Charging of nanograins in cold dusty plasmas: from noctulescent clouds to Enceladus plume and cometary environments

Nicole Meyer-Vernet

LESIA, Observatoire de Paris, CNRS, UPMC, Université Paris Diderot, Meudon, France

AGU FALL MEETING
San Francisco 9-13 December 2013
(invited talk)

nicole.meyer@obspm.fr
www.lesia.obspm.fr/perso/nicole-meyer/
Nano grains

• What are they?

• Where are they found?

• What makes them different?

• How are they charged in cold plasmas?

• … and in dusty plasmas
What are they?

- Original definition of a nanoparticle: a particle that consists of a countable number of atoms
What are they?

ISO TS 27687 **Nano-object**: has at least one external dimension between 1 and 100 nm

<table>
<thead>
<tr>
<th>Material</th>
<th>Radius (nm)</th>
<th>Number of atoms/molecules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td></td>
<td></td>
</tr>
<tr>
<td>compact spheres</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
What are they?

- The size may determine the structure

Cluster of $H_2O$ molecules
disordered structure

$n=123$

---

Graphite
Ice
Si
compact spheres

Number of atoms or molecules

Radius (nm)
What are they?

- The size may determine the structure

Cluster of $\text{H}_2\text{O}$ molecules
- disordered structure

- Smallest ice crystal
  - 90 – 115 K
  - 1.3 nm

[Pradzynski 2012]
What are they?

Nano particles

Macromolecule or nano grain?

Polycyclic Aromatic Hydrocarbons: \( \geq C_{32}H_{14} \)

Fullerenes: \( C_{60} \rightarrow C_{400} \)

Graphene

3-D

2-D

A various fauna ..

Biology

Insulin

Nanotechnology

Bohr radius

Bulk matter

100 nm

10 nm

1 nm

0.1 µm

10 Å

1 Å

Molecules

Nanoparticles or nano grain?
Where are they found?

- **Interstellar space**  
  *Inferred from:*
  
  - far UV extinction  
    \[ a < \frac{\lambda}{2\pi} \approx 10 \text{ nm} \]  
    [Weingartner & Draine 2001]
  
  - IR emission [Sellgren 1984; Draine & Li 2001]  
    due to stochastic heating (PAH’s)

- **Interstellar nanogranals cannot enter the heliosphere**  
  except embedded in larger grains

Presolar TiC nanocrystal

Dust density (10 nm) relative to value in ISM [Slavin et al. 2010]
Where are they found?

- **Planetary environments**
  - Polar mesosphere in summer: coldest place on Earth

  - **Smoke particles**: a few 0.1 nm to a few nm (from condensation of meteoritic matter)
  - **Charged aerosols**: a few nm to 100 nm
    [e.g. Friedrich & Rapp 2009]

T < water vapor frost point:

- Large quantities of charged nanodust (ice): up to a few $10^3$/cm$^3$
Where are they found?

- Planetary environments
  - Polar mesosphere in summer: coldest place on Earth
    - Nanodust produces:
      - Noctilucent Clouds (ground obs.)/ Polar Mesospheric Clouds (SC obs.): ice grains $a > 20$ nm scatter light
      - Decreases in electron density $n_e$ associated to increases in (negatively charged) dust density $n_d$
      - Polar Mesosphere Summer Echoes: strong backscatter of radio waves ($50 - 10^3$ MHz) [e.g.; Rapp & Lübken 2004]
Where are they found?

- **Planetary environments**
  - Farther out..
  - **Titan atmosphere**
    - [Coates et al. 2007, 2009]

Cassini/CAPS (Plasma Spectrometer)

**serendipitous** detection (charged nanodust of energy/charge in the range of the instrument)

Radius $a \sim 1.6 \text{ nm if } \rho \sim 10^3 \text{ kg/m}^3$

$a \sim 16 \text{ nm if } \rho \sim 1 \text{ kg/m}^3$
Where are they found?

- **Planetary environments**

  - Enceladus plume

  ![Enceladus](image)

  [Cassini (NASA)]

  [Jones et al. 2009]

  **Cassini/CAPS (Plasma Spectrometer)**  
  *serendipitous* detection (charged nanodust of energy/charge in the range of the instrument)

  ![Graph](image)

  [Hill et al. 2012]

  Mass ($m_p$) with $q = \pm e$  
  $a \sim 1.6$ nm (ice)
Where are they found?

- **Planetary environments** (and farther out)
  - Fast (~300 km/s) nanodust streams
    - ...accelerated by corotation electric field of Jupiter
    - ... and Saturn [Kempf et al. 2005]

Dust detectors on Ulysses/Galileo/Cassini: serendipitous detection outside calibration range

<table>
<thead>
<tr>
<th>Original results from calibration</th>
<th>From dynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V \sim 20-56 \text{ km/s}$</td>
<td>$V &gt; 200 \text{ km/s}$</td>
</tr>
<tr>
<td>$m \sim 10^{-19} - 10^{-16} \text{ kg}$ [Grün et al. 1992]</td>
<td>$m \sim 10^{-21} \text{ kg}$ [Zook et al. 1996]</td>
</tr>
</tbody>
</table>

- **Comets**
  - Ion mass spectrometers on Giotto & Vega-1: serendipitous detection: $m \sim 0.5 \times 10^{-21} \text{ kg}$ at $10^6 \text{ km}$ from nucleus of Halley [Utterback & Kissel 1990 Sagdeev 1985, 1989]
Where are they found?

- **Interplanetary medium**

Nano grains accelerated by the magnetized solar wind

**STEREO/WAVES:** serendipitous detection (voltage pulses from high-speed (~300 km/s) dust impacts on SC)


1 AU

![Graph showing cumulative flux and particle mass.]
What makes them different?

Transition between molecular and bulk properties

- Consensus on nanoparticles: their properties are different from those of bulk material
What makes them different?

- Large proportion of surface atoms
  - Surface atoms have too few bonding partners
    - free radicals = surface “dangling bonds”
    - mean-square displacements of surface atoms are relatively large
  - Melting point & latent heat decrease
  - Diffusion coefficient increases
  - Optical properties change
  - Much chemical activity at surface
  - Surface reconstruction
  - Coagulation decrease in surface energy
What makes them different?

- **Quantum confinement**

Heisenberg: \( \Delta x \Delta p = \frac{h}{2\pi} \)

electron confined in nanograin of radius \( a \):
\( \Delta x \sim a \rightarrow \) momentum: \( \Delta p = \frac{h}{(2\pi \Delta x)} \)

\( \rightarrow \) confinement energy: \( E_0 \sim \Delta p^2/2m_e \)

▶ Quantized energy levels \( E_n = \frac{n^2 h^2}{8m_e (\Delta x)^2} \)

Affects optical & electrical properties [e.g. Li 2004]
What makes them different?

- **Size compared to basic scales**

✓ **Electron free path in solids**

\[ \sim 1 \text{ nm} \]

for \( E < 100 \text{ eV} \)

atomic scale: \( 2 \, r_B \)

→ **electron secondary emission increases**

[Draine & Salpeter 1979; Chow et al. 1993]

→ **electron sticking coefficient decreases** if \( a \leq l_e \)
What makes them different?

- **Size compared to basic scales**

- **Photon scales**
  - Photon attenuation length $\sim 10 - 100$ nm
  - Photoelectron escape length $l_e \sim 0.5 - 5$ nm

- **Photoelectron yield increases** if $a \lesssim l_e$

  photoelectrons have a better chance to escape [Watson 1972; Draine 1978]

- **can be counterbalanced by:**

  - Increase of electron removal energy:
    $\sim$ work function + $\frac{3}{8} \frac{e^2}{4\pi\varepsilon_0a}$
    [Wong et al. 2003]
    Image charge contribution

  - Photon wave length (UV) $\lambda > a$
    $\rightarrow$ photon absorption cross-section$/\pi a^2 \propto a$ (Rayleigh)

  *Note: for $a > l_e$ : yield $\downarrow$
  *when $a \downarrow$ [de Heer 1993; Abbas et al. 2007]*
What makes them different?

- **Size compared to basic scales**

  ✓ **Plasma Landau radius**

  \[ \frac{e^2}{(4\pi\varepsilon_0 ar_L)} = \frac{mv^2}{2} \]

  - Coulomb energy
  - Kinetic energy

  \[ r_L = \frac{e^2}{(4\pi\varepsilon_0 k_B T)} \]

  → If \( a \lesssim r_L \), dipole induced by an approaching charge strongly curves its trajectory

  → Increases currents

  \[ r_{L_{nm}} = 1.4 \left/ \mathrm{T eV} \right. \]

  Concerns nanograinrs if \( T < 2 \text{ eV} \)

**Note:**

- \( a \ll L_D \Rightarrow \) grain’s capacitance \( C \approx 4\pi\varepsilon_0 a \)

**other plasma scales**

- \( a \ll \) free path \( \approx [n_e r_L^2 \ln(1/\Gamma)]^{-1} \)

In general

**Plasma coupling parameter**
What makes them different?

- **High charge-to-mass ratio**
  - Dynamics and pick-up in magnetized plasmas
  - Dusty plasma effects

- **Further charge effects of relative importance**

  - **Nucleation**: charged grain attracts molecular dipoles → decreases free energy
    \[ G_0 = 4\pi a^2 \sigma - Nk_B T \ln(S) \]  - Coulomb term
    \[ \propto a^3 \]
    - Energetic preference for condensation
    - Energy to form surface
    - Can suppress barrier of potential

  - **Electrostatic disruption**: stress \( \propto (q/a^2)^2 \)
    → makes grain explode → may determine minimum size
Electric charging: basics

• Charging governed by incoming plasma electrons until grain negative charge repels them sufficiently to balance other currents [e.g. Whipple 1981]

• Charging governed by escaping photoelectrons until grain positive charge binds them sufficiently for escaping photoelectrons to balance other currents

Q: grain’s charge; \( \Phi \): grain’s potential relative to ambient plasma
Electric charging: basics

- At equilibrium: potential energy = a few times kinetic energy of dominant charging particles
  \[ |e\Phi| \approx \eta \, k_B T \]
- Charge: \( q \approx 4\pi \varepsilon_0 a \Phi \)
  \[ |Z| = |q/e| \approx \eta \, a/r_L \]
  \[ r_L = e^2/(4\pi \varepsilon_0 k_B T) \]
  \( \eta \approx 1 \) (order of mag.) determined by details of charging processes

If \(|Z| >> 1\), i.e. \( a > r_L \),

\( T_e \) or \( T_{ph} \), a few eV
Electric charging

*Beware: tricky cases*

- **Secondary emission not negligible**
  
  Sensitivity to parameters near $T$ at which $J_{\text{sec}} \sim J_e$ [Laframboise et al. 1982]

- **Non-maxwellian plasma**
  
  → **Unstable solutions**

Secondary emission: $\delta = 3$

$E_M = 400 \text{ eV}; T = 25 \text{ eV}; T_H/T_e = 100$
Electric charging

Beware: tricky cases

- *Secondary emission not negligible*

Sensitivity to parameters near $T$ at which $J_{sec} \sim J_e$ [Laframboise et al. 1982]

- *Non-maxwellian plasma*

$\rightarrow$ Unstable solutions

\[ e \Phi / k_B T_e \rightarrow \text{bifurcations} \]

$\Phi$ vs. $J_{ph}/J_e$

- Infinitesimal increase of photoemission

$\Phi$ vs. $n_H/n_e$

- Infinitesimal increase of non-thermal electrons

$\Phi$ vs. $J_{sec}$

- Jump of potential

2-D cuts in multi-dimensional space of parameters

- Beware: tricky cases

- Secondary emission not negligible

- Non-maxwellian plasma

- Unstable solutions

- Infinitesimal increase of photoemission
Electric charging in **dusty** plasmas

\[ n_d \text{ grains/m}^3; \ n_e (n_i) \text{ electrons (ions)/m}^3 \]

\[ L_D = [4\pi r_L(n_e+n_i)]^{-1/2} \quad (T_e \sim T_i) \]

Fraction of charges carried by grains = \( Z n_d / (n_e+n_i) = \eta P \)

\[ P = 4\pi n_d aL_D^2 \]

- If \( P > 1 \), Debye sheaths overlap
  → electrons depleted
  → reduces grain’s charge
  [Havnes et al. 1984, Whipple et al. 1985]

- If \( P \gg 1 \): \( Z \sim -a/(Pr_L) \ll 1 \)
  Limit to el. depletion: \( n_e/n_i \sim 1/\mu \)
  [Mendis & Rosenberg, 1994; Mendis 2002]

\[ \mu = (s_e/s_i)(v_{the}/v_{thi})\sim(m_i/m_e)^{1/2} \gg 1 \]
Electric charging in **dusty** plasmas

\[ n_d \text{ grains/m}^3 ; n_e (n_i) \text{ electrons (ions)/m}^3 \]

\[ L_D = [4\pi r_L(n_e+n_i)]^{-1/2} \]

**Beware!**

Densities **inside** dusty plasma

Fraction of charges carried by grains = \( Z n_d / (n_e+n_i) = \eta P \)

\[ P = 4\pi n_d a L_D^2 \]

\( \eta = 180 \) (H\(_2\)O\(^+\))

- **P ≠ “Alfvén parameter”** which refers to \( n_e \) **outside** a “dust cloud” [Havnes 1987, 1989; Goertz 1989]

\[ \mu = 180 \]

\[ -\eta = Z r_L / a \]

\[ -1/P \]

\[ 1/\mu \]
Electric charging

- **Important limitations for nanodust**

- **Long charging time scales**:
  \[ \tau \sim RC \sim (dl/d\Phi)^{-1}C \sim [4\pi ar_L J/e]^{-1} \text{ if } a > r_L \]
  \[ \tau \sim [(2\pi a)^{3/2} r_L^{1/2} J_e]^{-1} \text{ if } a < r_L \]

- **Field emission limits negative charge**:

  Limiting electric field for (electron) field emission: \( \Phi/a \sim 10^9 \text{ V/m} \)

  Maximum number of electrons on a nanograin:
  \[ |Z_{\text{MAX}}| \sim 1 + 0.7 \ a^2_{(\text{nm})} \]
Electric charging in **cold** dusty plasmas

Nanodust: \( a \lesssim r_L \approx 1.4/T_{(eV)} \) nm

**Examples:**

- **Earth’s ionosphere:** \( r_L \approx 5 - 100 \) nm
- **Jupiter/IO torus:** \( r_L \sim 0.1 - 1.5 \) nm (Te from [Bagenal 1994]; [Moncuquet et al. 1995])
- **Saturn (3-10 \( R_S \))**: \( r_L \sim 0.3 - 3 \) nm (Te from [Sittler et al. 2006]; Schippers et al. 2013]
- **Comet plasma tail:** \( r_L \sim 1 \) nm (Te from [Meyer-Vernet et al. 1986] measure *in situ* of Giacobini-Zinner plasma tail by ICE/radio instrument: \( n_e \approx 10^3, T_e \approx 1 \) eV)
Electric charging in **cold dusty plasmas**

- Nanodust: $a \lesssim r_L \approx 1.4/T_{(eV)}$ nm

Two major consequences:

1. Approaching charge is strongly attracted by induced dipole
   Potential energy $\frac{e^2}{4\pi\epsilon_0a} \gtrsim k_BT$
   $\rightarrow$ increases currents
   $\rightarrow$ decreases charging time scales
   [Natanson 1960; e.g. Draine & Sutin 1987; Rapp & Lübken 2001]

2. Grain’s number of charges $|Z| \approx \eta a/r_L \gg 1$
   $\rightarrow$ statistical treatment: $f(Z) J_i(Z) = f(Z+1) J_e(Z+1)$
   [Draine & Sutin 1987] deduce moments, as:
   average charge state: $<Z> = \sum Z f(Z)$
Electric charging in **cold** dusty plasmas

**Examples:**

- Probability distribution of $Z = q/e$ at equilibrium

  - Earth mesosphere, $Z = -1$
    - Inhomogeneous Poisson process approach
    - Variation of grain’s potential with time

- $T_c = 0.015$ eV + hyperthermal electrons at 3.5 eV

- Saturn’s magnetosphere, $a=3$ nm
  - $n_h/n_c = 0.02$
  - $n_h/n_c = 0.01$

- Rosenberg et al. 2012

- Hsu et al. 2011
Electric charging in cold dusty plasmas

Average number of charges on a grain without field emission

no longer proportional to grain size

\[ <Z> \propto a \]

(if \( J_{ph} \) negligible)

\[ <Z> \not\propto a \]

\[ \text{H}_3\text{O}^+ \text{ions} \]

\[ n_e/n_i = 1 \]

\[ n_e/n_i = 0.1 \]

\[ n_e/n_i = 0.01 \]

\[ 3.6 \ a/r_L \]

[Meyer-Vernet 2013]
Electric charging in **cold** dusty plasmas

Average number of charges on a grain
no longer proportional to grain size

\[ < Z > \approx 1 \]

\[ < Z > \propto a \]

\[ Z_{\text{MAX}} \text{ due to field emission limit} \]

\[ T = 0.3 \text{ eV} \quad T = 1 \text{ eV} \]

\[ n_e / n_i = 1 \]

\[ n_e / n_i = 0.1 \]

\[ n_e / n_i = 0.01 \]

\[ 3.6 a/r_L \]

[if \( J_{\text{ph}} \) negligible]

[e.g. Draine & Sutin, 1987; Rapp & Lübke 2001; Hill et al. 2012]

[Meyer-Vernet 2013]
Conclusions

Beware of nanograin:

• Ubiquitous

• Physical properties different

• Secondary emission → multiple states → nasty for numerical simulations

• In cold \((a \lesssim r_L)\) dense plasmas, nanograin carries \(|<Z>| \sim 1\) electron
  \(\rightarrow \frac{q}{m} \propto a^{-3}\) (instead of \(a^{-2}\))

• Were detected serendipitously in most environments …
  Will crop up when you don’t expect them