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 D[i], Umea University, Sweden*

41st EPS Conference on Plasma Physics
Berlin 2014
(invited paper)

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

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?

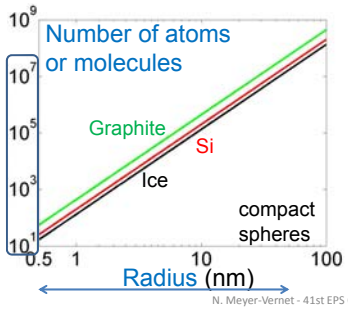
➢ **Original definition of a nanoparticle:** a particle that consists of a countable number of atoms

What are they?

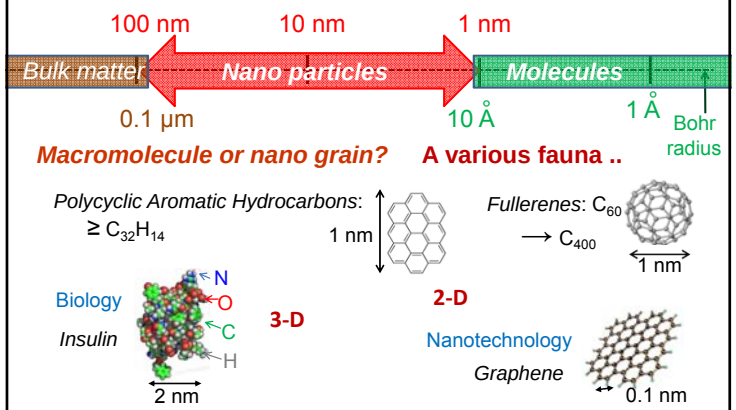
➢ Size

International Council of Chemical Associations

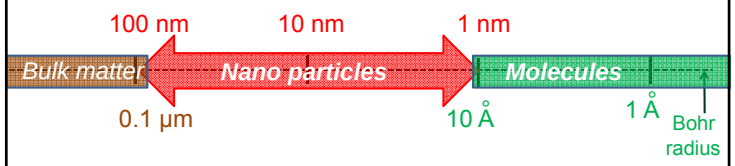
ISO TS 27687 Nano-object: has at least one external dimension between 1 and 100 nm



What are they?



What makes them different?



Transition between molecular and bulk properties

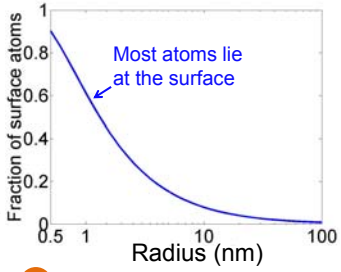
- ***Consensus on nanoparticles:* their properties are different from those of bulk material**

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?

- *Size smaller than basic scales*

✓ **De Broglie wavelength** $\hbar/m_e v$
(Quantum confinement)

Heisenberg: $\Delta x\, \Delta p = h/2\pi$

electron confined in nanograin of radius a:

$\Delta x \sim a \rightarrow$ momentum: $\Delta p = h/(2\pi a)$

→ confinement energy: $E_0 \sim \Delta p^2/2m_e$

Affects optical & electrical properties when $E_0 \gtrsim k_B T$ [e.g. Li 2004]

Equivalent to $a \lesssim \hbar/m_e v$ with $v \sim (k_B T/m_e)^{1/2}$

⇒ Concerns nanodust if T < 300 K

What makes them different?

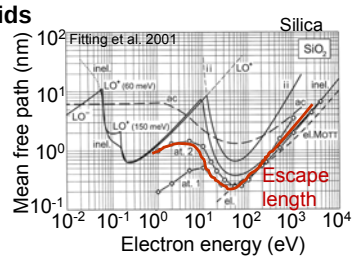
- *Size smaller than basic scales*

✓ **Electron free path in solids**

~ 1 nm

for E < 100 eV

atomic scale: 2 r_B ⟶



→ **electron secondary emission increases**
[Draine & Salpeter 1979; Chow et al. 1993]

→ **electron sticking coefficient decreases** if $a \lesssim l_e$

What makes them different?

- *Size smaller than basic scales*

✓ **Photon scales**
- Photon attenuation length ~ 10 – 100 nm
  ≫
- Photoelectron escape length l_e ~ 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:

~ work function + $(3/8)\,(e^2/4\pi\varepsilon_0 a)$
[Wong et al. 2003] Image charge contribution

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

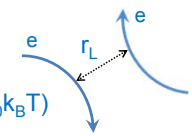
What makes them different?

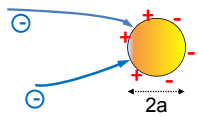
- *Size smaller than basic scales*

✓ **Plasma Landau radius**

$e^2/(4\pi\varepsilon_0 a r_L) = mv^2/2$ ➡ $r_L = e^2/(4\pi\varepsilon_0 k_B T)$

Coulomb energy — kinetic energy





→ If $a \lesssim r_L$, dipole induced by an approaching charge strongly curves its trajectory
→ increases plasma currents

$r_{L\,nm} = 1.4 / T_{eV}$

➡ Concerns nanodust if T < 2 eV

What makes them different?

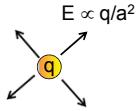
- *These effects change their electric charge in plasmas*
- *Their electric charge plays a major role*

➢ Dynamics and pick-up in magnetized plasmas

B

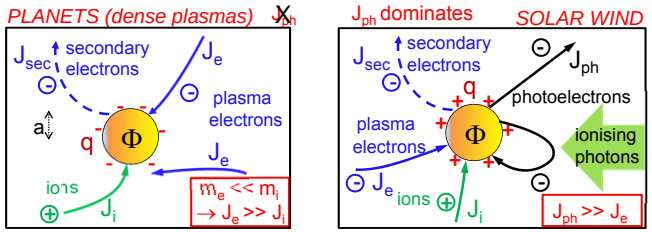
➢ Dusty plasma effects

➢ Electrostatic disruption: stress $\propto (q/a^2)^2$



→ makes grain explode
→ may determine minimum size

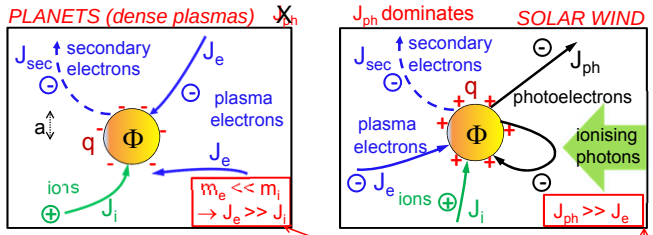
Basics of electric charging in space



Q: grain's charge; Φ: grain's potential relative to ambient plasma

- 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

Basics of electric charging in space



- At equilibrium: potential energy = a few times kinetic energy of dominant charging particles ➡ $|e\Phi| \approx \eta\, k_B T$
- Charge: $q \approx 4\pi\varepsilon_0 a \Phi$ ➡ $|Z|=|q/e| \approx \eta\, a/r_L$

capacitance of a sphere

$\eta \sim 1$ (order of mag.) determined by details of charging processes

$e^2/(4\pi\varepsilon_0 k_B T)$

T_e or T_{ph} — a few eV

if $|Z| >> 1$, i.e. $a > r_L$

Electric charging in space **dusty** plasmas

n_d grains/m^3 ; n_e (n_i) electrons (ions)/m^3

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

$\Delta r \sim n_d^{-1/3} >> a$

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

$P = 4\pi\, n_d\, a L_D^2$

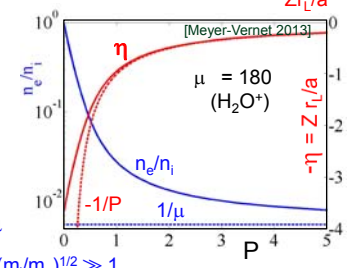
- If P > 1, Debye sheaths overlap
  → plasma electrons depleted
  → reduces grain's charge

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

- If P >> 1: $Z \sim -a/(P\, r_L) << 1$
  limit to el. depletion: $n_e/n_i \sim 1/\mu$

[Mendis & Rosenberg, 1994; Mendis 2002]

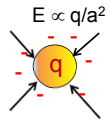
$\mu = (s_e/s_i)(v_{the}/v_{thi}) \sim (m_i/m_e)^{1/2} \gg 1$



Electric charging in space

➢ Important limitations for nanodust

- **Long charging time scales**:
  $\tau \sim RC \sim (dI/d\Phi)^{-1}C \sim [4\pi a r_L J/e]^{-1}$ if $a > r_L$
  $\tau \sim [(2\pi a)^{3/2}\, r_L^{1/2}\, J_e]^{-1}$ if $a < r_L$
- **Field emission limits negative charge**:



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

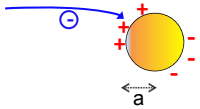
➡ Maximum number of electrons on a nanograin:

$|Z_{MAX}| \sim 1 + 0.7\, a^2_{(nm)}$

Charging in **cold** dusty space plasmas

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

Two major consequences:



1. Approaching charges are strongly attracted by induced dipole

   Potential energy $e^2/(4\pi\varepsilon_0 a) \gtrsim k_B T$

   → 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: $\langle Z \rangle = \sum Z\, f(Z)$

probability for charge state Z

Charging in **cold** dusty space plasmas

⇒ **Average number of charges on a grain**

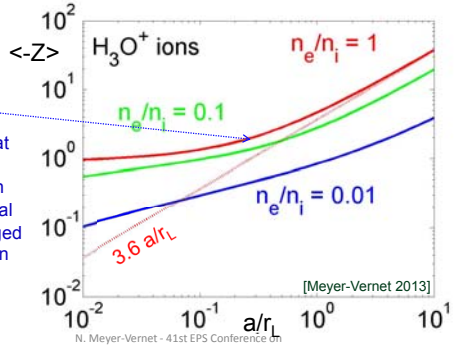
Approximation neglecting field emission

no longer proportional to grain size

$\langle Z \rangle \not\propto a$

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

(if J_{ph} negligible)



Charging in **cold** dusty space plasmas

Average number of charges on a grain

Z_{MAX} due to field emission limit

T = 0.3 eV T = 1 eV

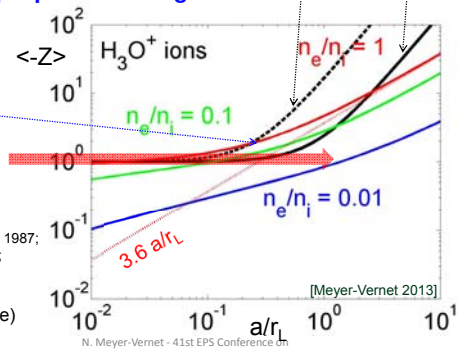
no longer proportional to grain size

$\langle Z \rangle \not\propto a$

$\langle -Z \rangle \approx 1$

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

(if J_{ph} negligible)



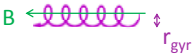
⇨ $q \propto a$ (or = -e) $m \propto a^3$ (if compact)

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

Nanograins have large charge-to-mass ratios

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

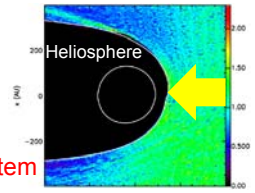
⇒ Lorentz force plays a major role



Charged grains follow magnetic field lines if $r_{gyr} <$ B scale

Gyroradius: $r_{gyr} = |(v - V_{plasma})_\perp| / \omega_{gyr} \propto m/q$

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



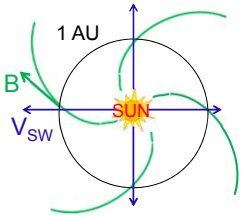
⇒ *Interstellar nanodust cannot enter the heliosphere*

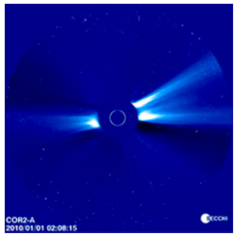
⇒Nanodust produced in the solar system

Dynamics in magnetized space plasmas

Nanodust produced in inner solar system where dust concentration is large

✓ **Solar wind**





- B: Parker spiral
- For nanodust: Lorentz force >> gravitational force

r_{gyr} < B scale

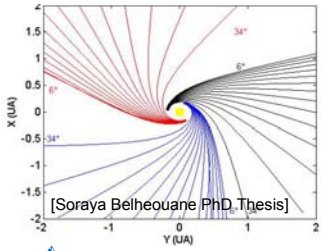
→ Nano dust picked-up & accelerated
[Mann et al. 2007, Czekowski & Mann 2010, 2012]

Dynamics in magnetized space plasmas

Nanodust produced in inner solar system where dust concentration is large

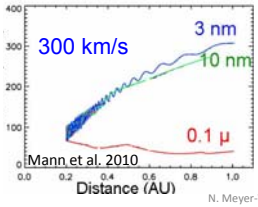
✓ **Solar wind**

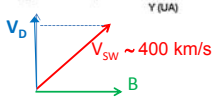
Nano grains trajectories projected in solar equatorial plane



Nanograins accelerated to plasma drift velocity:

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



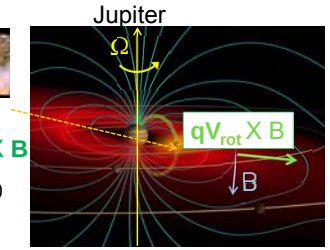


⇒ nanodust speed at 1 AU
~ $V_{SW}/2^{1/2}$ ~ 300 km/s for a ≲ 10 nm

Dynamics in magnetized space plasmas

Nanodust produced in planetary environments

✓ **Rotating planetary magnetospheres**



$\mathbf{V_{rot}} = \mathbf{\Omega} \times \mathbf{r}$

Lorentz force: $F_E = q(v - V_{rot}) \times B$

outwards for Jupiter & Saturn if q > 0

Grains are accelerated and ejected at speed:

gravitational attraction

$v_{ej}^2 \sim (MG/r_0)[2\, F_E/F_G - 1]$ [Hamilton & Burns 1993, Burns et al. 2001]

acceleration starts

⇒ nanodust speed ~ 300 km/s for a ≈ 10 nm

How and where are they **detected** *in situ*?

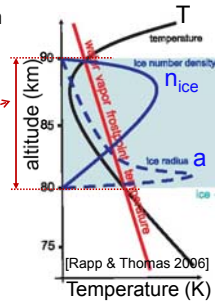
➢ **Planetary environments**

o 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 $10^3/cm^3$



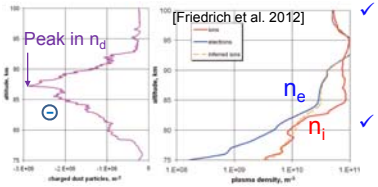
How and where are they detected *in situ*?

➢ **Planetary environments**

o 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 - 10^3MHZ) [e.g; Rapp & Lübken 2004]

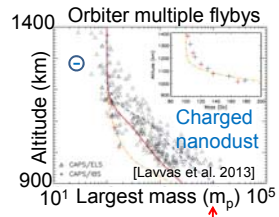
How and where are they detected *in situ*?

➢ **Planetary environments**

Farther out ..

o Titan atmosphere

[Coates et al. 2007, 2009]



Radius a ~ 1.6 nm if ρ ~ 10^3 kg/m^3

a ~ 16 nm if ρ ~ 1 kg/m^3

Cassini/CAPS (Plasma Spectrometer)

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

How and where are they detected *in situ*?

➢ **Planetary environments**

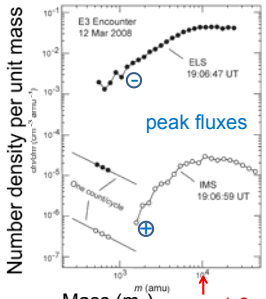
o Enceladus plume

[Jones et al. 2009]

Cassini/CAPS (Plasma Spectrometer)

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

[Hill et al. 2012]



Mass (m_p) with q = ± e

a ~ 1.6 nm (ice)

How and where are they detected *in situ*?

➢ **Planetary environments** (and farther out)

o Fast (~300 km/s) nanodust streams

▪ accelerated by corotation electric field of Jupiter [Zook et al. 1996]

▪ … and Saturn [Kempf et al. 2005]

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 ~ 10^{-21} kg at 10^6 km from nucleus of Halley [Utterback & Kissel 1990 Sagdeev 1985, 1989]

How and where are they detected *in situ*?

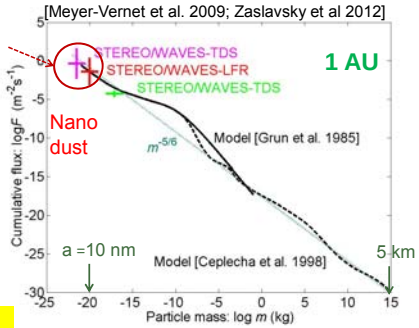
➢ **Interplanetary medium**

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]

[Meyer-Vernet et al. 2009; Zaslavsky et al 2012]



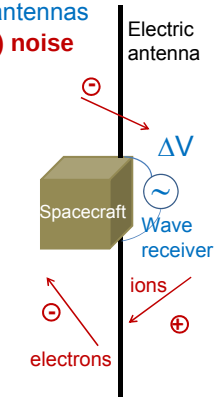
In situ detection with WAVE instrument! designed to study solar radio emissions

How are they detected *in situ* via waves?

Context: passing-by **plasma particles** produce electric potential fluctuations detected by electric antennas [Meyer-Vernet 1979] **= plasma quasi-thermal (QT) noise**

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

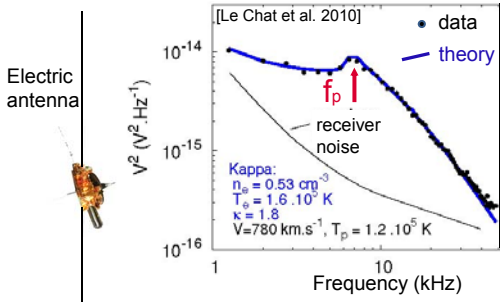
➡ Wave instruments on space missions measure plasma properties via spectroscopy of plasma QT noise [Meyer-Vernet et al. 1998]

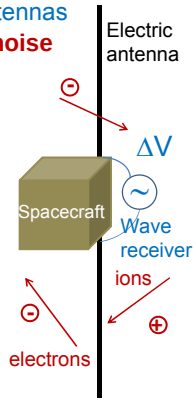


How are they detected *in situ* via waves?

Context: passing-by **plasma particles** produce electric potential fluctuations detected by electric antennas [Meyer-Vernet 1979] **= plasma quasi-thermal (QT) noise**

Example: **Ulysses** in the solar wind ⇒ f_p, T_e, κ





How are they detected *in situ* via waves?

Impact of fast dust particle

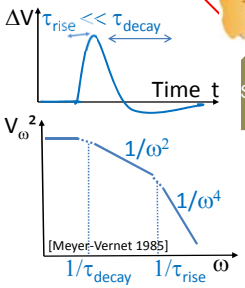
Vaporized & ionized produces expanding plasma cloud

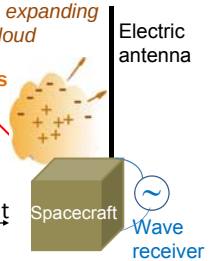
Released charge Q ∝ m v$^{3.5}$

⇒ **10 nm grain at 300 km/s produces 10^7 electrons**
similar charge as 0.2 μm grain at 20 km/s

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

… and ***power spectral density***

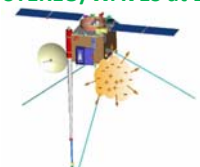




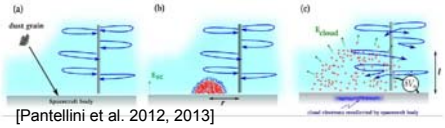
ΔV = Q/C
↑
Spacecraft capacitance

How are they detected *in situ* via waves?

STEREO/WAVES at 1 AU



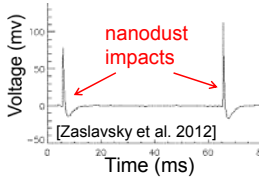
Electric pulses produced by destabilization of photoelectrons surrounding antenna



[Pantellini et al. 2012, 2013]

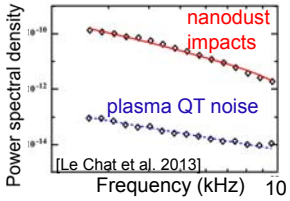
Two different wave instruments:

- time domain sampler (TDS)



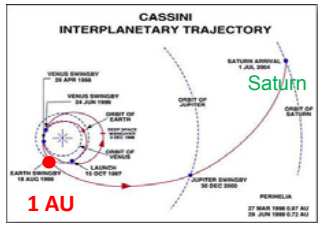
[Zaslavsky et al. 2012]

- frequency receiver (LFR)



[Le Chat et al. 2013]

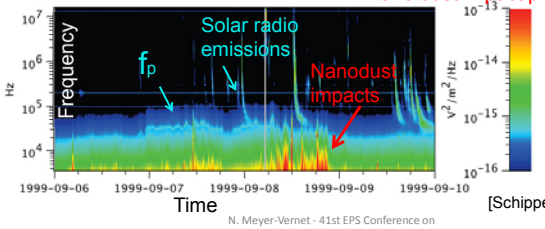
How are they detected *in situ* via waves?



Cassini RPWS

10 m

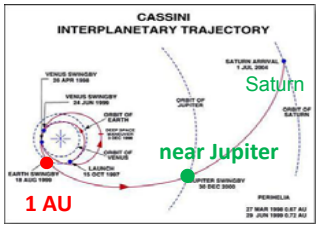
Electric pulses produced by recollection of electrons of the nano dust impact plasma



SC surface larger than STEREO by factor of 10

[Schippers et al. 2014]

How are they detected *in situ* via waves?

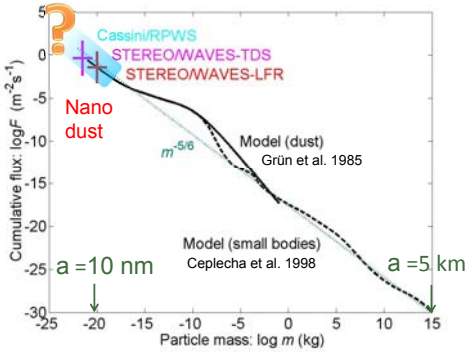


Cassini RPWS

10 m

- ✓ 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

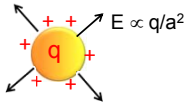
Flux from nanodust to large bodies near 1 AU



Open questions

- Size distribution? smallest nanoparticle?

may be determined by electrostatic disruption



disruption if electrostatic stress $\varepsilon_0 E^2$ > tensile strength S

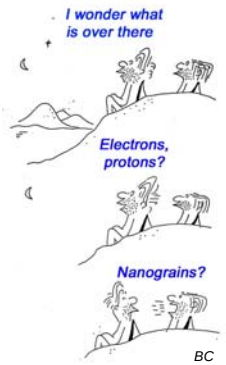
a_{min} > 1 nm if tensile strength S < 10^9 N/m^2

S badly known for nanodust (uncertain transition between microscopic & macroscopic)

- Composition & physical structure?

Beware of nanodust particles

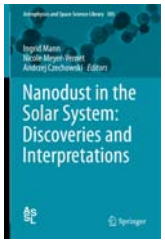
- Ubiquitous
- Physical properties different
- Were detected **serendipitously** in most environments …



Will crop up when you don't expect them

With thanks to the International Space Science Institute, and

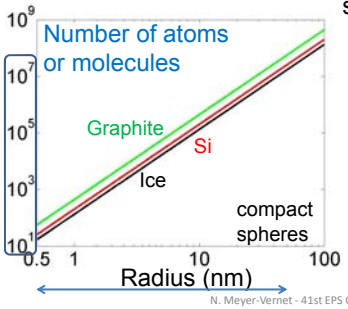
Andrzej Czechowski
Hsiang-Wen Hsu
Geraint Jones
Vasili Kharchenko
Yuki Kimura
Harald Krueger
Nicholas Lewkow
Aigen Li
Frank Postberg
Peter Wurz
Arnaud Zaslavsky



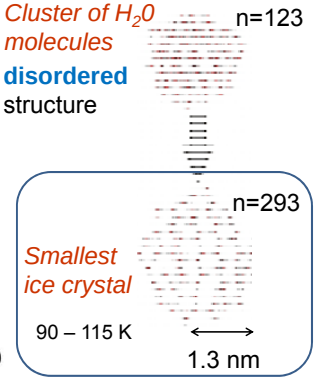
Supplementary material

What are they?

- *The size may determine the structure*



Cluster of H_20 molecules
disordered structure



[Pradzynski 2012]