Detection of nanodust in the solar system

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What are they?

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

• 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?

- **Nano particles**
  - 100 nm
  - 10 nm
  - 1 nm

- **Bulk matter**
  - 0.1 µm

- **Molecules**
  - 1 Å

**Macromolecule or nano grain?**

- Polycyclic Aromatic Hydrocarbons: ≥ C_{2n}H_{14}
- Fullerenes: C_{60} → C_{400}
- Nanotechnology
- Biology
- Insulin
- Graphene

**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 decreases in surface energy

**What makes them different?**

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

- **Size smaller than basic scales**

  - Electron free path in solids
    
    - For $E < 100$ eV
      
      \[ \sim 1 \text{ nm} \]
    
    - Atomic scale: $2 r_B$

  - Electron secondary emission increases
    
    [Draine & Salpeter 1979; Chow et al. 1993]

  - Electron sticking coefficient decreases if $a \lesssim l_e$

  - Photons 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)

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

  - Photon escape length $l_e \sim 0.5 - 5$ nm
    
    - Size smaller than basic scales

  - Plasma Landau radius
    
    \[ r_L = \frac{e^2}{4\pi \varepsilon_0 k_B T} \]
    
    - If $a \lesssim r_L$, dipole induced by an approaching charge strongly curves its trajectory
    
    - Increases plasma currents

    \[ r_{L \text{ nm}} = 1.4 \sqrt{T_{eV}} \]
    
    - 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 $\propto (q/a^2)^2$
    
    - Makes grain explode
    
    - May determine minimum size

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Basics of electric charging in space

**PLANETS (dense plasmas)**

**SOLAR WIND**

- 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**

- If $P > 1$, Debye sheaths overlap → plasma electrons depleted → reduces grain’s charge
- If $P >> 1$: $Z \sim a^{-2}$
- Limiting electric field for (electron) field emission: $\Phi/a \sim 10^9 \text{ V/m}$

**Electric charging in space dust plasmas**

- Long charging time scales:
  - $\tau \sim RC \sim (dI/d\Phi)^{-1} \sim \mu^{-1}$ if $a > \lambda_L$
  - $\tau \sim (2\sigma a)^{3/2} \lambda_L^{1/2} J_e^{-1}$ if $a < \lambda_L$

- 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:
    
- Important limitations for nanodust

- Maximum number of electrons on a nanograin:
Charging in cold dusty space plasmas

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 $|Z| \approx \eta a/r_L \gg 1$
   → statistical treatment: $f(Z) J_i(Z) = f(Z+1) J_e(Z+1)$
   [Draine & Sutin 1987] deduce moments, as:
   average charge state: $<Z> = \sum Z f(Z)$
   $f$ is probability for charge state $Z$

Average number of charges on a grain

$<Z> \sim 1$

$<Z> \approx 1$

Nanodust: $a \leq r_L \approx 1.4/T(eV)$ nm

Two major consequences:

Average number of charges on a grain

$<Z> \neq a$

Because proba. that uncharged grain collects an electron
$> proba.$ that neutral or negatively charged grain collects an ion

Charging in cold dusty space plasmas

Interstellar nanodust cannot enter the heliosphere

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

Gyroradius: $r_{gyr} = |(v-V_{plasma})/\omega_{gyr}|$

$\omega_{gyr} \sim m/q$

Interstellar nanodust cannot enter the heliosphere

Nanodust produced in the solar system

Charging in cold dusty space plasmas

Approximation neglecting field emission

Nanograins have large charge-to-mass ratios

Example: for $a = 5$ nm, $q/m = 10^4 e/m_p$ in the solar wind

$\propto a$ (or $=-e$) $m \propto a^3$ (if compact)

Charge to mass ratio: $q/m \propto a^2$ or $a^3$

Nanodust produced in the solar system

$<Z> \neq a

$H_3^{+}$ ions

$<Z> = 1$

$e/m_i = 1$

$e/m_i = 0.1$

$e/m_i = 0.01$

$3.6 a/r_L$

$10^2$ $10^3$ $10^4$ $10^5$

$10^{-2}$ $10^{-1}$ $10^0$ $10^1$ $10^2$

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Heliosphere

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

$B_{gyr}$不得进入日球层

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Heliosphere
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
  \[ r_{gr} < B \text{ scale} \]
  \[ \rightarrow \text{Nano dust picked-up & accelerated} \]

\[ \text{[Mann et al. 2007, Czekowski & Mann 2010, 2012]} \]

• Solar wind

1 AU

\[ \text{V}_{SW} \]

\[ \text{SUN} \]

\[ \text{B} \]

\[ \text{V}_{\text{rot}} \]

Dynamics in magnetized space plasmas

Nanodust produced in planetary environments

- Rotating planetary magnetospheres
  \[ \text{V}_{\text{rot}} = \Omega \times r \]

Lorentz force: \[ \text{F}_{E} = q(\text{v}-\text{V}_{\text{rot}}) \times \text{B} \]
  outwards for Jupiter & Saturn if \( q > 0 \)
  Grains are accelerated and ejected at speed:
  \[ \text{v}_{ej}^2 \approx \left( \frac{\text{MG}}{r_0} \right) \left[ \frac{2 \text{F}_{E}}{\text{F}_{\text{grav}}} \right]^{-1} \]
  \[ \text{[Hamilton & Burns 1983, Burns et al. 2001]} \]

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

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 10^4/cm^3

\[ \text{Rapp & Thomas 2006} \]

\[ \text{Temperature (K)} \]

\[ \text{N. Meyer-Vernet - 41st EPS Conference on Plasma Physics - Berlin 2014} \]
**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 $a > 20$ 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. Rees & Lubken 2004]

**Peak in $n_d$**

![Graph of peak in $n_d$](image)

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

5 km


How are they detected in situ? in situ detection with WAVE instrument!

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]

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

Stereo wave noise (QT noise)

Power spectrum:
peak at the plasma frequency (~ n_e)
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]

Example: Ulysses in the solar wind

How are they detected in situ via waves?

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

Impact of fast dust particle

Vaporized & ionized produces expanding plasma cloud

Released charge Q ~ m * 3^0.5

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

 released charge Q = \frac{Q}{C}

Spacecraft capacitance

Electric antenna Wave receiver

Time t
How are they detected \textit{in situ} via waves?

**STEREO/WAVES at 1 AU**

- Electric pulses produced by destabilization of photoelectrons surrounding antenna

- **Two different wave instruments:**
  - time domain sampler (TDS)
  - frequency receiver (LFR)

- **[Pantellini et al. 2012, 2013]**

- **nanodust impacts**

- **[Zaslavsky et al. 2012]**

- **Time (ms)**

- **[Le Chat et al. 2013]**

- **Frequency (kHz)**

- **10**

**How are they detected \textit{in situ} via waves?**

- **Cassini RPWS**

- **1 AU**

- **Solar radio emissions**

- **SC surface larger than STEREO by factor of 10**

- **[Schippers et al. 2014]**

**Flux from nanodust to large bodies near 1 AU**

- **Saturn**

- **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
Open questions

- Size distribution? **smallest nanoparticle?**
  - E = q/a^2
  - May be determined by electrostatic disruption
  - Disruption if electrostatic stress E^2 > tensile strength S
  - a_{min} > 1 nm if tensile strength S < 10^9 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

Supplementary material

What are they?

- The size may determine the structure

<table>
<thead>
<tr>
<th>Cluster of H_2O molecules</th>
<th>Smallest ice crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>disordered structure</td>
<td>1.3 nm</td>
</tr>
<tr>
<td>90 – 115 K</td>
<td></td>
</tr>
</tbody>
</table>

- Number of atoms or molecules
- Graphite
- Si
- Ice
- compact spheres

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**[Pradzynski 2012]**