Dusty plasmas: astrophysical applications

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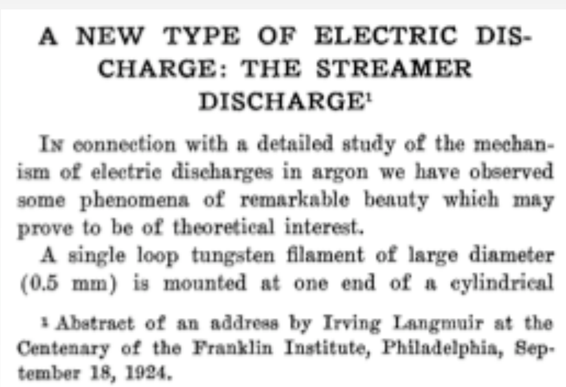
Outline

- **Introduction**
  - Astrophysical phenomena
  - Connections with laboratory studies
  - Comparison of plasma parameters
- Outstanding issues
  - Physics of dust charging
  - Particle formation
  - Magnetic field effects
  - Coupling between dust and plasma
- Research opportunities
- Summary

Dust and dusty plasmas

- Dust is an “old” problem in astronomy and astrophysics
  - Often as a nuisance – gets in the way of “important” objects
  - Also a precursor for all of the “important” objects
  - Occasional papers would discuss dust and possible charging effects

- Key Events
  - 1924: Langmuir reports “globules of tenths of mm” in a discharge
  - 1968: Lunar horizon glow – dust levitating on near the terminator
  - 1981: Voyager mission – first observation of spokes
  - 1989: Reports of dust formation and suspension in processing plasmas

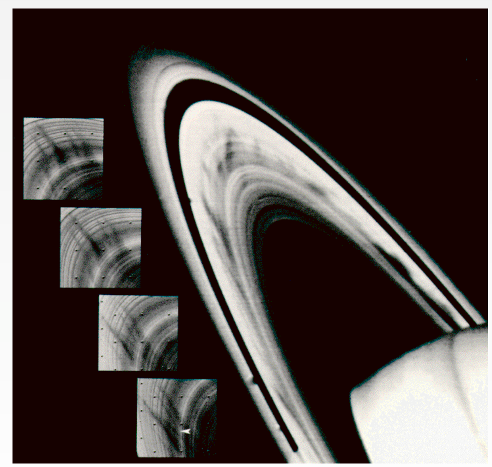


A NEW TYPE OF ELECTRIC DISCHARGE: THE STREAMER DISCHARGE[1]

In connection with a detailed study of the mechanism of electric discharges in argon we have observed some phenomena of remarkable beauty which may prove to be of theoretical interest.

A single loop tungsten filament of large diameter (0.5 mm) is mounted at one end of a cylindrical

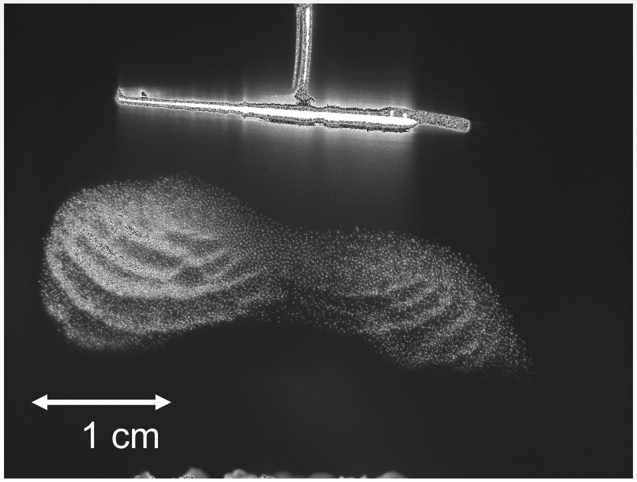
[1] Abstract of an address by Irving Langmuir at the Centenary of the Franklin Institute, Philadelphia, September 18, 1924.



Introduction: dusty (complex) plasmas

- Dusty plasmas are four component plasma systems consisting of ions, electrons, neutrals, and **charged** microparticles *(i.e.*, dust).
- Because the dust grains are charged, they are **electrically coupled to** and **fully interact with** the background plasma.
- In the astrophysical context, all of the phenomena (e.g., plasma processes, radiation, magnetic fields) discussed at this meeting will have an effect on charged dust through the coupling with the background plasma.
- As with other topics discussed here, a vast range of scales ~10^{20}

In the laboratory, dusty plasmas allow direct visualization of the kinetic behavior of plasma phenomena.



Dusty plasmas in astrophysical environments

<u>Star forming regions</u> (Eta Carina)

Photoionization from stellar material charges the dust in the nebula. The presence of charged dust may lead to enhanced coagulation of small particles AND to repulsion between larger particles.

[F. Verheest, PPCF, 41, A445 (1999)]

Modification of Jean instability (gravitational collapse)

$\lambda_{nJ} = c_{th}/\omega_J$ -> scale length of stable region

Charged dust:

$\lambda' = c_{da}/\omega_J >> \lambda_{nJ}$ -> larger stable region

Charged dust + magnetic field:

$\lambda'' = V_m/\omega_J > \lambda'$

Where:

$c_{da} > c_{th}$

$V_m = [V_{dA}^2 + c_{da}^2]^{1/2}$

$\omega_J = [4\pi GmN]^{1/2}$

Dusty plasmas in astrophysical environments – Saturn’s rings

- Early work in dusty plasmas in the solar system were driven by Voyager observations of Saturn’s rings (1980-1981).
- The rings are observable from Earth, but time evolving structures known as “spokes” were an unexpected observation.
- Spoke formation and evolution is believed to be a charged dust phenomenon.

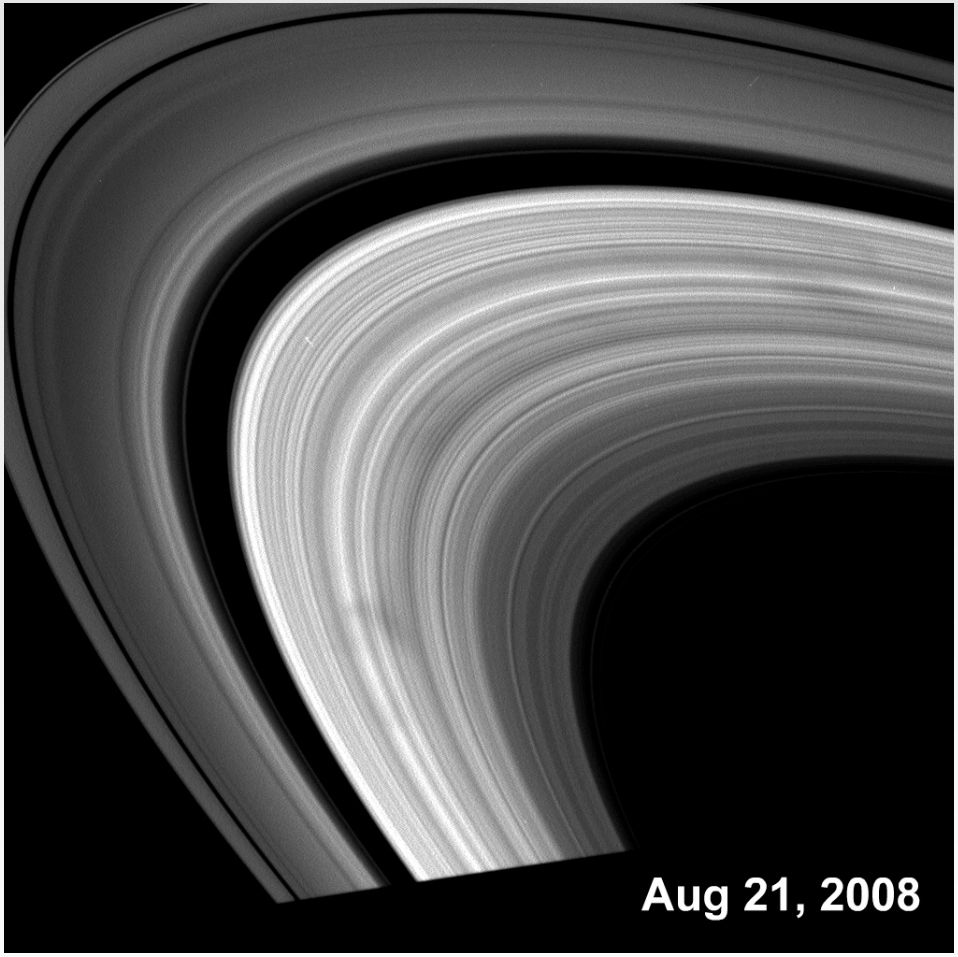
Voyager observation of spokes

Dusty plasmas in astrophysical environments – Saturn's rings

- When Cassini first arrived at Saturn (2004), there were, initially, no spokes observed – although models expected them to be present.

- This led to a careful re-evaluation of the Voyager data to understand possible changes in the plasma environment.

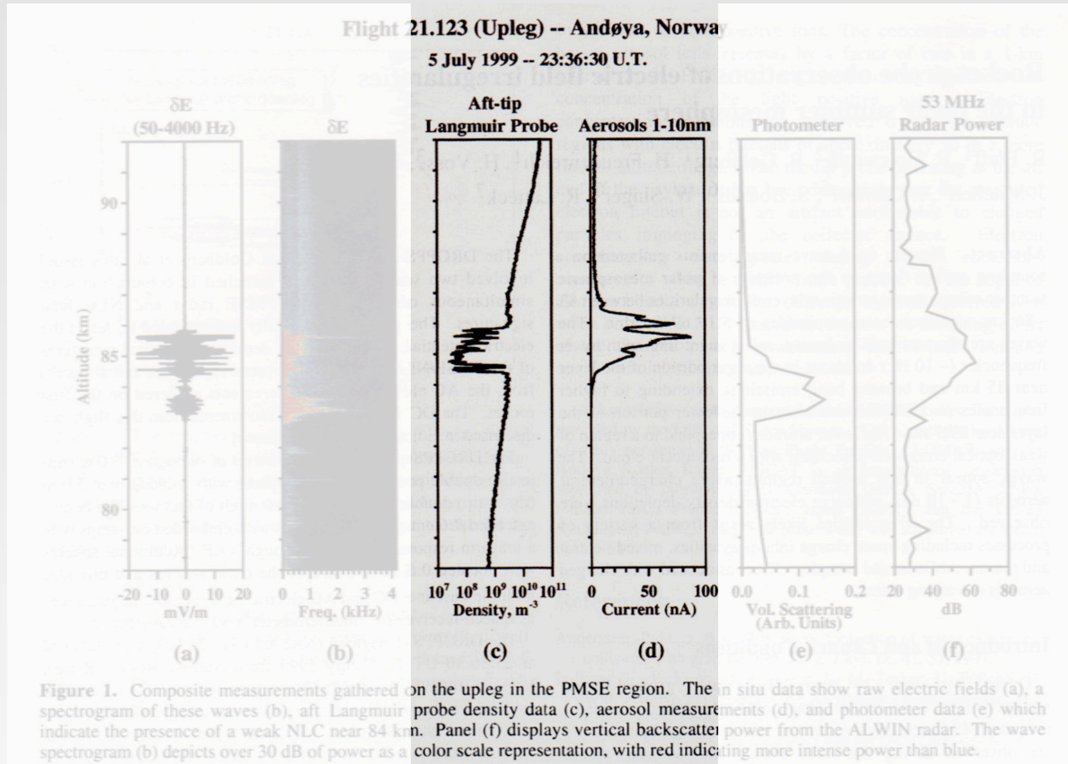
- In 2006, the spokes reappeared and models have been updated with the new understanding of the plasma environment at Saturn.



Cassini observation of spokes

Dusty plasmas in terrestrial environments

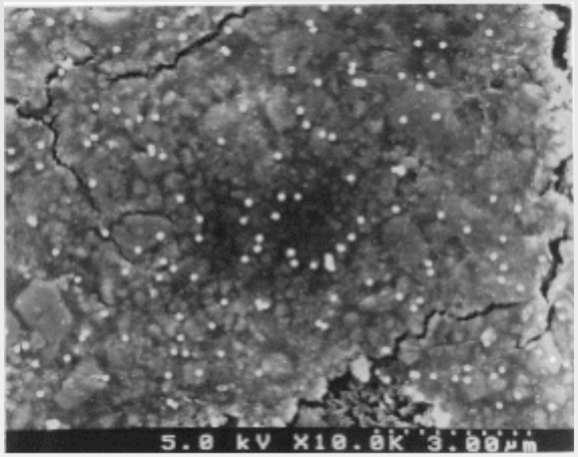
- Noctilucent clouds (NLC's) form at extremely high altitudes, about 85 km, that literally (as the name suggests) shine at night.
- They form in the cold, summer polar mesopause and are believed to be charged ice crystals.
- They are believed to be associated with radar backscatter phenomena (PSME's) observed during the northern summers.



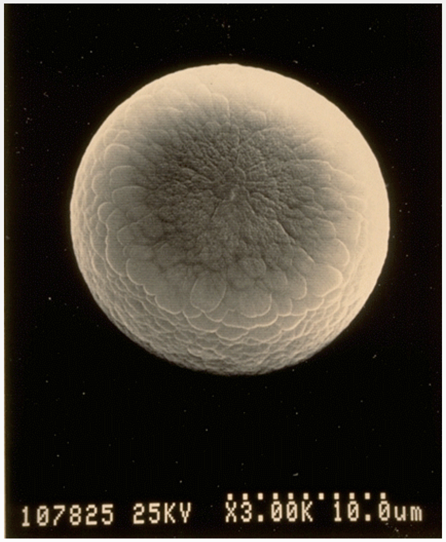
From: http://lasp.colorado.edu/noctilucent_clouds/

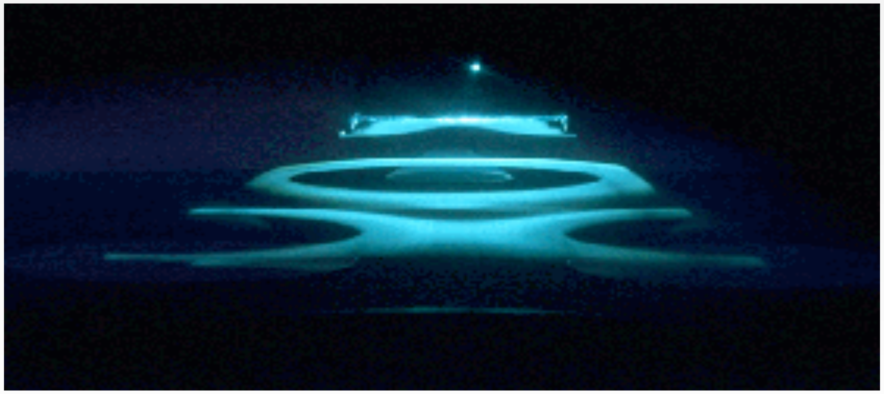
Laboratory studies: astrophysical relevance

Dust formation and growth (contamination issues)



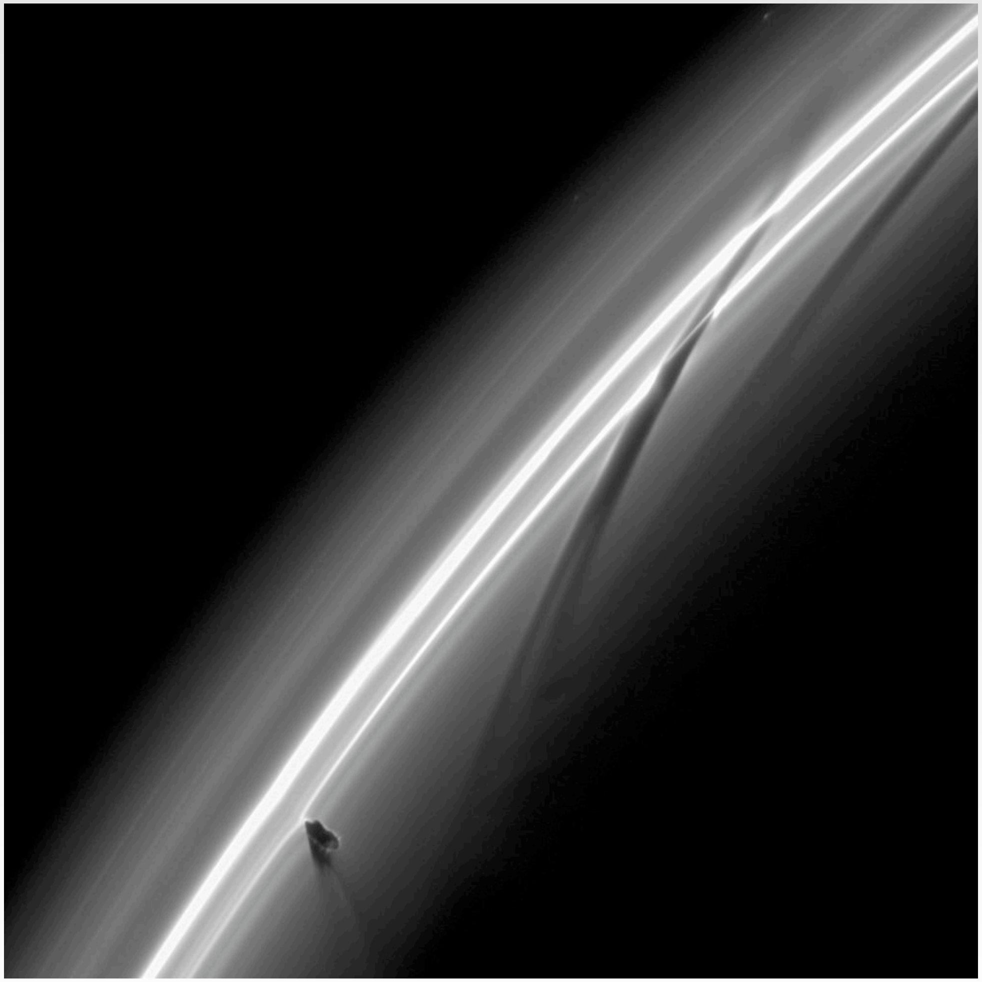
- Much of the initial growth of dusty plasmas during the 1990's was driven by the formation of microparticles in plasma processing reactors.
- In industry and fusion, dust contamination remains an important technological problem.
- The physics and chemistry of particle formation from the gas phase is highly relevant to dust formation in astrophysical environments.
- Differences: thermal environment, radiation?



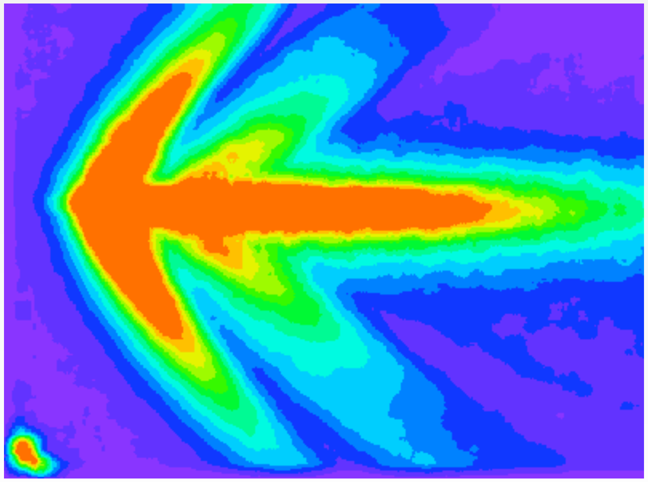


From: http://fjwsys.lanl.gov/bpw/contamination.html - G. Selwyn, LANL

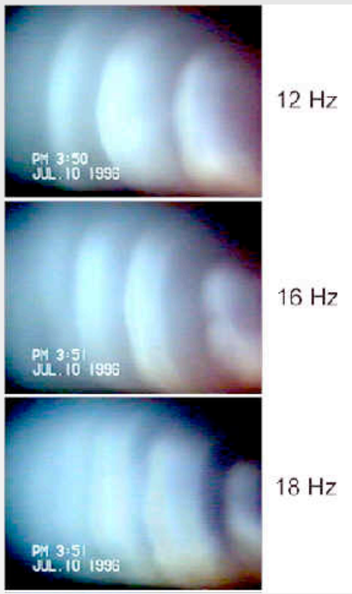
Laboratory studies: astrophysical relevance

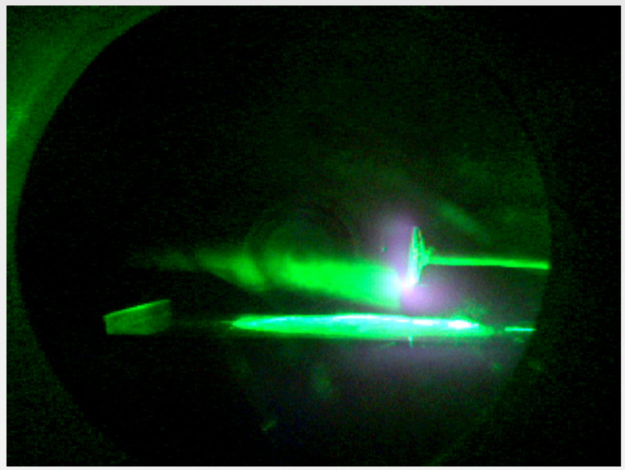


- Havnes, et. al. (JGR, 1995) proposed using **mach cones** in Saturn's rings as a way to probe their properties.
- Laboratory experiments shortly thereafter showed that mach cones could be produced in dusty plasmas.



Laboratory studies: astrophysical relevance





Evolution of dust acoustic wave
(R. Merlino, Univ. Iowa)

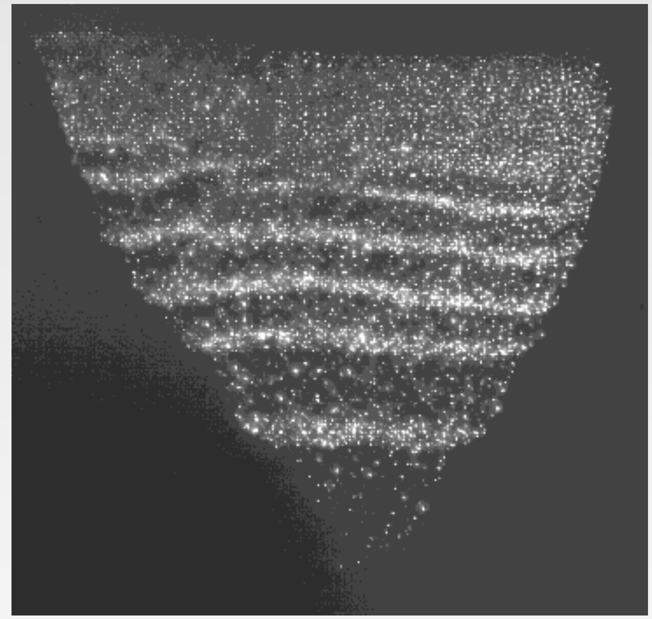


Image sequence of dust acoustic wave (Thomas, Auburn Univ.)

- Collective effects are a large component of laboratory studies of dusty plasmas
- The presence of the charge dust modifies existing plasma modes (e.g., dust-ion cyclotron or dust-Alfven) or generated new modes (dust cyclotron, dust acoustic)

Comparison of dusty plasma parameters: space and laboratory

Table 1. Nominal parameters of dust-laden plasmas

	n_i (cm^{-3})	T_e (eV)	n_d (cm^{-3})	d/λ_D	a (μm)	n_n (cm^{-3})
Saturn's E-ring	10	$10 - 10^2$	10^{-7}	.1	1	1
Saturn's F-ring	10	$10 - 10^2$	$\lesssim 10$	$\lesssim 10^{-3}$	1	-
Interstellar molecular clouds	10^{-3}	.001	10^{-7}	.3	< 1	10^4
Noctilucent clouds	10^3	.013	10	.2	.1	10^{14}
process plasma	3×10^9	2	$10^3 - 10^8$	.1-3	$\lesssim 1$	3×10^{15}
'plasma crystal'	10^9	2	$10^4 - 10^5$	~ 1	~ 5	$\sim 10^{16}$

In spite of wide differences in basic plasma parameters, the grain size and relevant dimensionless quantity, ratio of inter-grain separation (d) to Debye length (λ_D) are remarkably similar.

[From: M. Rosenberg, *J. Phys. IV France*, **10**, Pr5-73 (2000)]

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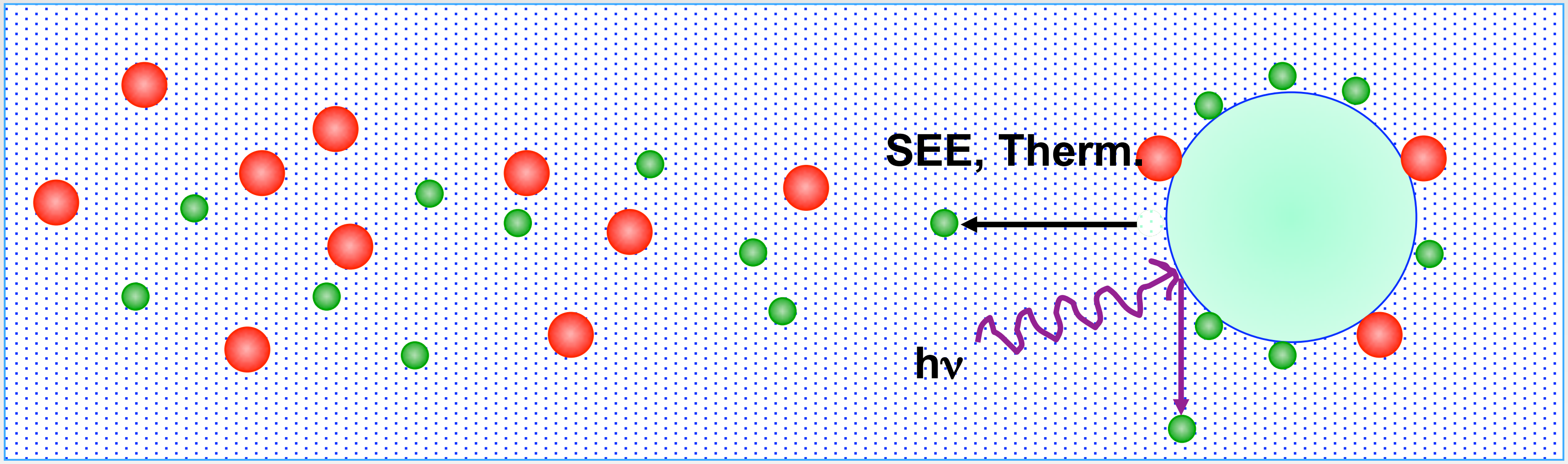
Dust grain charging

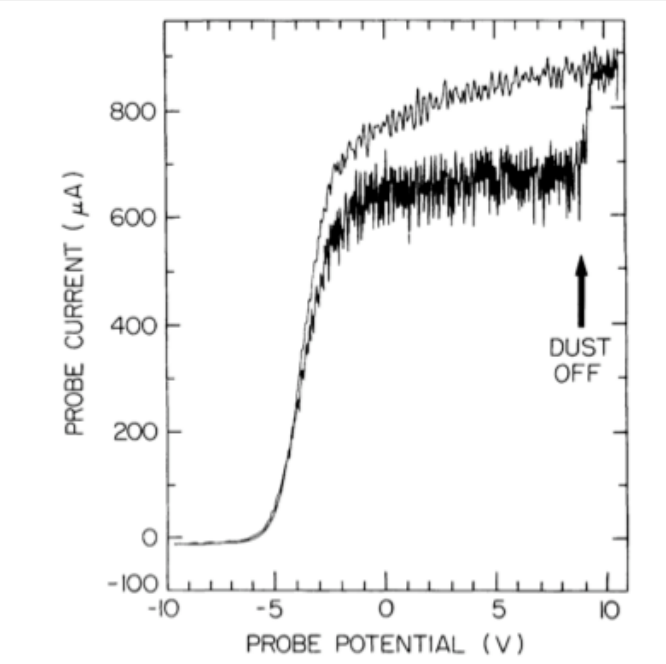


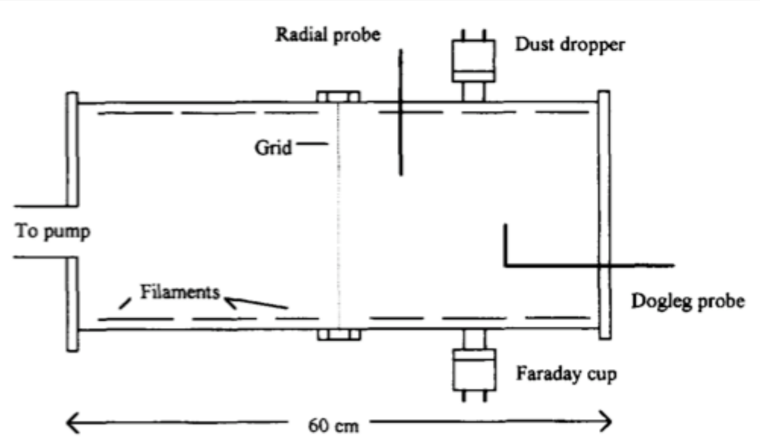
Ions
Electrons

- A particle in the plasma acquires charge through a variety of mechanisms.
- A dynamic equilibrium is established as the grain electrically floats in the plasma: $I_{total} = I_{electron} + I_{ion} + I_{see} + I_{thermionic} + I_{h\nu} = f(n_j, T_j, \varphi; \underline{r}, t)$

Early laboratory studies of charging

- Experiments have demonstrated that the grains become charged in a plasma environment.
- Almost all laboratory studies performed under conditions where ionizing radiation and secondary emission effects were negligible.
- Performing *in-situ* studies of grain charging in space environments has proven to be challenging.





Relevance of dust charging

- All "dusty plasmas" effects are determined by the charge state of the grains.
- Many calculations show that grains can charge either **positive** or **negative** in astrophysical environments – with a net charge, $Z \leq 10$.
- **CONSIDER:** the force balance between gravitational and electrostatic forces for spherical silica particles with $Z = 5$

  - Corresponds to particles of size $\langle r \rangle \sim 100$ μm
- Charging effects are mostly relevant for smaller particles.

Issues discussed in report

Charging is the underlying physical phenomena that affects all other dusty plasma processes.

In the report, three major issues are discussed:

- How does the plasma influence the agglomeration, growth, and/or decomposition of macroscopic particles in astrophysical environments?
- What is the role of magnetic fields in influencing charged macroscopic particles?
- How does the presence of neutrals atoms and/or charged or neutral macroscopic particles affect the evolution of the plasma environment?

Core question: *How are planets and stars formed from clouds of gas and dust?*

Particle formation

Relevance:

- Current models of the planetary formation begin with the formation of planetesimals from the dust and gas in nebula.
- The planetesimals are formed from the agglomeration and growth of small dust grains – some of which may be charged.
- The amount of charge, the sign of the net charge, the dielectric properties and magnetic susceptibility of the grain material, and the distribution of charge on these grains and their aggregates can all have an influence on the rate of planetesimal formation.

Particle formation

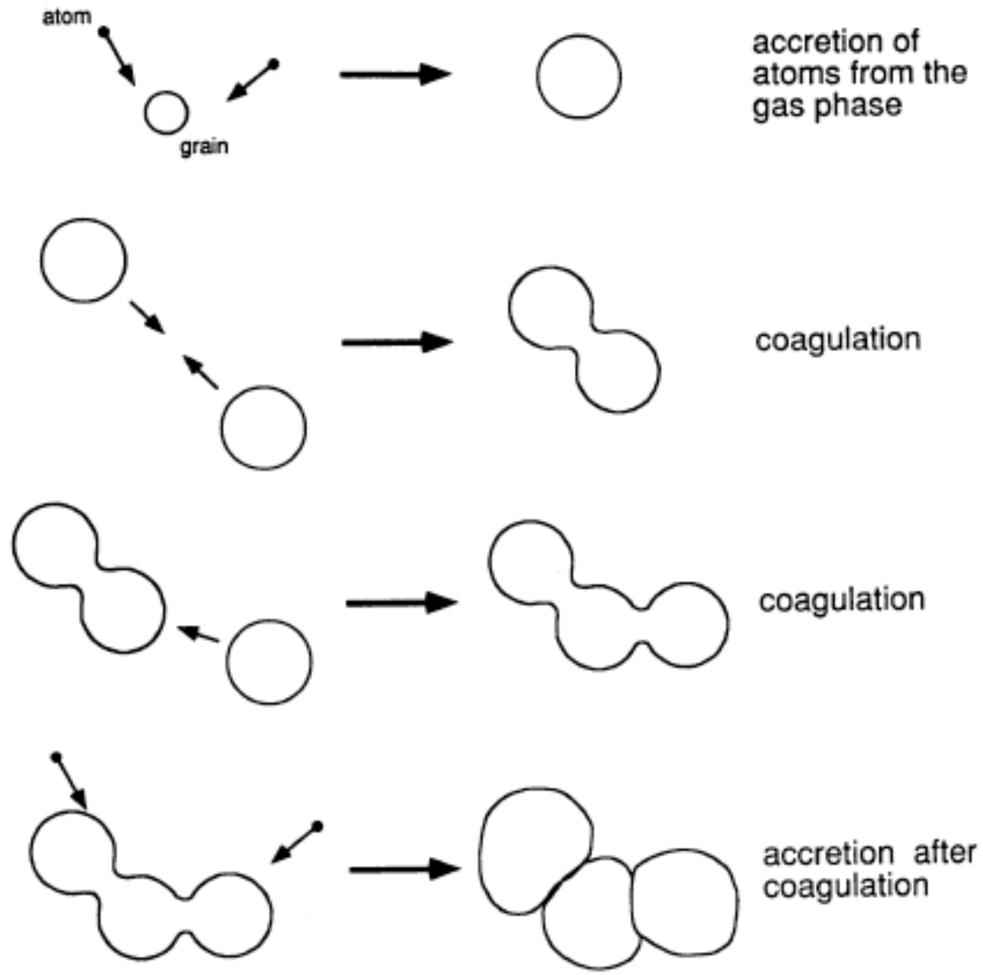


FIG. 1.—Grain growth processes. After an initial step of nucleation, grains can grow by accretion of atoms or by coagulation.

Grain growth processes

- steps are valid for space, processing, fusion or laboratory plasmas
- sedimentation due to gravity places experimental limits on understanding astrophysical processes

[From Praburam and Goree, ApJ (1995)]

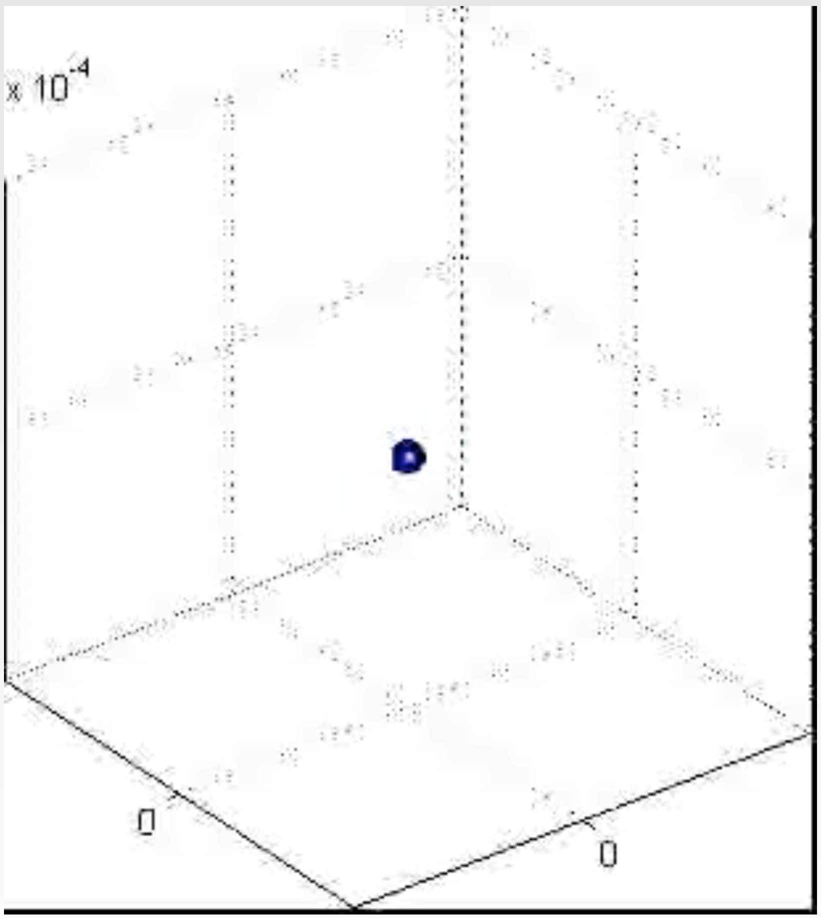
Particle formation

Formation/breakup processes:

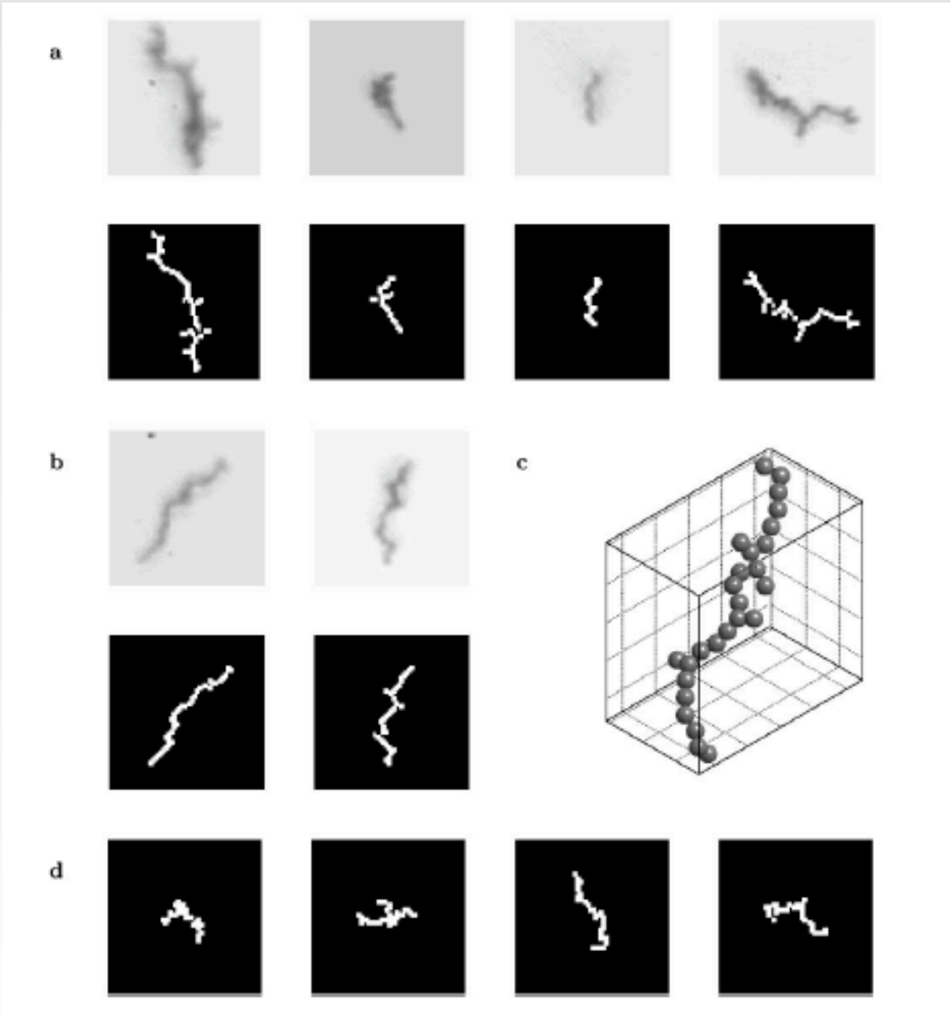
- In the gas phase the growth of particles is believed to be driven by a Brownian motion growth process for particles up to ~100 nm.
- As particles grow to larger sizes, environmental features begin influence the growth process.
    - density and temperature of source materials (neutral atoms, plasma ions, and smaller agglomerates)
    - thermal properties of the grains (surface temperature vs. kinetic energy)
    - electromagnetic properties of the local environment
- If these particles can be become charged, this can have a significant impact on the rate at which further particle growth can occur – possibly even to electrostatic disruption (breakdup) of the grains.

P. Meakin, Fractal Aggregates in Geophysics, Rev. Geophys., **29**, 317 (1991)
S. Kempf, et al., N-Particle-Simulations of Dust Growth…, Icarus, **141**, 388 (1999)
J. Blum, et al., Growth and Form of Planetary Seedlings: …, Phys. Rev. Lett., **85**, 2426 (2000)
A. Mendis, Role of Field Emission in the Electrostatic Disruption…, Astrophys. Space Sci., **176**, 163 (1991)

Particle formation



Simulation: L. Matthews, *IEEE TPS*



Experiment: Blum, *PRL* (2000).

Particle formation

Outstanding issues:

- What is the role of the dust grain charge?
- Under what conditions (shocks, turbulence, etc.) can grains be disrupted?
- The planetesimals are formed from the agglomeration and growth of small dust grains – some of which may be charged.
- The amount of charge, the sign of the net charge, the dielectric properties and magnetic susceptibility of the grain material, and the distribution of charge on these grains and their aggregates can all have an influence on the rate of planetesimal formation.

Magnetic field effects

Relevance:

- Just as plasmas are ubiquitous in the universe, magnetic fields are just as pervasive
- Although some early studies recognized the role of magnetic fields, only recently has there been substantial research effort – particularly in the area of magnetized dusty plasmas.
- The magnetic field can shape the properties of the background plasma.
- Subsequently, the magnetic field may have both *direct and indirect* influences on the charged dust particles.

Magnetic field effects

STAR FORMATION IN MAGNETIC DUST CLOUDS

L. Mestel and L. Spitzer, Jr

(Received 1956 July 27)*

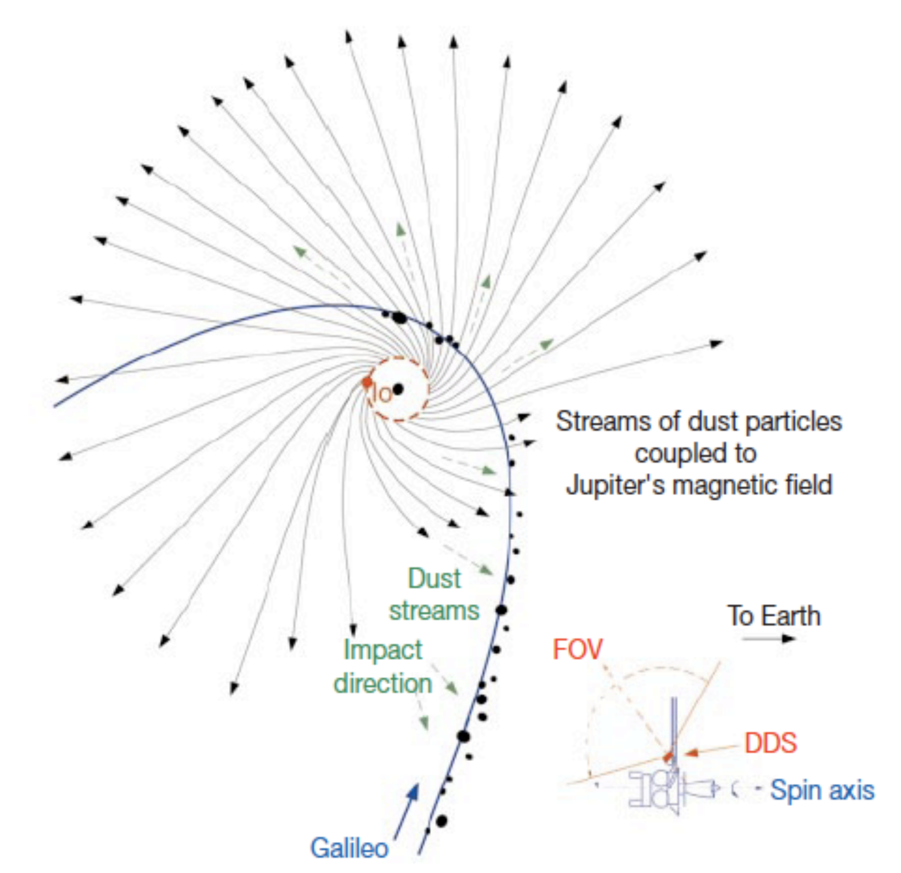
Summary

The paper deals with the problem of gravitational condensation in the presence of a magnetic field. It is shown that as long as the field is frozen into the contracting cloud the magnetic pressure sets a lower limit to the mass that can remain gravitationally bound: if the field is taken as 10^{-6} gauss in regions of density 10 H atoms/cm^3, this lower limit is $\simeq 5 \times 10^2 \odot$. However, if the bulk of the cloud is obscured from galactic starlight by dust grains, the plasma density within the cloud will decline rapidly, as ions and electrons attach themselves to the grains. When the plasma density is low enough the frictional coupling between plasma and neutral gas will be so small that the distorted magnetic field will be able to straighten itself, dragging the remains of the plasma with it, while the bulk of the cloud contracts across the field. With the magnetic energy so reduced to a small fraction of the gravitational energy, the cloud is able to break up into stars.

Mestel and Spitzer, ApJ, **116**, 503 (1956)

Magnetic field effects

- Most often, the role of the magnetic field in incorporated in the dynamics of the charged dust.
- This has been particularly important for interpreting phenomena within the solar system.
- One example are the dust streams emanating from Jupiter due to volcanic activity at Io.

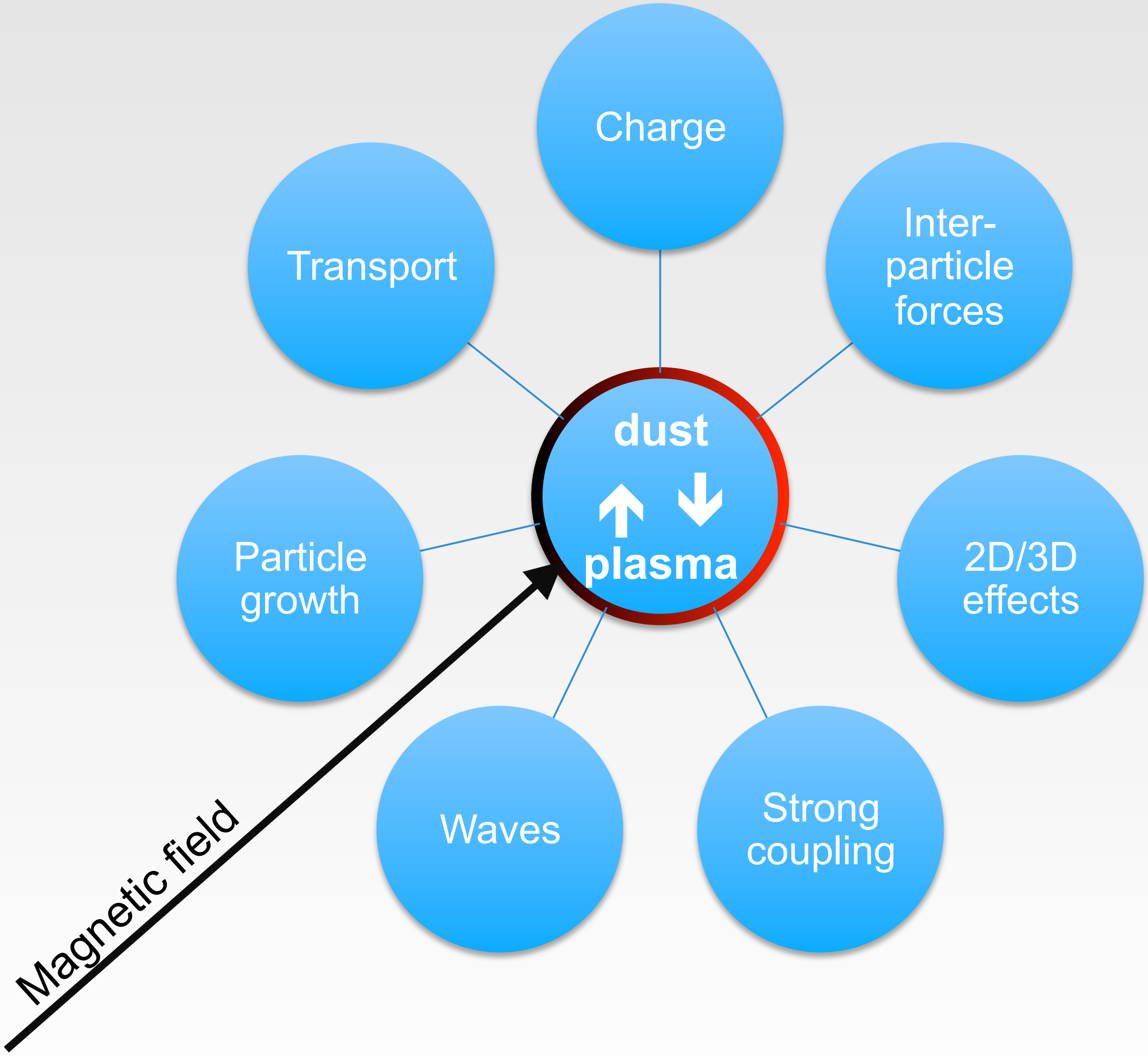


$$m\frac{d\vec{v}}{dt} = q_d\left(\vec{E} + \vec{v}\times\vec{B}\right) + \vec{F}_G + \vec{F}_d + \vec{F}_r$$

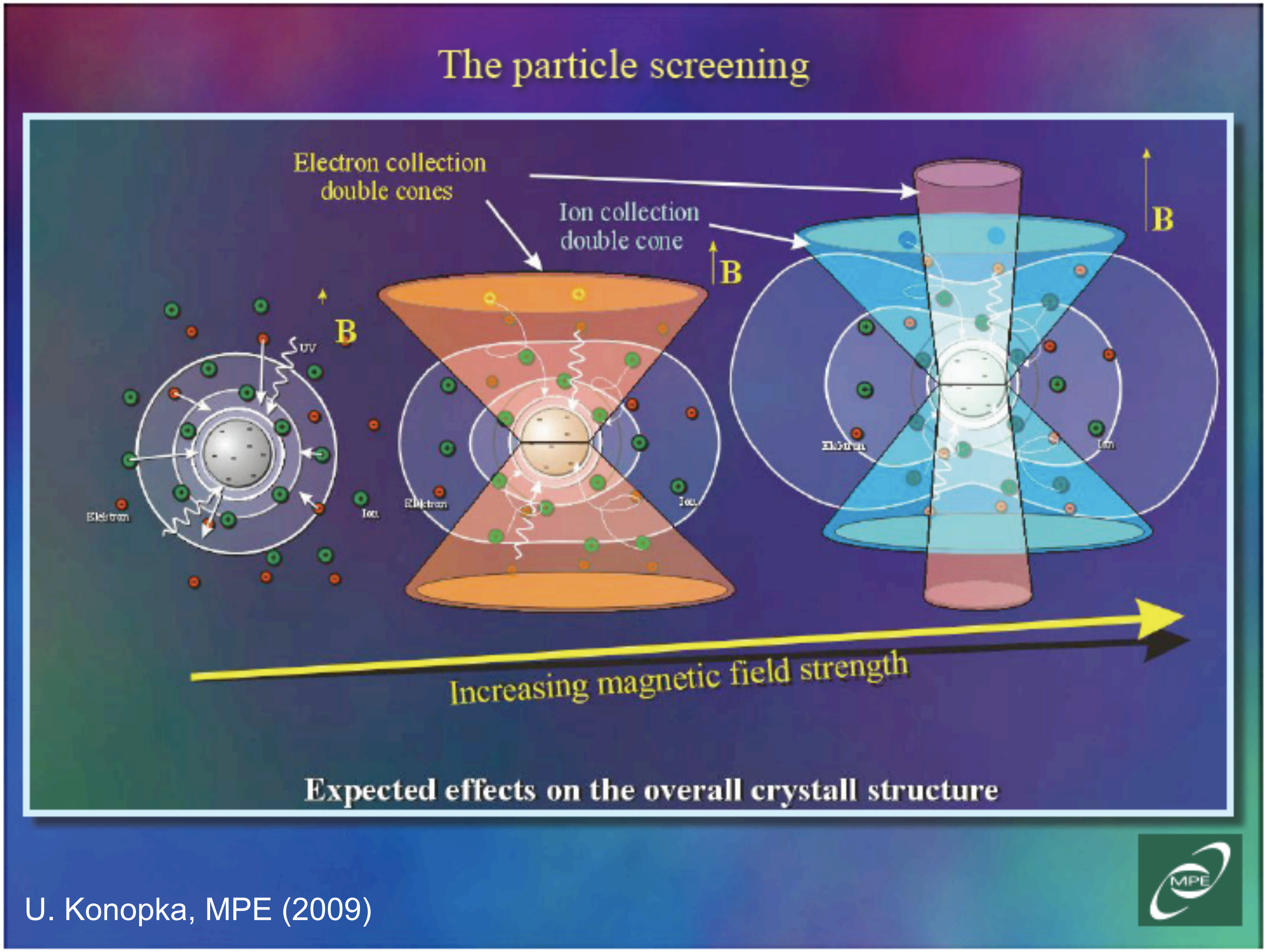
A. Graps, et al., Nature, **405** (2000)

Magnetic field effects

Magnetic field not only alters transport of ions, electron and the dust, but also has the potential to modify the coupling between the dust and the plasma.



Magnetic field effects



U. Konopka, MPE (2009)

Magnetic field effects

Outstanding issues:

- Additional fundamental work needs to be done to better understand the coupling between magnetic fields, plasmas, and charged dust.
- Supporting laboratory work is minimal – new efforts are under development.
- Are there remote observations can provide the evidence of the coupling between magnetic fields, dust, and plasmas?

Coupling between dust and plasma

Relevance:

- In the astrophysical plasma environment, dust and neutral particles can have a significant dissipative effect of the plasmas.
- The dust can also be a source and/or sink of ions, electrons and neutrals.
- This is particularly true regions that transition from a highly ionized to partially ionized regimes (e.g., stellar chromospheres or planetary ionospheres).
- Observations in there transitional regimes are often challenging because observational techniques and theoretical interpretations are at odds in these regions.
- Moreover, neutrals and dust can substantially alter the collective behavior (i.e., waves and instabilities) in the plasma leading to new types of phenomena.

Coupling between dust and plasma

Observations in the laboratory:

- The emergence laboratory studies of dusty plasma has led to the observation of a wide variety of dust-driven and dust-modified plasma modes.

✓ **Dust modified**
- Electrostatic dust-ion cyclotron waves
- Dust-ion acoustic waves
- Dust-ion acoustic shocks

✓ **Dust driven**
- Dust acoustic waves
- Dust lattice waves
- Mach cones

Coupling between dust and plasma

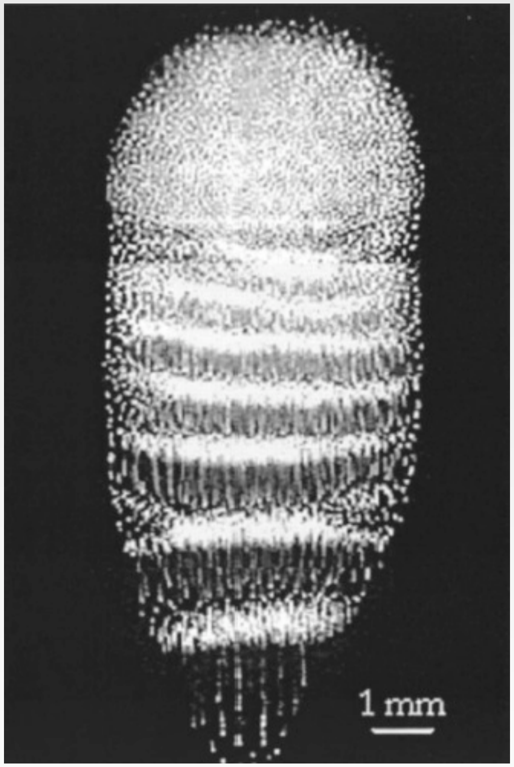
- Dust acoustic wave (dd): the fluid dispersion relation contains the effects of ion drift, thermal effects, and collisions.

$$1 = \frac{\omega_{pi}^2}{\Omega_i\left(\Omega_i + i\nu_{in}\right) - k^2 V_{ti}^2} + \frac{\omega_{pe}^2}{\Omega_e\left(\Omega_e + i\nu_{en}\right) - k^2 V_{te}^2} + \frac{\omega_{pd}^2}{\Omega_d\left(\Omega_d + i\nu_{dn}\right) - k^2 V_{td}^2}$$

$$\text{Where: } \Omega_\alpha = \omega - k u_{\alpha 0},\ \omega_{p\alpha} = \left(\frac{n_\alpha q_\alpha^2}{\varepsilon_0 m_\alpha}\right)^{1/2},\ V_{t\alpha} = \left(\frac{k_B T_\alpha}{m_\alpha}\right)^{1/2}$$

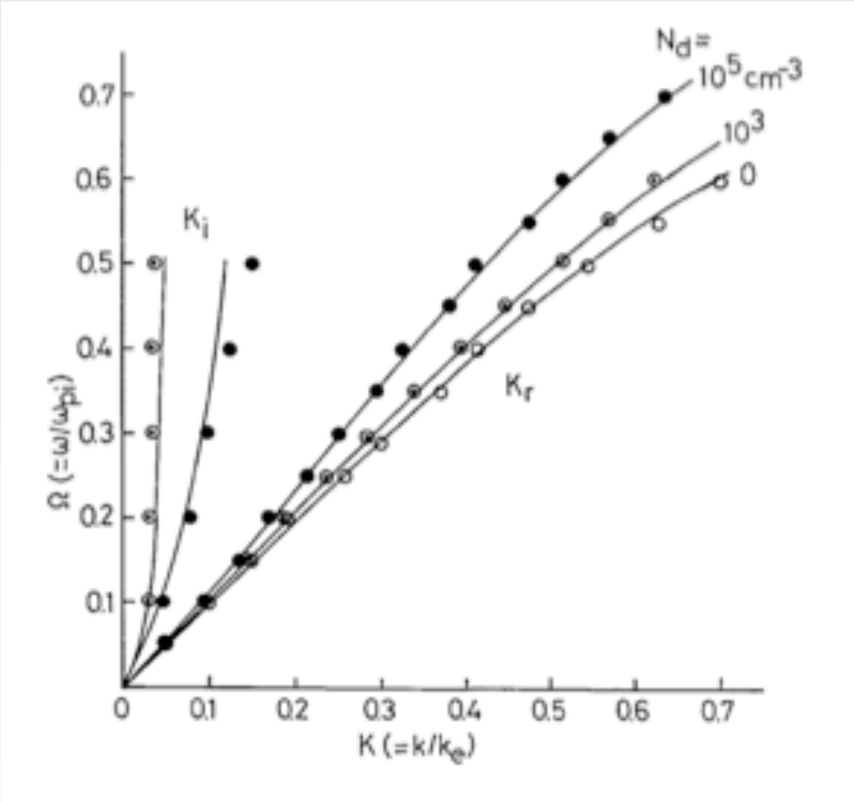
A number of authors have studied various forms of the dispersion relation:

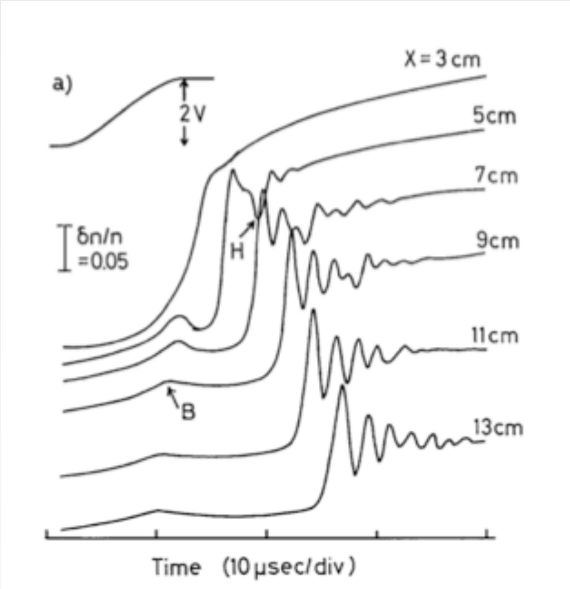
Kaw and Singh, PRL (1997), Mamun and Shukla, PoP (2000), Merlino and D'Angelo, PoP (2005), Piel, et al., PRL (2007), Williams and Thomas, PoP (2008)



From: V. Fortov, et al., PoP (2000)

Coupling between dust and plasma





Evolution of a dust ion acoustic shock in a double plasma device
[Y. Nakamura, et al., PRL (1999)]

Coupling between dust and plasma

Outstanding issues:

- Extensive laboratory work on these phenomena exists – there are few, if any, astrophysical observations of these processes.
- Extensive body of theoretical work for both dust-driven and dust-modified plasma modes.
- Are there remote observations can provide the evidence of the collective behavior of astrophysical dusty plasmas?

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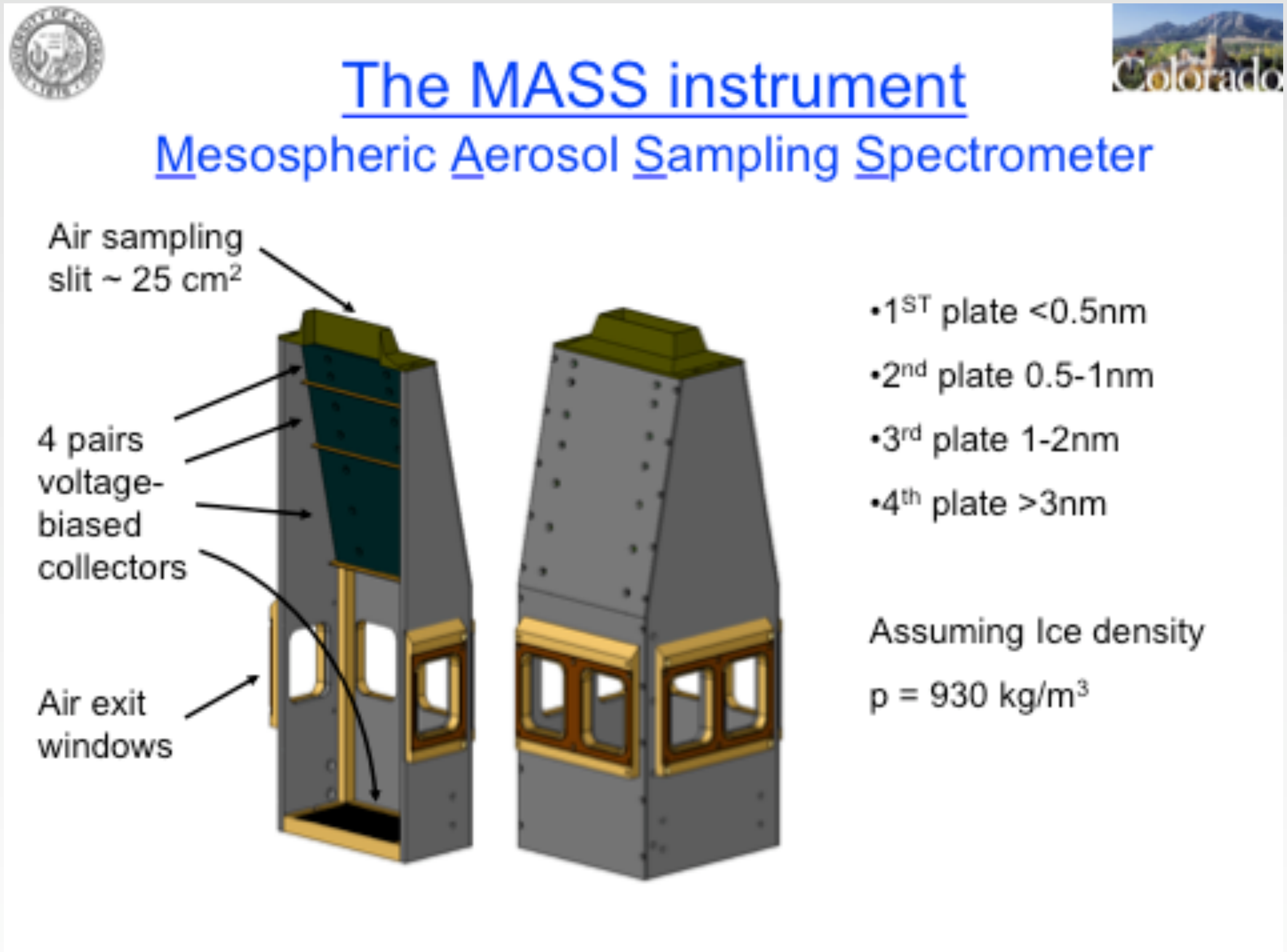
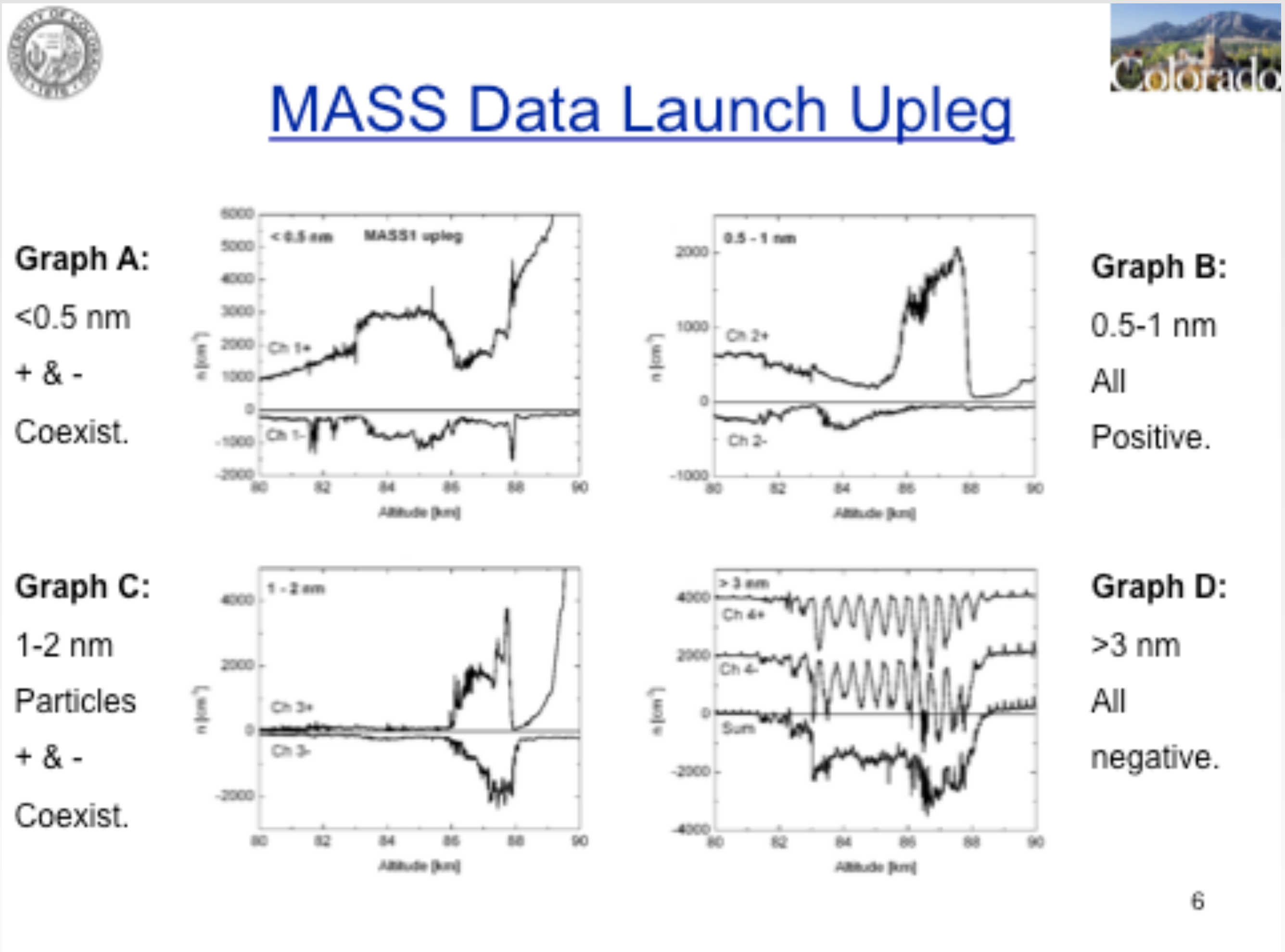
Near-earth studies – *in-situ* observations



Sounding rocket studies of dust in near-earth space environment
Knappmiller, et al., URSI (2010)

Near-earth studies – *in-situ* observations

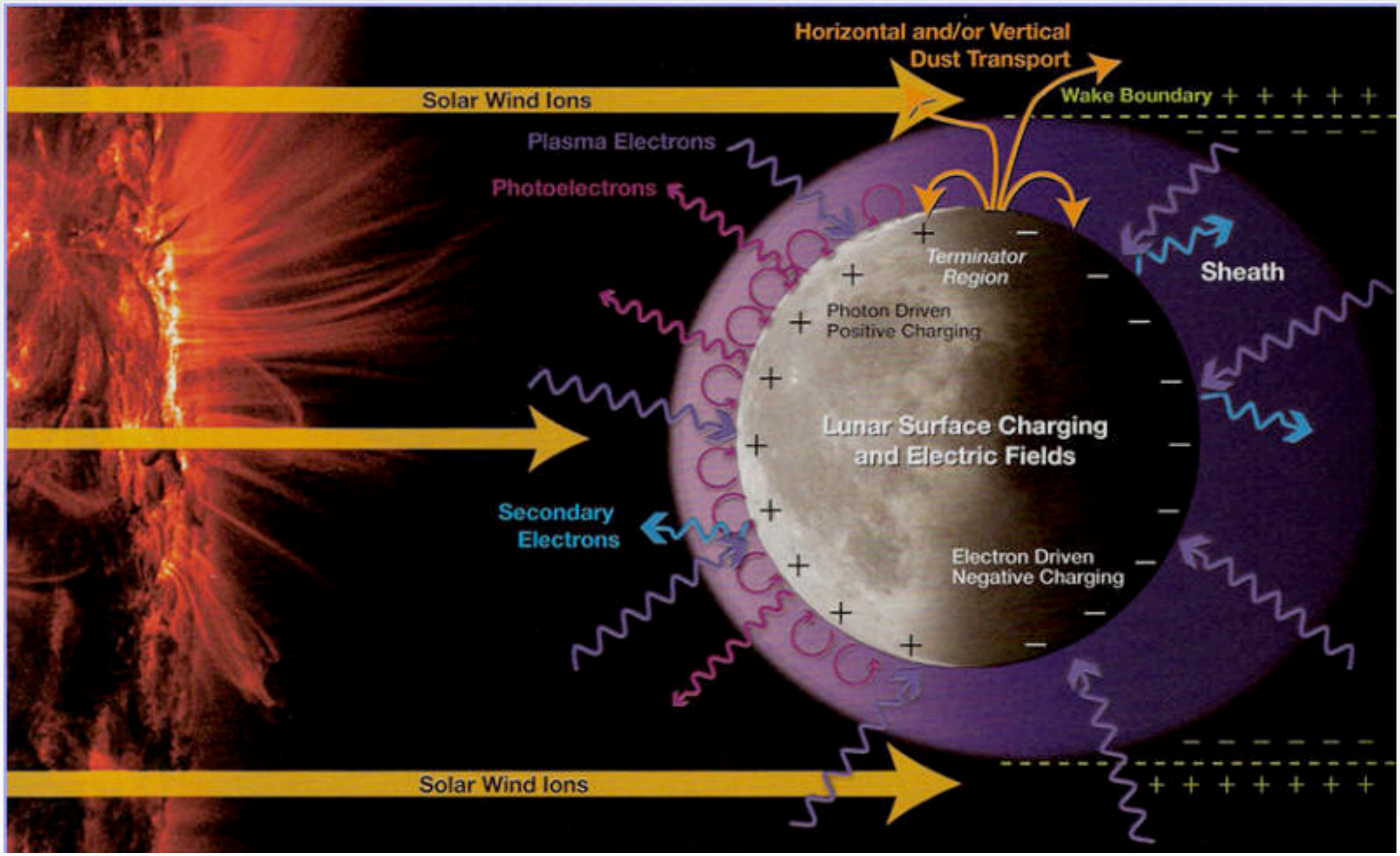


Future studies:

Combination of sounding rocket, satellite, and radar studies of NLC.

Sounding rocket studies of dust in near-earth space environment
Knappmiller, et al., URSI (2010)

Lunar dust studies – Laboratory and *in-situ* observations



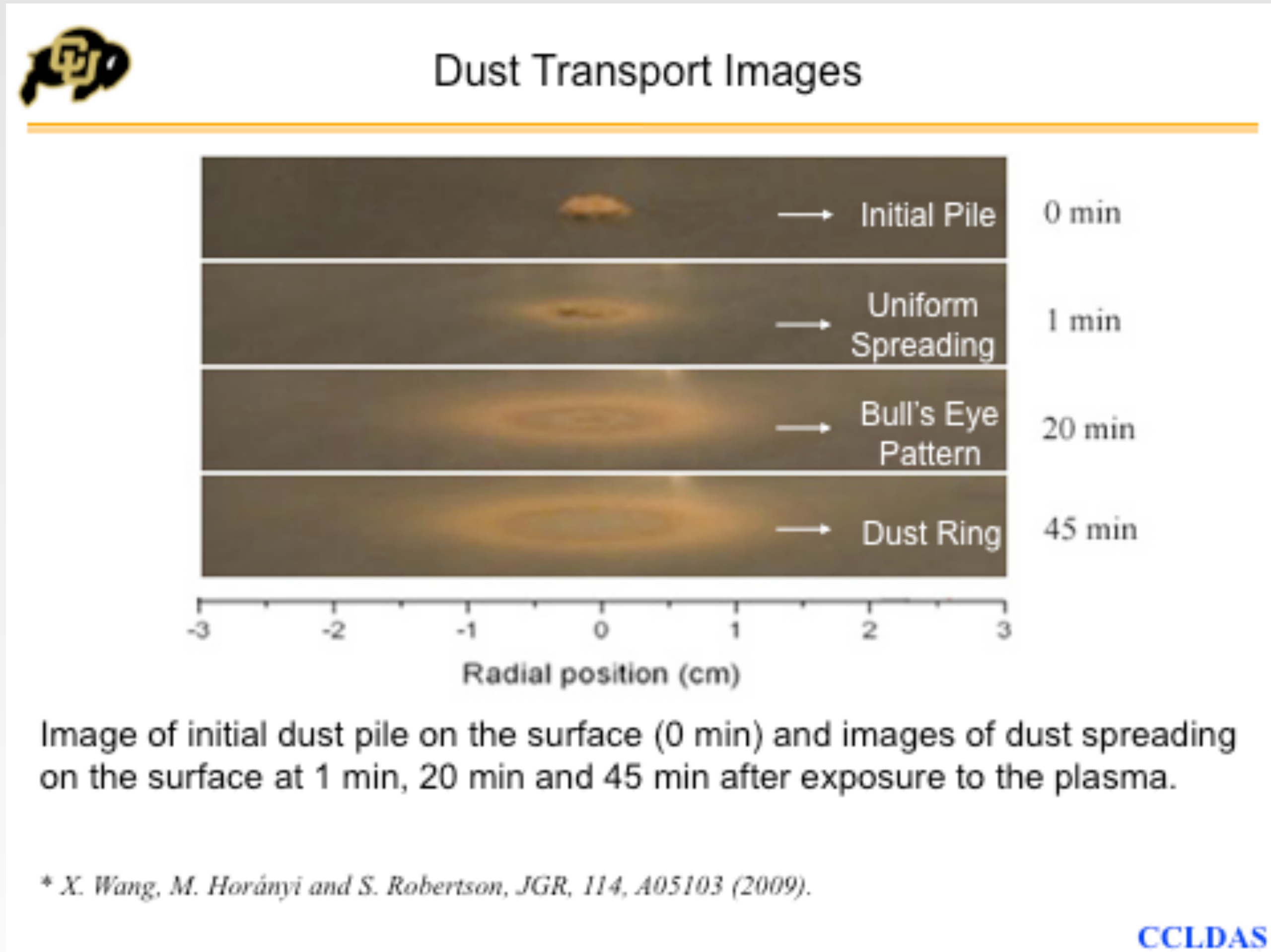
Lunar plasma environment
Wang, et al., URSI (2010)

Lunar dust studies – Laboratory and *in-situ* observations

The image of lunar horizon glow taken shortly after sunset [Criswell, 1973]

Future studies:

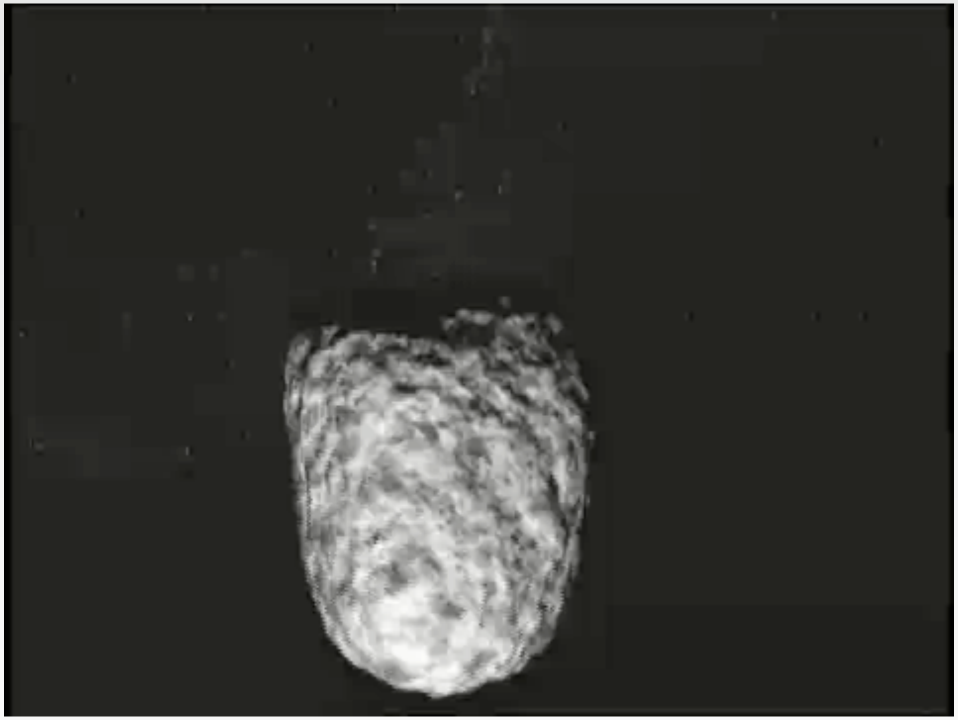
New laboratory and lunar surface studies are underway.



Laboratory and observational studies of charged dust transport in lunar environment
Wang, et al., URSI (2010)

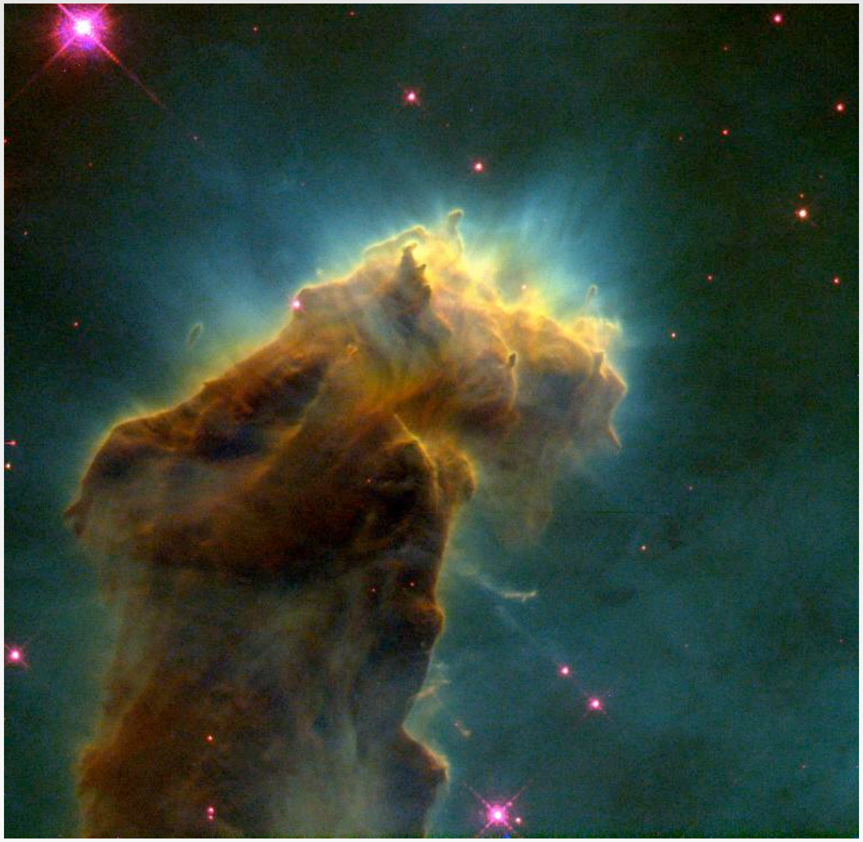
Solar system observations

- *Cassini* observations of Saturn are on-going and complemented by ground-based and space-based telescope observations.
- *Stardust* sample and return mission from a comet.
- *Stardust-NExT* and *Rosseta* missions to perform *in-situ* studies of cometary dust.
- *Ulysses* and *Galileo* both had dust detectors used to make measurements of dust particles from solar (Jupiter) and extra-solar sources.



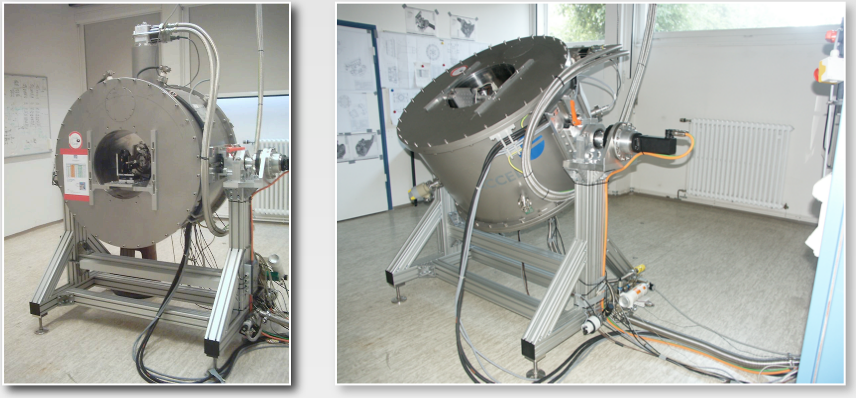
Extra-solar observations

- Is there a need for a mission to probe the properties of charged dust – e.g., studying solar system formation?
- What methods can be used to remotely determine the charge state of dust?
- What ground-based studies are needed to validate these remote measurements?

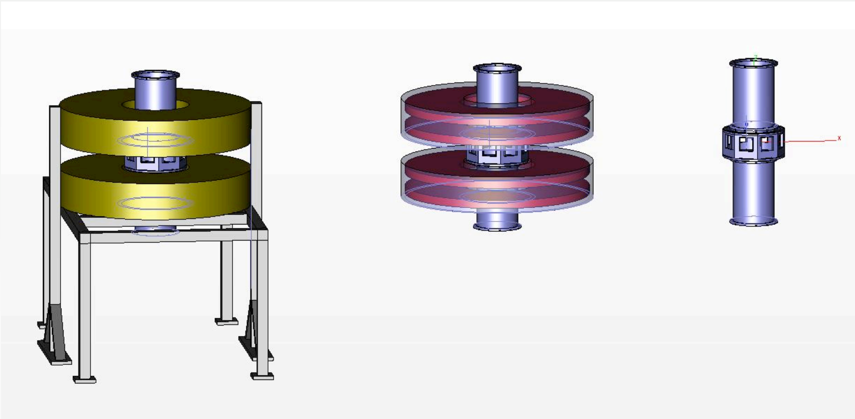


Laboratory studies

- Laboratory studies of dusty plasmas remain a vibrant area of research.
- The strong connections between lab, industrial and processing communities offers opportunities for studying basic processes such as charging and particle growth.
- Lab studies of waves and instabilities also remains very active.
- Several groups are beginning to pursue active studies of magnetic field effects in dusty plasmas – **particle growth, transport, charging, instabilities and magnetic materials**.



Uniform B experiment at MPE



Initial designs for new magnetized dusty plasma experiment with B and grad-B control.

Outline

- Introduction
  - Astrophysical phenomena
  - Connections with laboratory studies
  - Comparison of plasma parameters
- Outstanding issues
  - Dust charging
  - Particle growth
  - Magnetic field effects
  - Coupling between dust and plasma
- Research opportunities
- **Summary**

Summary

- Properties of charged dust affect wide range of astrophysical phenomena

- Outstanding issues
  - Charging
  - Particle formation
  - Magnetized dusty plasmas
  - Dust driven, dust modified instabilities

- Opportunities
  - Ionospheric studies
  - Lunar science
  - Magnetized dusty plasmas
  - Dust driven, dust modified instabilities