Detection of nanodust in the solar system

N. Meyer-Vernet, I. Mann*, G. Le Chat, P. Schippers, S. Belheouane, K. Issautier, A. Lecacheux, M. Maksimovic, F. Pantellini, A. Zaslavsky

LESIA, Observatoire de Paris, CNRS, UPMC, Université Paris Diderot, Meudon, France
* EISCAT, Kiruna, Sweden & Physics Dept., Umeå University, Sweden

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Nano dust particles

• What are they?
• What makes them different?
• How are they charged and accelerated in plasmas?
• How and where are they detected in situ?

What are they?

➢ Original definition of a nanoparticle: a particle that consists of a countable number of atoms

What are they?

➢ Size

ISO TS 27687 Nano-object: has at least one external dimension between 1 and 100 nm
What are they?

- **Nano particles**
- **Molecules**
- **Bulk matter**

<table>
<thead>
<tr>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 nm</td>
<td><strong>Nano particles</strong></td>
</tr>
<tr>
<td>10 nm</td>
<td><strong>Molecules</strong></td>
</tr>
<tr>
<td>1 nm</td>
<td><strong>Bulk matter</strong></td>
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Macromolecule or nano grain?

A various fauna..

- Polycyclic Aromatic Hydrocarbons: $\geq C_{20}H_{14}$
- Fullerenes: $C_{60}$
- Nanotechnology
- Biology
- Insulin
- Graphene

2-D

What makes them different?

- **Large proportion of surface atoms**
  - Surface atoms have too few bonding partners
  - $\rightarrow$ 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

Most atoms lie at the surface

Radius (nm) vs. Frequency of atoms

- Size smaller than basic scales
- De Broglie wavelength $\hbar/m_\text{e}v$ (Quantum confinement)
  - Heisenberg: $\Delta x \Delta p = \hbar/2\pi$
  - Electron confined in nanograin of radius $a$: $\Delta x \sim a \rightarrow \Delta p = \hbar/(2\pi a)$
  - Confinement energy: $E_0 \sim \Delta p^2/2m_\text{e}$
  - Affects optical & electrical properties when $E_0 \geq k_B T$ [e.g. Li 2004]
  - Equivalent to $a \leq \hbar/m_\text{e}v$ with $v \sim (k_B T/m_\text{e})^{1/2}$
  - Concerns nanodust if $T < 300 K$
What makes them different?

- **Size smaller than basic scales**

  - **Electron free path in solids**
    - $\sim 1$ nm for $E < 100$ eV
    - atomic scale: $2r_B$
    - $\Rightarrow$ electron secondary emission increases
      - [Draine & Salpeter 1979; Chow et al. 1993]
  
  - **Electron sticking coefficient decreases** if $a \leq l_e$

- **Photon scales**
  - Photon attenuation length $\sim 10 - 100$ nm
  - Photoelectron escape length $l_e \sim 0.5 - 5$ nm
  - $\Rightarrow$ Photoelectron yield increases if $a \leq l_e$
    - photoelectrons have a better chance to escape
      - [Watson 1972; Draine 1978]
  - $\Rightarrow$ can be counterbalanced by:
    - Increase of electron removal energy:
      - work function $+ \left[ \frac{3}{2}(\frac{e^2}{4\pi\varepsilon_0a}) \right]$
      - photon absorption cross-section $\sim \frac{a}{\lambda}$ (Rayleigh)

- **Plasma Landau radius**
  - $r_L = \frac{e^2}{4\pi\varepsilon_0k_BT}$
  - $r_{L\text{ nm}} = 1.4 \sqrt{T_eV}$
  - Concerns nanodust if $T < 2$ eV

- **These effects change their electric charge in plasmas**

  - **Their electric charge plays a major role**
    - Dynamics and pick-up in magnetized plasmas
    - Dusty plasma effects
    - Electrostatic disruption: stress $\sim (q/a^2)^2$
      - makes grain explode
      - may determine minimum size
Basics of electric charging in space

- 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

**Electric charging in space dusty plasmas**

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

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

\[ \Phi = 4\pi n_d a L_D \]

- If \( P > 1 \), Debye sheaths overlap
- Plasma electrons depleted
- Reduces grain's charge

[Havnes et al. 1984, Whipple et al. 1985]

- If \( P >> 1 \): \( Z \approx a \left( P r_i \right) \cdot 1 \)
- Limit to el. depletion: \( n_i/n_e \approx 1/\mu \)

[Mendis & Rosenberg, 1994; Mendis 2002]

**Electric charging in space**

- Important limitations for nanodust
  - Long charging time scales:
    \[ \tau \sim RC \sim (d/l)(\Phi) \cdot C \sim \left( 4\pi n_ar_i J/e \right) \]
    \[ \tau \sim \left( (2\pi a)^{3/2} r_i L_i J \right)^{-1} \]

- 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:
    \[ |Z_{\text{MAX}}| \sim 1 + 0.7 a^{2/3} \text{ (nm)} \]
Charging in cold dusty space plasmas

**Nanodust:** \( a < \ell_i \sim 1.4/T_{\text{eV}} \) nm

**Two major consequences:**

1. Approaching charges are strongly attracted by induced dipole.
   - Potential energy \( e^2/(4\pi\varepsilon_0 a) \gg k_B T \)
   - Increases currents
   - Decreases charging time scales
   [Natanson 1960; e.g. Draine & Sutin 1987; Rapp & Lübken 2001]

2. Grain’s number of charges \( |Z| \sim \eta a/\ell_i \gg 1 \)
   - Statistical treatment: \( f(Z)J_e(Z) = f(Z+1)J_e(Z+1) \)
   - Average charge state: \( \langle Z \rangle = \sum Z f(Z) \)
   - Probability for charge state \( Z \)

\[ n_e/n_i = 0.1 \]
\[ n_e/n_i = 0.01 \]

\[ \ell_i \sim 1 \]

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

**Approximation neglecting field emission**

- Average number of charges on a grain
- No longer proportional to grain size
- \( \langle Z \rangle \neq a \)

\[ \langle Z \rangle \approx 1 \]

**Nanodust produced in the solar system**

Nanograins have large charge-to-mass ratios

- Example: for \( a = 5 \) nm, \( q/m = 10^4 e/m_p \) in the solar wind
- Lorentz force plays a major role
- Charged grains follow magnetic field lines if \( r_{gyr} < B \) scale
- Gyradius: \( r_{gyr} = |(v-v_{\text{plasma}})/eB_s| \), \( eB_s \sim m/q \)

\[ B \text{ (mG) } \]

Interstellar nanodust cannot enter the heliosphere

Heliosphere dust density (10 nm) relative to value in ISM [Slavin et al. 2010]

Nanodust produced in the solar system
Dynamics in magnetized space plasmas

Nanodust produced in inner solar system where dust concentration is large

- B: Parker spiral
- For nanodust: Lorentz force >> gravitational force $r_{gr} < B$ scale → Nano dust picked-up & accelerated

Solar wind

$V_{SW} \times B$ outwards for Jupiter & Saturn if $q > 0$

Grains are accelerated and ejected at speed:

$v_{ej}^2 \sim (MG/r_0)[2 F_E/F_G - 1]$  

acceleration starts

$\Rightarrow$ nanodust speed $\sim 300 \text{ km/s for } a \approx 10 \text{ nm}$

How and where are they detected in situ?

- 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$^3$

Dynamics in magnetized space plasmas

Nanodust produced in inner solar system where dust concentration is large

Nano grains trajectories projected in solar equatorial plane

Nanograins accelerated to plasma drift velocity:

$v_0 = -(V_{SW} \times B) \times B / B^2$

$\Rightarrow$ nanodust speed at 1 AU $\sim V_{SW}/2^{1/2} \approx 300 \text{ km/s for } a \leq 10 \text{ nm}$
How and where are they detected in situ?

- **Planetary environments**
  - Polar mesosphere in summer: coldest place on Earth
    - **Nanodust produces:**
      - NoctuLescent Clouds (ground obs.)
      - Polar Mesospheric Clouds (SC obs.): ice grains \( a > 20 \text{ nm} \) 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 \text{ MHZ}) [e.g. Rapp & Lübken 2004]

- **Planetary environments**
  - Titan atmosphere
    - [Coates et al. 2007, 2009]
  - Enceladus plume
    - Cassini/CAPS (Plasma Spectrometer) serendipitous detection (charged nanodust of energy/charge in the range of the instrument)
  - Dust detectors on spacecraft Ulysses/Galileo/Cassini: serendipitous detection outside calibration range

- **Comets**
  - Dust impact ion mass spectrometers on Giotto & Vega-1: serendipitous detection; \( m \sim 10^{-21} \text{ kg} \) at \( 10^6 \text{ km} \) from nucleus of Halley [Ullateb & Kissel 1990; Sagdeev 1985, 1989]
How and where are they detected in situ?

Interplanetary medium

Nano grains accelerated by the magnetized solar wind as predicted by theory

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

Confirmed by 5 years of data [Le Chat et al. 2013]

In situ detection with WAVE instrument!

Example: Ulysses in the solar wind

1 AU

How are they detected in situ via waves?

Context: passing-by plasma particles produce electric potential fluctuations detected by electric antennas

Power spectrum:
peak at the plasma frequency (~ n_0)
whose shape reveals the temperature and suprathermal particles [Meyer-Vernet & Perche, 1989]

Wave instruments on space missions measure plasma properties via spectroscopy of plasma QT noise [Meyer-Vernet et al. 1998]

How are they detected in situ via waves?

Impact of fast dust particle

Vaporized & ionized produces expanding plasma cloud

Released charge Q \propto m^{3.5}

10 nm grain at 300 km/s produces 10^7 electrons similar charge as 0.2 \mu m grain at 20 km/s

Charge separation or recollection produces electric pulse detected by the radio receiver

... and power spectral density

\[ \Delta V = Q/C \]

Spacecraft capacitance
How are they detected in situ via waves?

STEREO/WAVES at 1 AU

Electric pulses produced by destabilization of photoelectrons surrounding antenna

[Pantellini et al. 2012, 2013]

Two different wave instruments:

- time domain sampler (TDS)
- frequency receiver (LFR)

Nanodust impacts

[Le Chat et al. 2013]

ster 10 kHz

- nanodust impacts
- plasma QT noise

How are they detected in situ via waves?

Two different wave instruments:

- Cassini RPWS
- 1 AU

Saturn

Electric pulses produced by recollection of electrons of the nano dust impact plasma

[Schippers et al. 2014]

Near Jupiter

Detected nanodust flux similar to value measured on STEREO

Detected nanodust [Meyer-Vernet et al., 2009] simultaneously to detection of Jovian nanodust by conventional detectors

Flux from nanodust to large bodies near 1 AU

Cassini RPWS

Nanodust

Model (dust) Grün et al. 1985

Model (small bodies) Ceplecha et al. 1998

a = 10 nm

a = 5 km

10^{-13}

10^{11}

10^{9}

10^{7}

Solar radio emissions

Nanodust Impacts

Limited surface larger than STEREO by factor of 10

SC frequency (kHz) 10

[Le Chat et al. 2013]

nanodust impacts

[Zaslavsky et al. 2012]
Open questions

- Size distribution? smallest nanoparticle?
  - may be determined by electrostatic disruption
  
  \[ E = \frac{q^2}{a^2} \]
  
  disruption if electrostatic stress \( \varepsilon E^2 > \) tensile strength \( S \)
  
  \( a_{\text{min}} > 1 \text{ nm} \) if tensile strength \( S < 10^9 \text{ N/m}^2 \)
  
  \( S \) badly known for nanodust (uncertain transition between microscopic & macroscopic)

- Composition & physical structure?

Beware of nanodust particles

- Ubiquitous
- Physical properties different
- Were detected serendipitously in most environments ...

Will crop up when you don’t expect them

With thanks to the International Space Science Institute, and

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- Peter Wurz
- Arnaud Zaslavsky

Supplementary material

What are they?

- The size may determine the structure

\[ \begin{align*}
\text{Number of atoms or molecules} & \\
\text{Radius (nm)} & \\
10^3 & \\
10^2 & \\
10 & 0.5 \quad 1 \quad 10 \quad 100
\end{align*} \]

- Cluster of \( H_2O \) molecules
- disordered structure
- compact spheres
- Smallest ice crystal
- 90 – 115 K
- 1.3 nm

(Pradzynski 2012)

Note: other plasma scales

- a << L \Rightarrow \text{grain's capacitance } C = 4\pi\varepsilon_0 a
- a << \text{free path} = [n_e r_e^2 \ln(1/\Gamma)]^{1/2}

In general

Plasma coupling parameter

1 nm

[H_2O clustering on ice

Gumbel & Megner 2009]

Energetic preference for condensation

G_0 = 4\pi a^2 N k_B T \ln(S)

\sim a^3

Nucleation: charged grain attracts molecular dipoles \rightarrow decreases free energy

Coulomb term

Energy to form surface

Can suppress barrier of potential

Examples of trajectories [Soraya Belheouane PhD Thesis]

Projective perpendicular to solar equatorial plane

\[q/m = 10^8 e/m_p\]

\[w_{gyr} = qB/m\]

Larmor frequency

\[\Phi/a \sim 10^9 V/m\]

Field emission limit

Ejected electron near surface of grain of charge Ze < 0 subjected to electric field amplitude \[(Z+1) e / 4\pi\varepsilon_0 a^2\]

Limiting electric field for (electron) field emission: \[\Phi/a \sim 10^9 V/m\]

Maximum number of electrons on a nanograin:

\[|Z_{MAX}| \sim 1 + 0.7 a^2_{(nm)}\]
**Electric charging in dusty plasmas**

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

\[ L_D = \left[ \frac{4 \pi}{\pi} r_L (n_e+n_i)^{1/3} \right]^{1/2} \]

Densities inside dusty plasma

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

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

\( P \neq \text{"Alfvén parameter" which refers to } n_b \text{ outside a "dust cloud" [Havnes1987, 1989; Goertz 1989]} \)

**Density measurement with QTN**

- Measurement of frequency
- Limitation: frequency resolution of receiver
- Requires antenna length \( L > L_D \) (since Langmuir wavelength \( \gg L_D \))

Meyer-Vernet and Perche (1989) J. Geophys. Res. 94 2405

**Temperature measurement with QTN**

\[ V_T^2 = \frac{d^2}{2 \pi^2 c^2} \int d^3 k F(k) \frac{d^3 \sigma f_V (\omega) k (\omega k + \omega) \nabla |k|}{|k|^2 |k(\omega k + \omega)|^2} \]

\( F(k) \) depends on antenna geometry for example if wire dipole antenna \( k \times x \):

\[ F(k) = \left( \frac{4 \pi^2 \sigma f_V (\omega) \omega k}{k^2} \right)^2 \]

Meyer-Vernet et al. (1998) AGU Monograph 103 205

**Velocity distributions**

- Suprathermal particles are collisionless
- Non-thermal processes \( \Rightarrow \) Kappa-like velocity distributions should be ubiquitous in space plasmas
Fast (∼300 km/s) nanodust streams
- accelerated by corotation electric field of Jupiter
  \[ \text{[Zook et al. 1996]} \]

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

Original results from calibration
\[ \text{From dynamics, } \begin{array}{l}
V \sim 20-56 \text{ km/s} \\
V \sim 200 \text{ km/s} \\
V \sim 200 \text{ km/s}
\end{array} \]
\[ \begin{array}{l}
m \sim 10^{-19} - 10^{-16} \text{ kg} \quad \text{[Grün et al. 1992]} \\
m \sim 10^{-21} \text{ kg} \quad \text{[Zook et al. 1996]} \\
m \sim 10^{-21} \text{ kg} \quad \text{[Krüger 2003; Hsu et al. 2012]} \\
\end{array} \]

closed field lines ⇒ ejection requires \( r_{\text{gyr}} > B \) scale