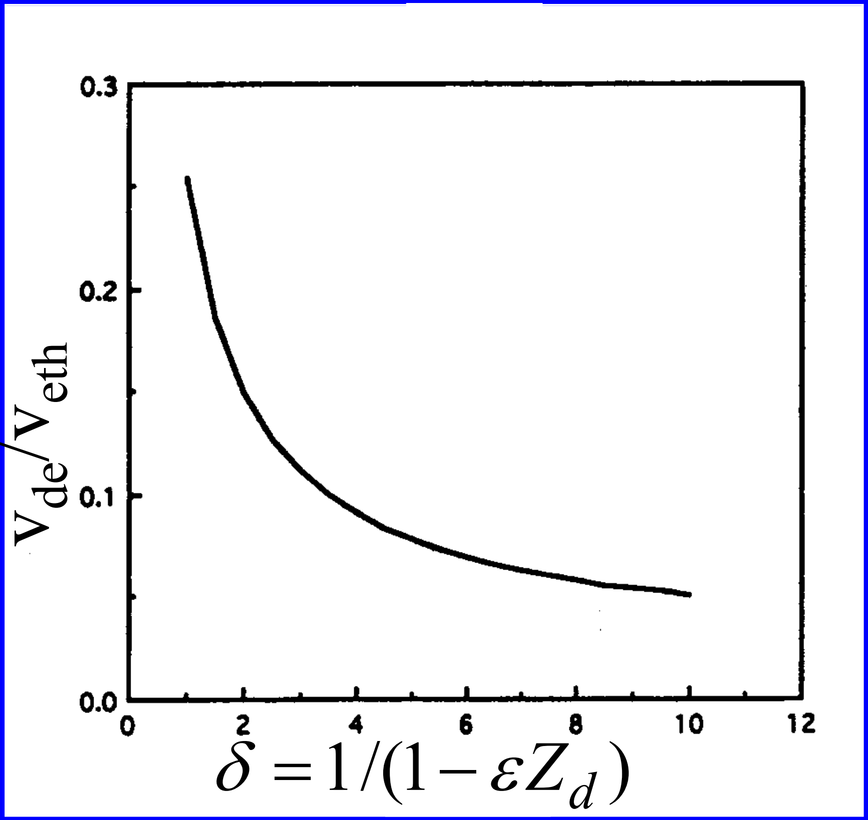
Electrostatic dust ion-cycloton instability (EDIC)





EDIC- kinetic theory results

- EIC instability driven by current along B
- As more negative charge is carried by the dust, the critical drift needed to excite the instability decreases
- *the instability is easier to excite in a dusty plasma*



V. W. Chow & M. Rosenberg, Planet. Space Sci. 44, 465 (1996)

Dust acoustic waves

Dust dynamics

$$\frac{\partial n_d}{\partial t} + \frac{\partial (n_d v_d)}{\partial x} = 0$$

$$m_d n_d \left[\frac{\partial v_d}{\partial t} + v_d \frac{\partial v_d}{\partial x} \right] + kT_d \frac{\partial n_d}{\partial x} - eZ_d n_d \frac{\partial \varphi}{\partial x} = 0$$

Electrons & Ions

$$kT_e \frac{\partial n_e}{\partial x} - en_e \frac{\partial \varphi}{\partial x} = 0; \qquad kT_+ \frac{\partial n_+}{\partial x} + en_+ \frac{\partial \varphi}{\partial x} = 0$$

Quasineutrality

$$n_+ = n_e + Z_d n_d$$

Combining the dust momentum equation with the plasma equations we see that (for the case of cold dust, $T_d = 0$).

$$m_d n_d \frac{\partial v_d}{\partial x} = -\frac{\partial}{\partial x}(p_e + p_+)$$

where $p_e + p_+$ is the total pressure due to electrons and ions.

In the dust acoustic wave the inertial is provided by the massive dust particles and the electrons and ions provide the restoring force

DA Dispersion relation

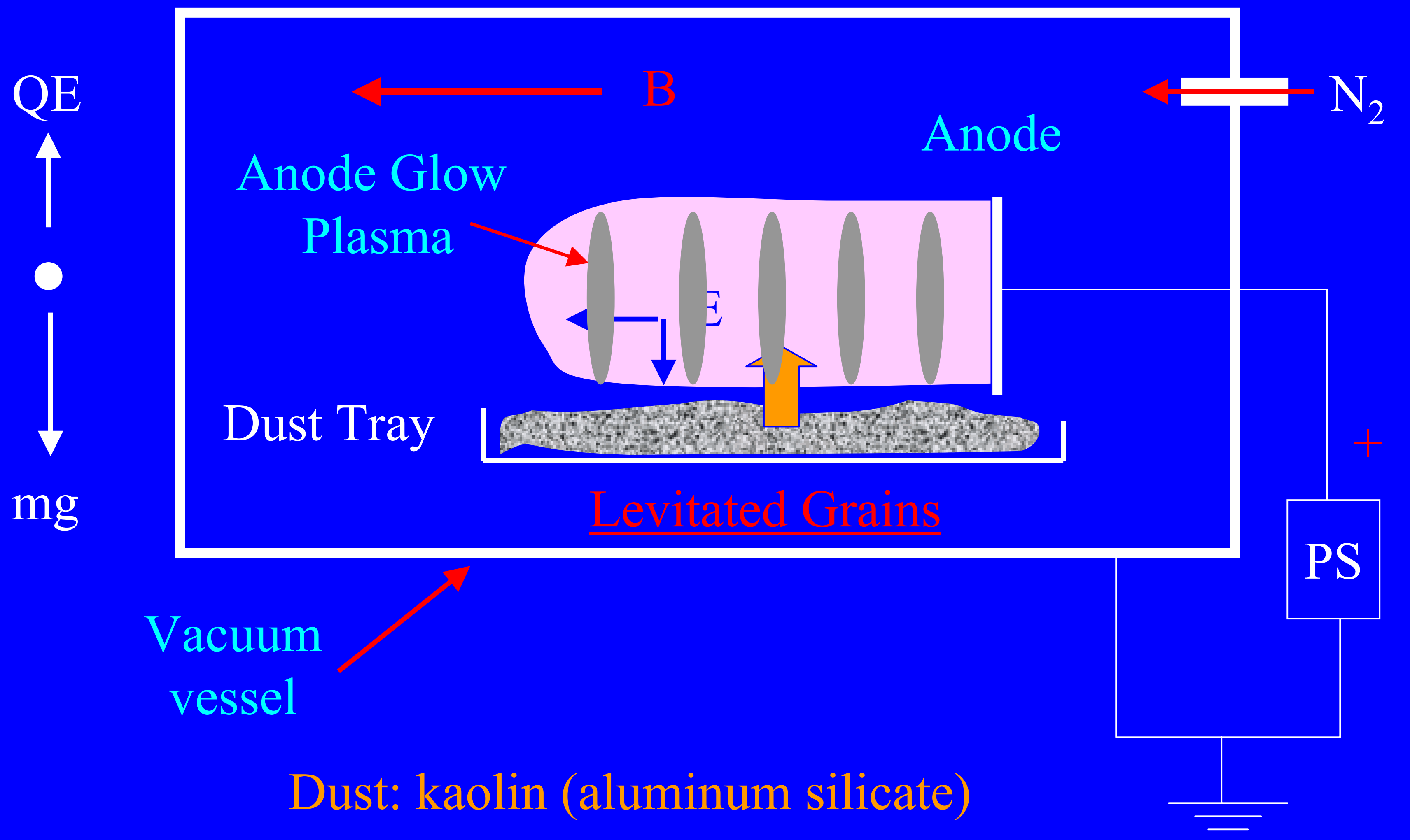
Monochromatic plane wave solutions
for $T_e = T_i = T$

$$f\,\lambda = C_{DA} = \sqrt{\frac{kT}{\underline{m_d}}\,Z_d\,\frac{1-\varepsilon}{1+\varepsilon}}$$

where $\varepsilon = n_{do}/n_{+o}$

dust mass

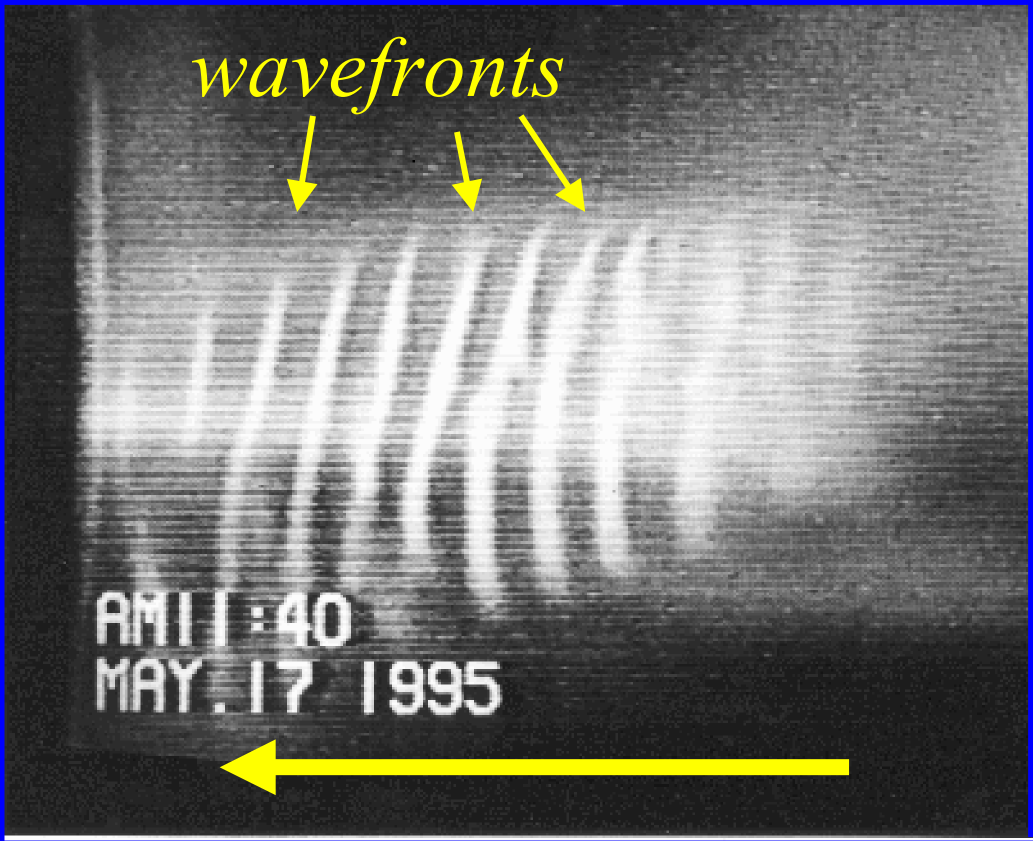
DUST IN A GLOW DISCHARGE



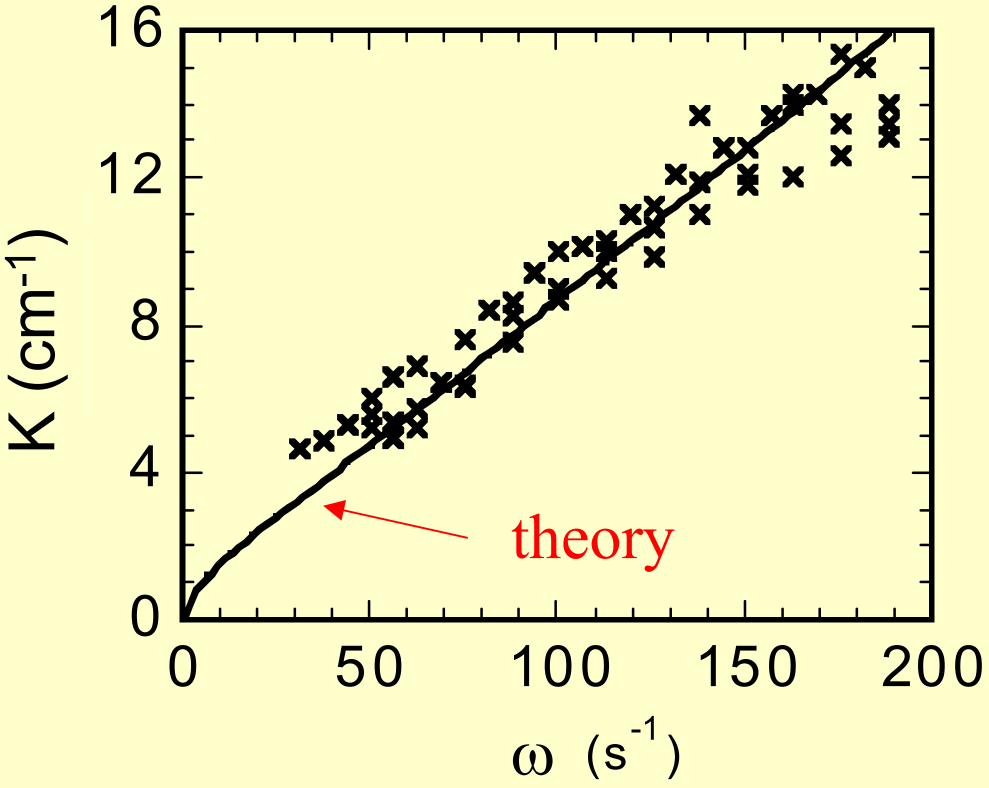
Dust: kaolin (aluminum silicate)

Dust Acoustic Wave Image

DA Movie



Dust Acoustic Wave Dispersion Relation



Electrostatic dust cyclotron mode

- EDIC – involves cyclotron motion of the dust – *magnetized dust*
- Dispersion relation:

$$\omega^2 = \Omega_{cd}^2 + K_\perp^2 \left[\frac{kT_d}{m_d} + \varepsilon Z_d^2 \frac{1}{1 + (T_i / T_e)(1 - \varepsilon Z_d)} \right]$$

$$= \Omega_{cd}^2 + K_\perp^2 C_{DA}^2$$

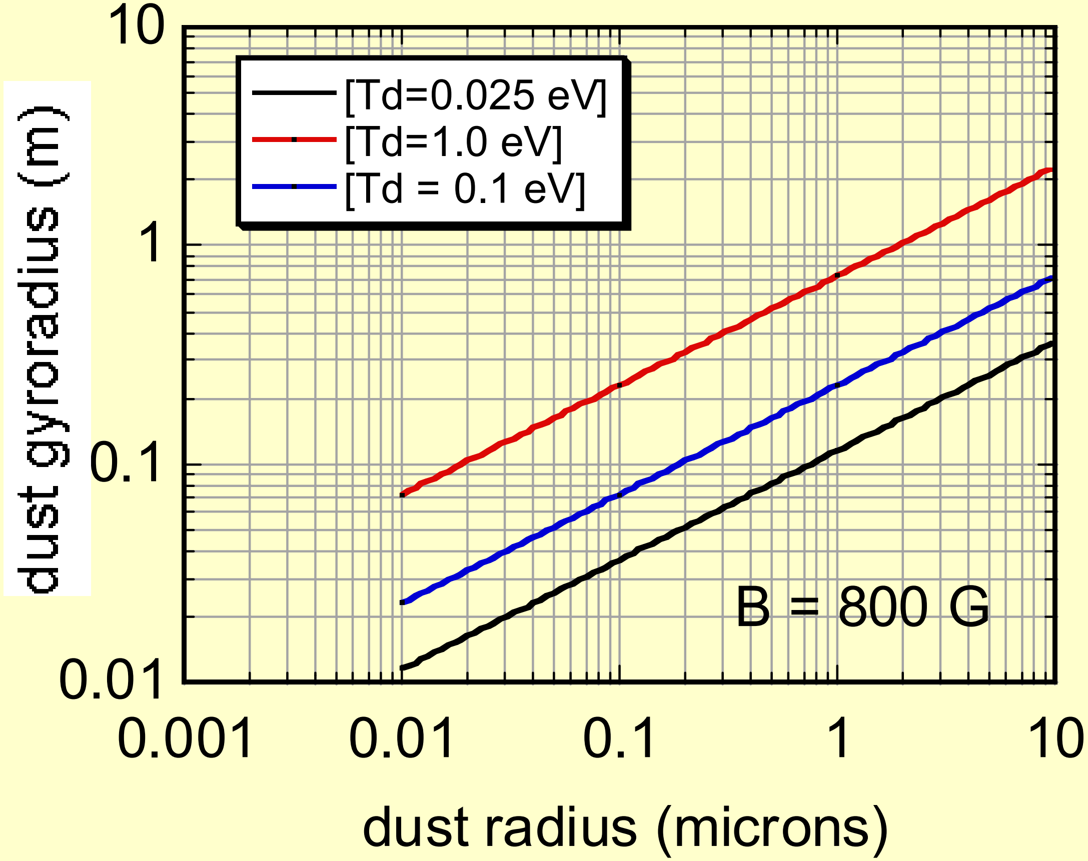
Gyroradius of dust particles

$$r_d = \frac{m_d v_d}{e Z_d B}$$

$$m_d \propto a^3, \quad Z_d \propto a, \quad v_d = \sqrt{\frac{kT_d}{m_d}}$$

$$r_d \propto a^{\frac{1}{2}}$$

Gyroradius of dust particles

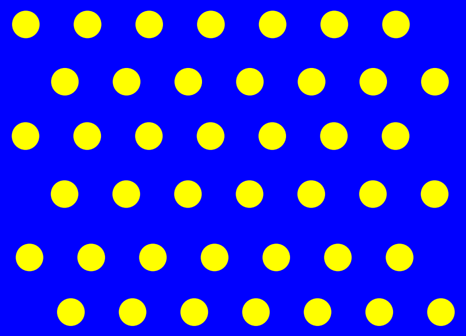


Solid state dusty plasmas

In a typical plasma $$\Gamma = \frac{e^2 Z^2 / 4\pi\varepsilon_o d}{kT_d} << 1$$

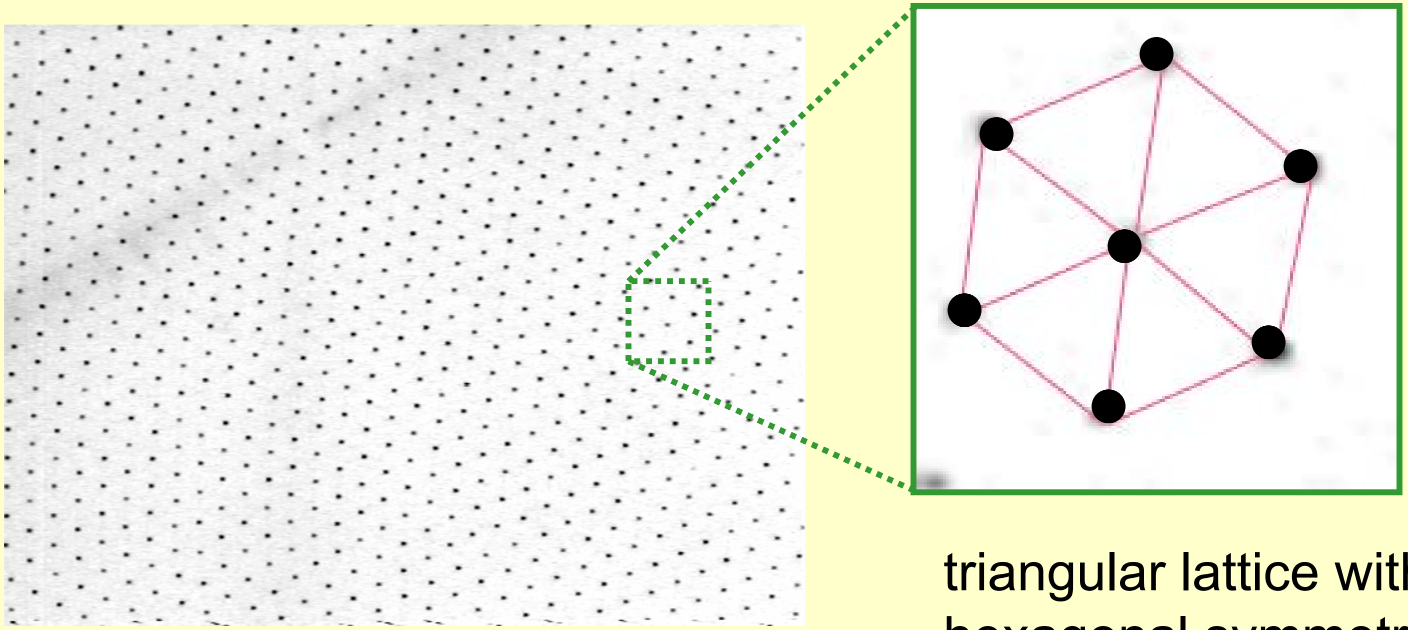
- In a dusty plasma the interaction energy is multiplied by Z_d^2 which can be very large, so that $\Gamma > 1$ is possible

- The dust grains may then arrange themselves in a regular lattice.



Coulomb Crystal

John Goree – Univ. Iowa

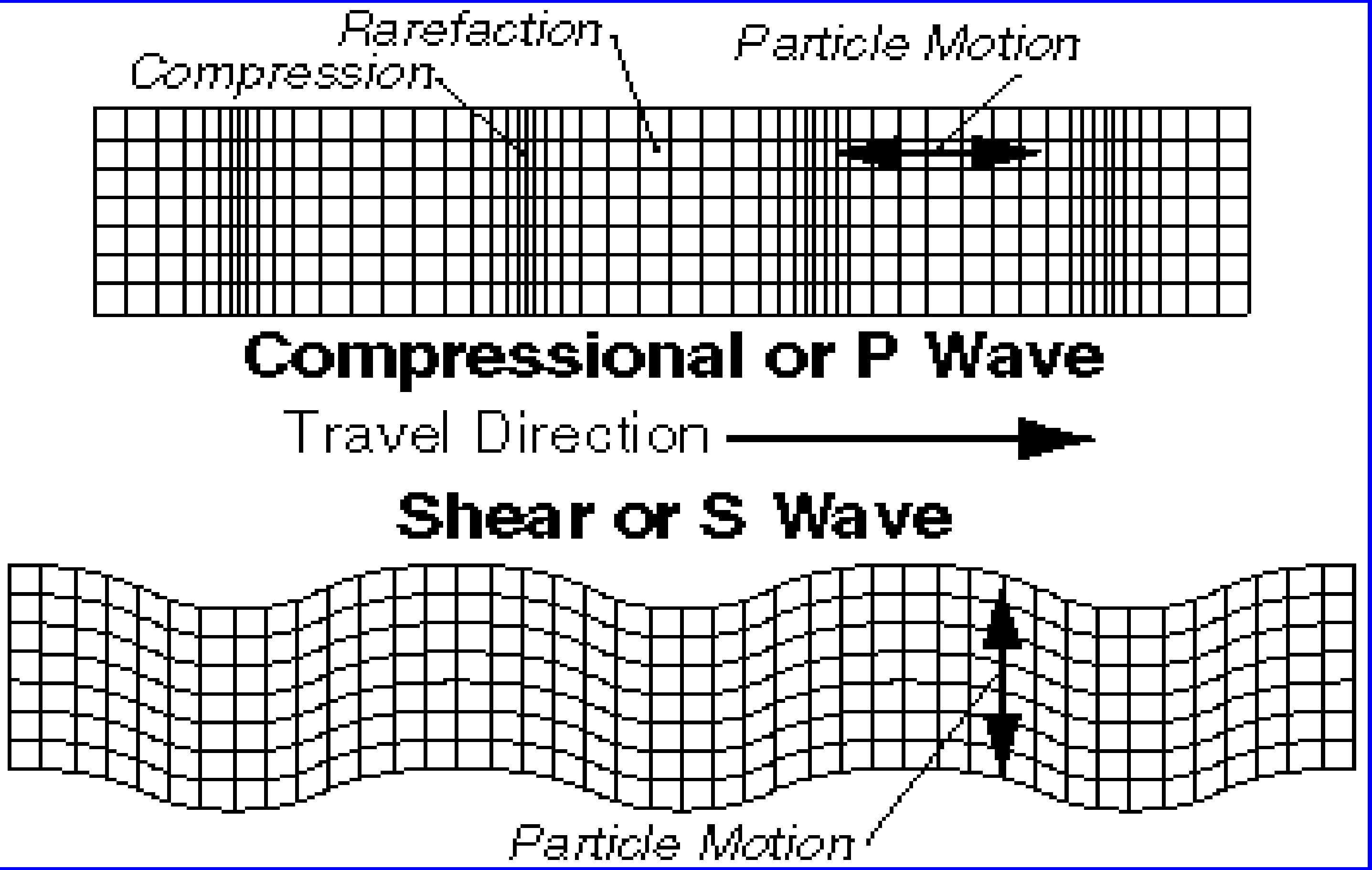


triangular lattice with
hexagonal symmetry

Waves in strongly coupled dusty plasmas

- The presence of short scale correlations gives rise to novel modifications of the collective behavior
- Both compressional and transverse shear waves are possible

Compressional and shear waves



Summary/Conclusions

- Dusty plasmas are not uncommon in the lab and are ubiquitous in the Universe
- Presence of dust modifies both the excitation and propagation of plasma waves
- New, very low frequency dust modes
- Collective fluctuations in dusty plasmas may provide mechanism for structuring