Detection de nanoparticules dans le milieu interplanétaire

Nicole Meyer-Vernet

[1] LESIA, Observatoire de Paris

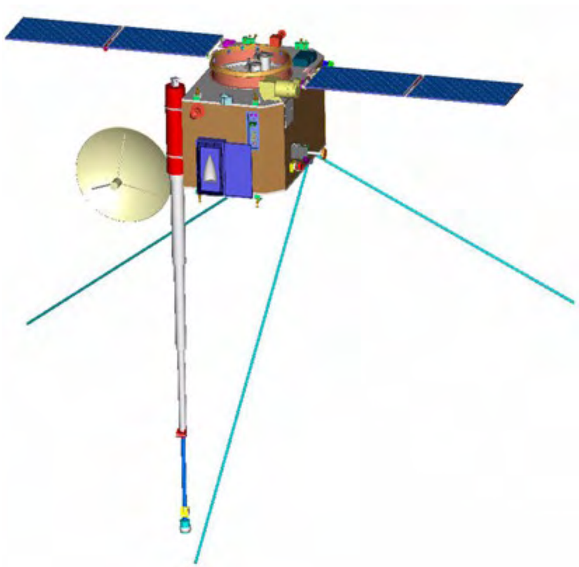
avec: M.Maksimovic[1] , A.Lecacheux[1], K.Issautier[1], G.Le Chat[1], A. Czechowski[2], I. Mann[3], I. Zouganelis[7], K. Goetz[4], M.L. Kaiser[5], O.C. St. Cyr[5], S.D. Bale[6]

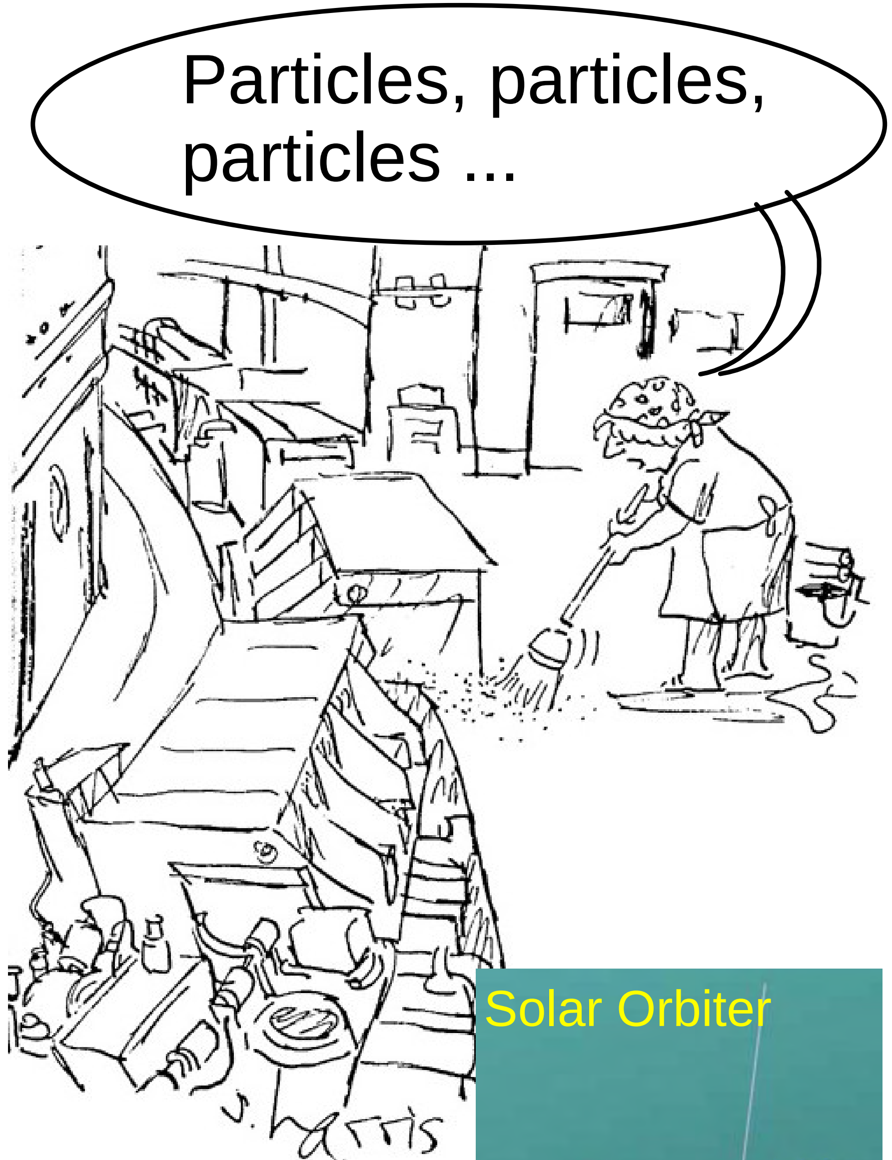
[2] Space Research Centre, Polish Academy of Sciences, Warsaw
[3] School of Science and Engineering, Kindai University Kowakae, Osaka
[4] School of Physics and Astronomy, University of Minnesota
[5] NASA-GSFC
[6] Space Sciences Laboratory, University of California
[7] LPP, UPMC, Ecole Polytechnique

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

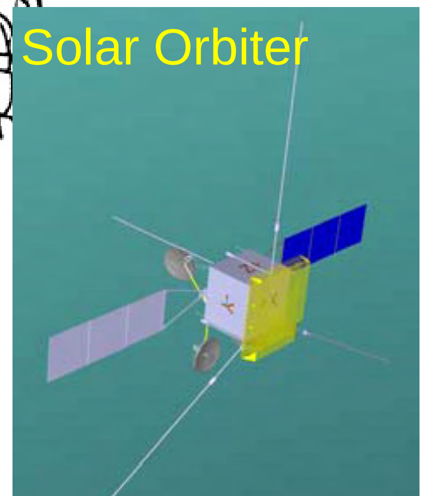
OUTLINE

- Nanoparticules
- Nano-poussières dans l'héliosphère
- Principe de détection avec un instrument "ondes"
  - plasma
  - micro dust
  - nano dust

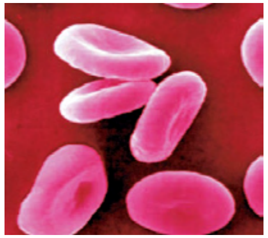




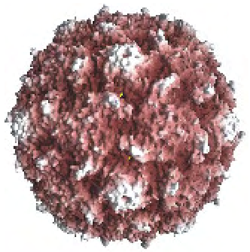
- Detections
- Perspectives



Nanoparticles



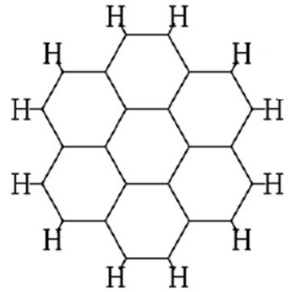
Red blood cells: 7µ



Flu virus 100nm

DNA ~ 2 nm wide

C_{60} - 0.7nm



PAH: $C_{24}H_{12}$

100 nm nanoparticles 1 nm

bulk matter 0.1 µ

Interplanetary medium at 1 AU: $F_{EM}/F_G \sim 2\ 10^4 / a^2_{nm}$

10 Å molecules

ions, electrons PLASMAS

⇒ Lorentz force dominates

Lorentz force negligible

interaction with plasma, magnetic fields, solar wind ions

Lorentz force dominates

Nanoparticles

Transition between dust and molecular ions

★ surface/mass ∝ 1/size ⇒ large surface-to-mass ratio

☞electric charge ∝ size ⇒ **large charge-to-mass ratio**

Lorentz force : $F_{EM} = q\ V \times B \propto a$ (particle size)

Gravitational force : $F_G = m M_\odot G/d^2 \propto a^3$ (for 3-D particles)

⇒ Interplanetary medium at 1 AU: $F_{EM}/F_G \sim 2\ 10^4 / a^2_{nm} > 1$

Radiative force : $F_R = a^2 Q L_\odot / d^2 \propto a^3$ for $a < \lambda$ since $Q \propto a$

$< F_G$

⇒ Lorentz force dominant

⇒ interaction with magnetic field

☞**chemical reactivity** ⇒ interaction with solar wind ions

Nanoparticles

Further consequences of small size:

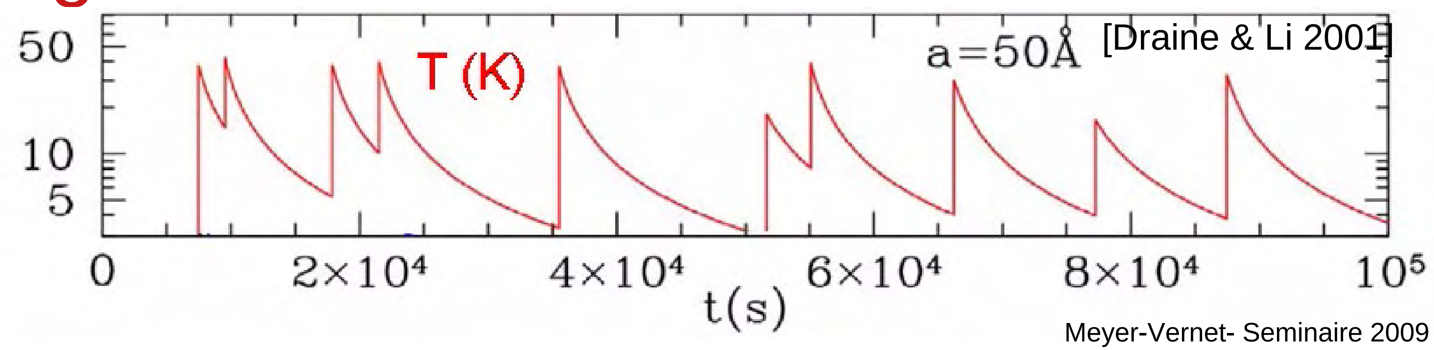
★ quantum effects

$\Delta p \, \Delta r \sim \hbar$

⇒ change optical, magnetic & electrical properties

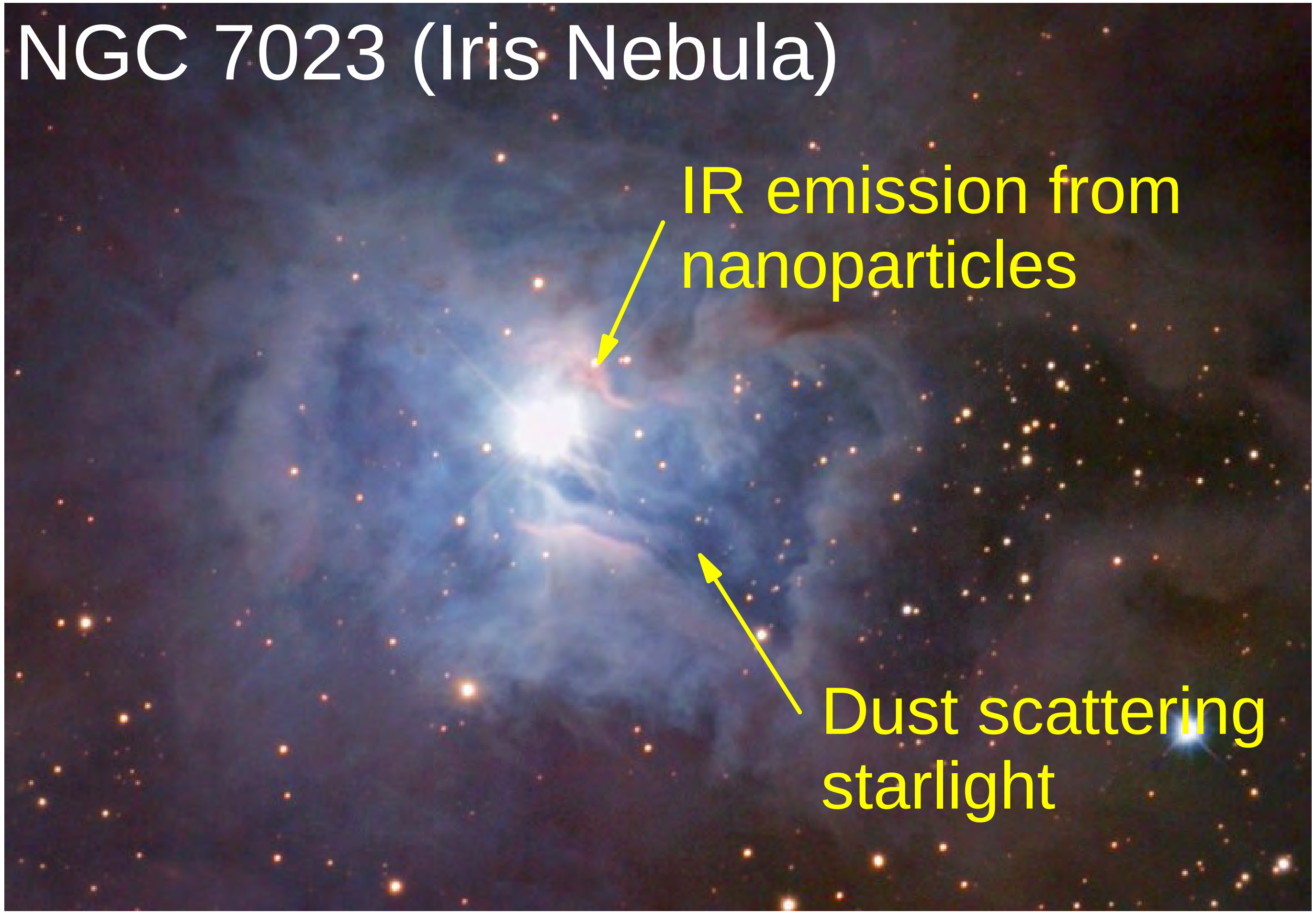
Small heat capacity ⇒ energy of 1 photon $h\nu \sim c \, \Delta T$

⇒ stochastic heating



Astrophysics

➡ Interstellar nanoparticles

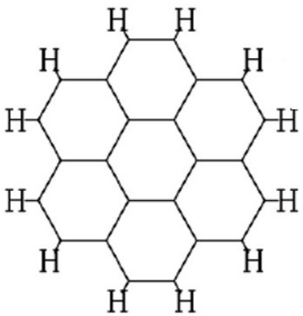


- far UV extinction
  (Weingartner & Draine 2001)

  a< $\lambda/2\pi$ ~10 nm

- IR emission (Sellgren 1984; Léger & Puget 1982, Draine & Li 2001)

  due to stochastic heating ?



PAH ? Nanodiamonds [Jones & d'Hendecourt 2000, Chang et al. 2006] ?

Nanosilicon [Li 2004] ?

- Indirect: photoelectric heating [Weingartner & Draine 2001]

- Nanoparticules
- Nano-poussières dans l'héliosphère
- Principe de détection avec un instrument "ondes"
  - plasma
  - micro dust
  - nano dust
- Detections
- Perspectives

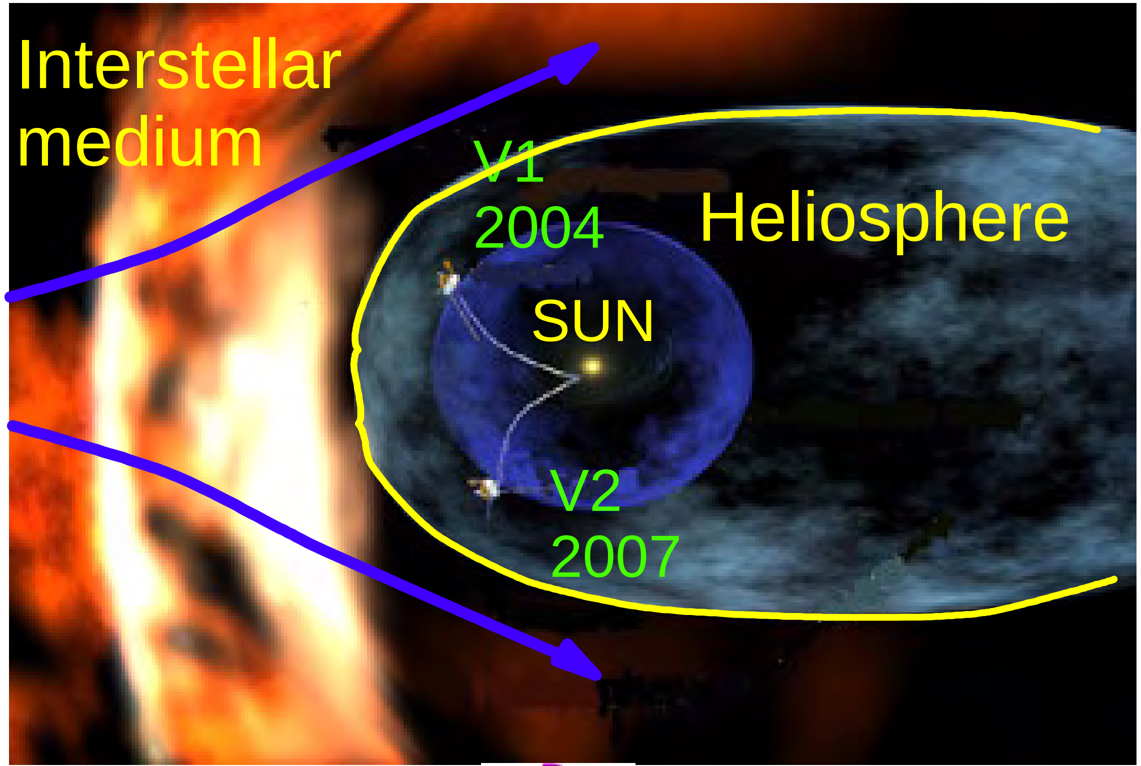
Interstellar nano-dust

in heliosphere?

- Scale of heliosphere:

L ~ 200 AU

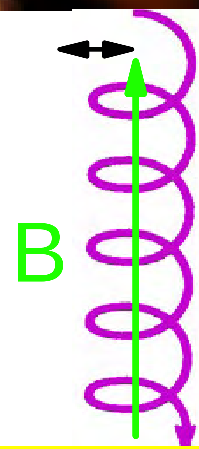
(1 AU = 1.5 10^{11} m)



- electric charge q

⇒Gyroradius in magnetic field B:

mv/qB << L



➡ Interstellar nanodust cannot enter into heliosphere

[Kimura & Mann 1999] except included within larger grains

Interplanetary dust

Detection

- zodiacal light (scattered sunlight)

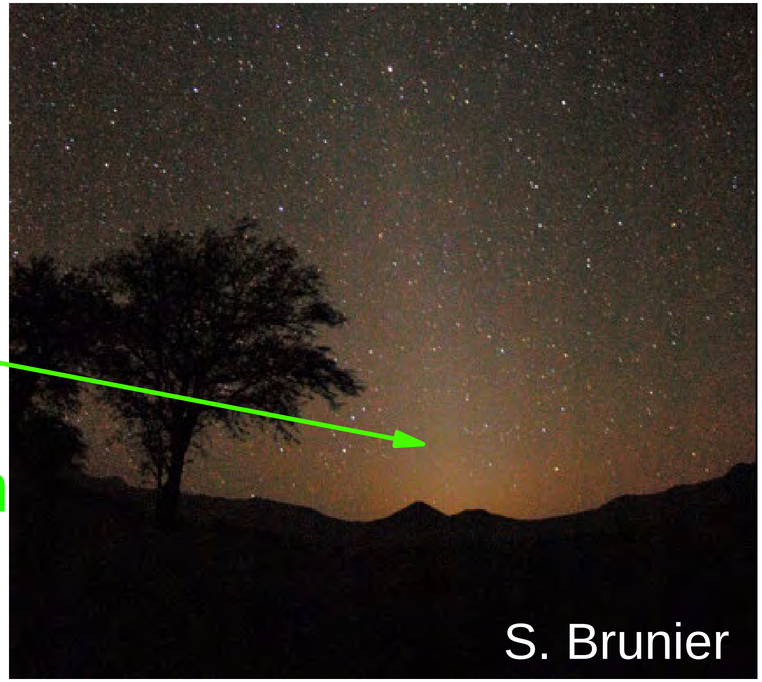
near the Sun: "F-corona"

Fraunhofer lines

$a > \lambda$

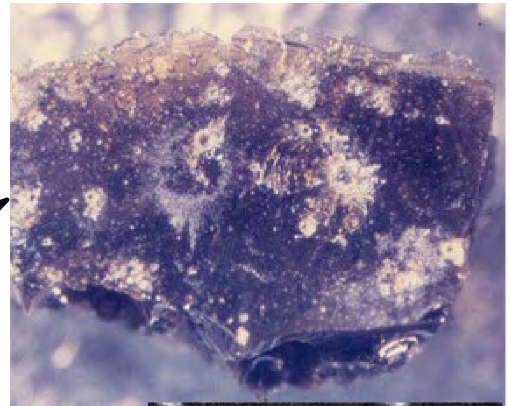
3-300 μm

- IR thermal emission



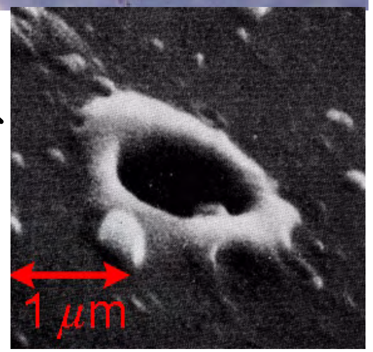
- Meteor trails - optical, radar - > 100 μm

~ 4 10^6 kg/year/on Earth



- Lunar micro craters

10^{-8}-10^{-3} m



- Marine isotope records

~ 4 10^7 kg/year/on Earth

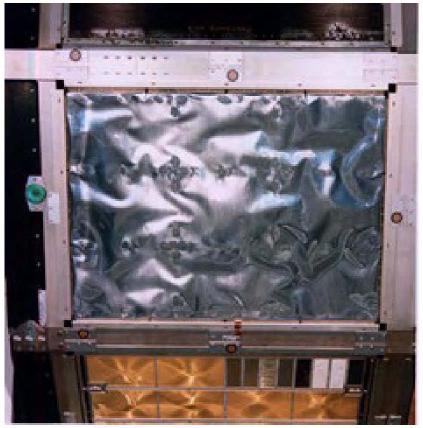
[Peucher-Ehrenbrink 1996]

Interplanetary dust

In situ measurement in space

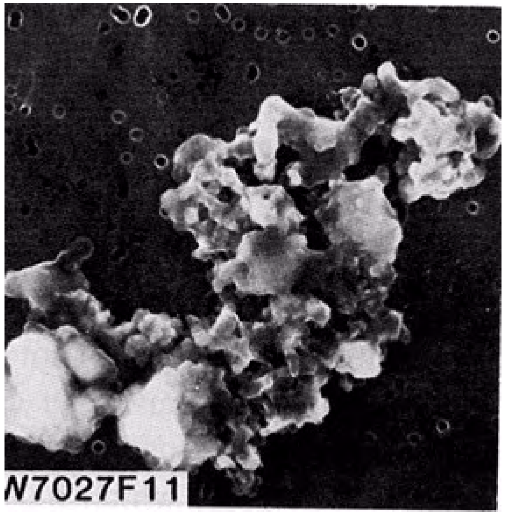
Interplanetary dust

- In situ collection near Earth



LDEF (NASA)

3-100 μm



9 μm × 17 μm

~ 4 10^7 kg/year/on Earth

~100 tons/day

[Love & Brownlee 1993; refs in Mann & al.SSRev 2010]

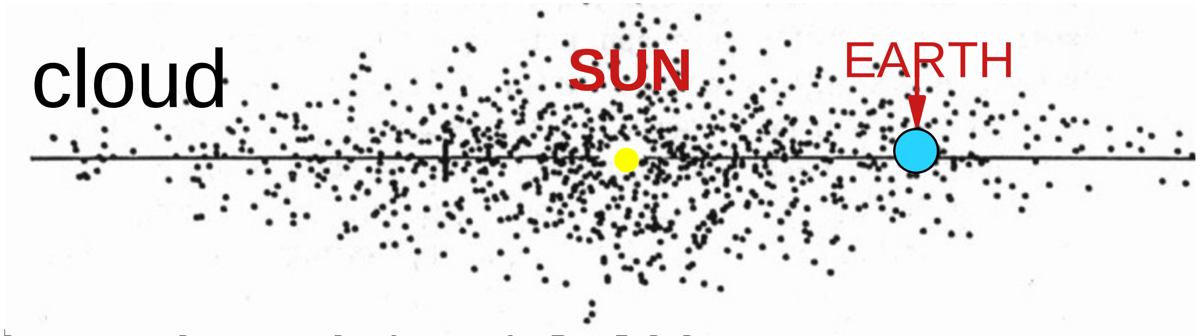
- In situ dust analysers on interplanetary probes
  - ➤ penetration
  - ➤ impact ionisation

0.05-100 μm

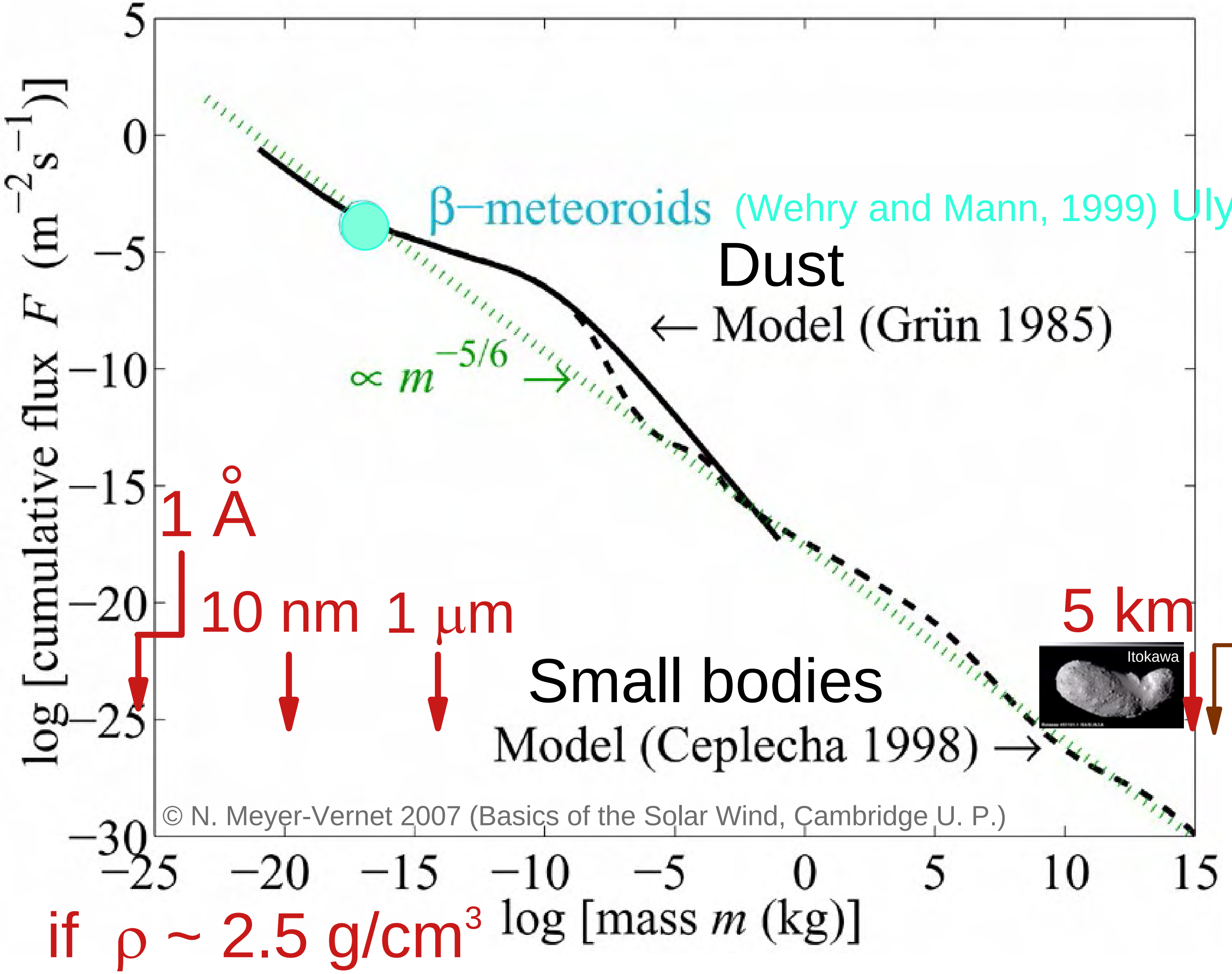
not calibrated for nanoparticles

Cassini- CDA
[Srama 2004]

Interplanetary dust cloud



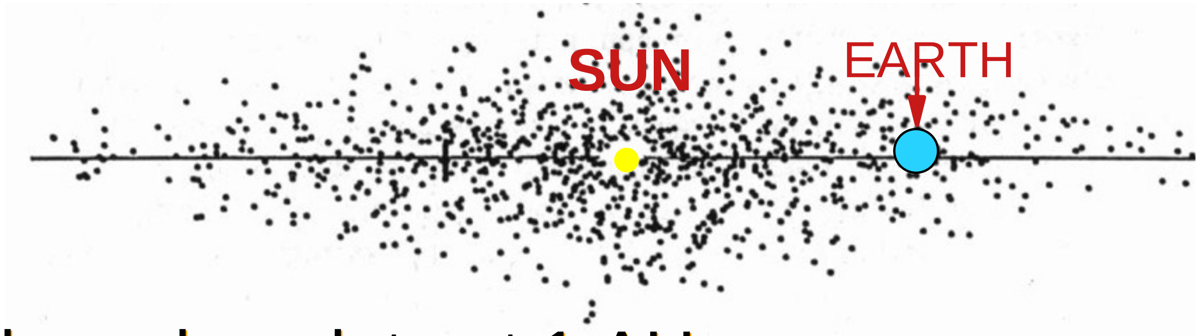
Cumulative interplanetary flux based on data at 1 AU



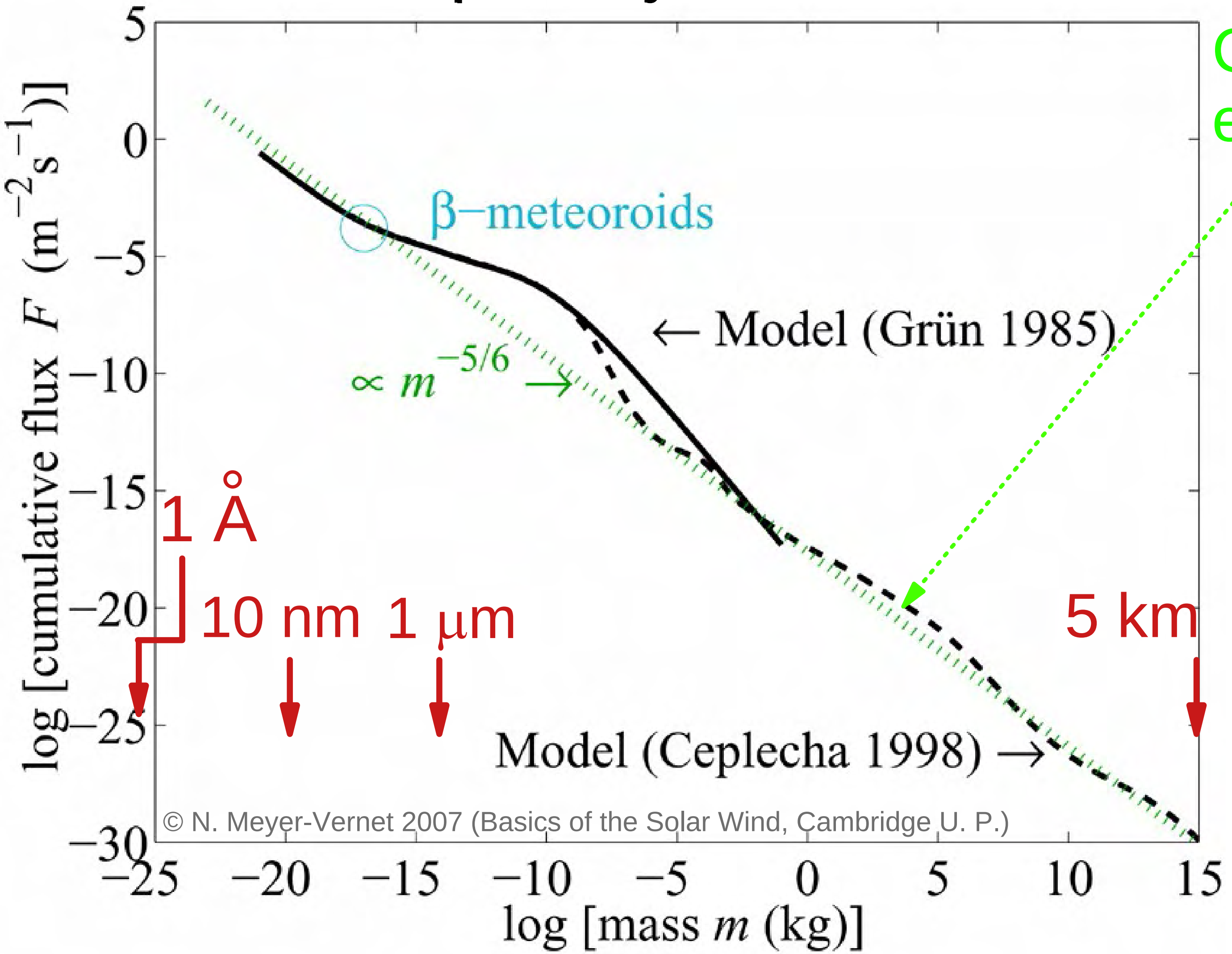
65 millions years

$2\ 10^{-8}$/year on Earth

Interplanetary dust



Cumulative interplanetary flux based on data at 1 AU



Collisional fragmentation equilibrium [Dohnanyi 1969]

Total mass crushed in mass log interval independent on mass

- steeper slope

⇒ less large particles

⇒ yields less small particles

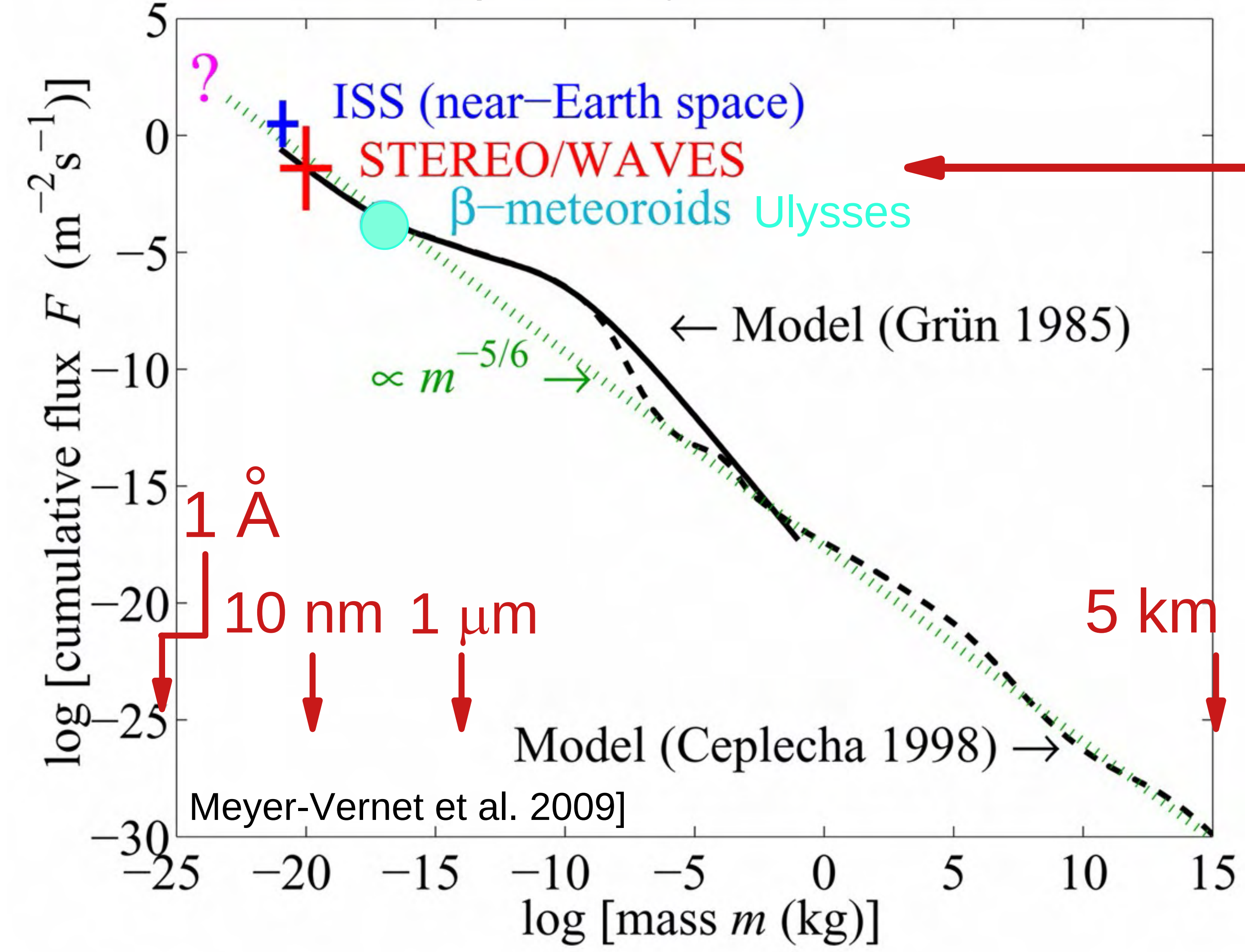
⇒ decreases slope

- smaller slope... the reverse

Note:distribution of fragments $\propto a^{-3.5}$

Interplanetary nano dust

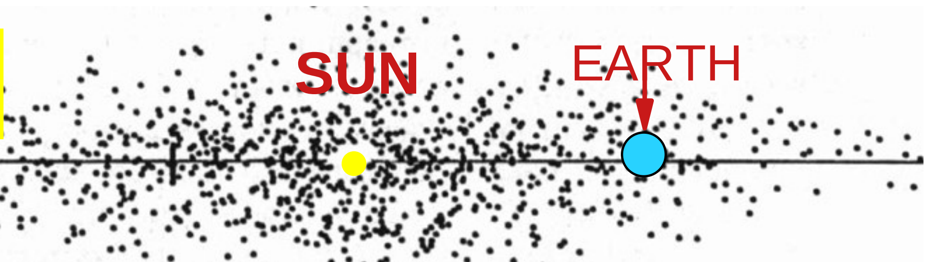
Cumulative interplanetary flux data at 1 AU



Serendipitous discovery 2009

if $\rho \sim 2.5$ g/cm^3

Interplanetary nano dust



First detection not surprising since:

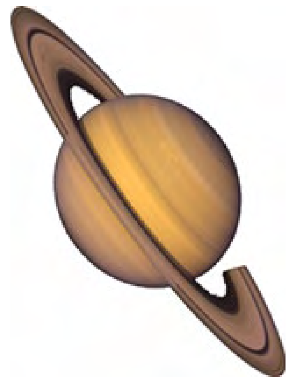
- agrees with collisional fragmentation equilibrium

- predicted from collisional fragmentation in interplanetary dust cloud and dynamics [Mann & al. 2007]

- detected near comets ★ Halley [Utterback & Kissel 1990]

★ PAH's in sample returned by Stardust to comet 81P/Wild2 [Sanford & al. 2006]

and in Tempel2 ejecta? [Lisse et al 2006]



- detected near planets

★ Jupiter [Zook & al. 1996, Krüger & al. 2006]

★ Saturn [Kempf et al. 2005]

- Nanoparticules
- Nano-poussières dans l'héliosphère
- **Principe de détection avec un instrument "ondes"**
  - Detection plasma
  - Detection micro
  - Detection nano rapides
- Detections
- Perspectives

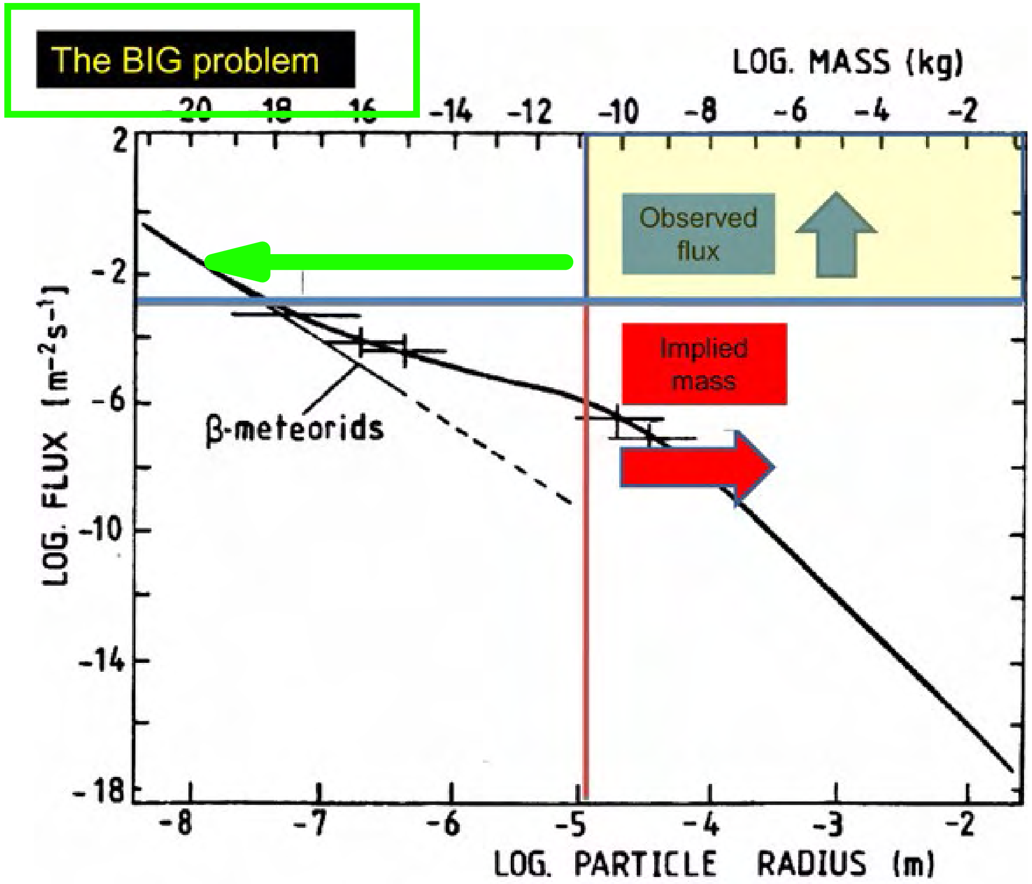
How can wave instruments detect nano dust ?

Preliminary interpretation of STEREO dust [Kaiser et al. 2008]

Observed dust flux exceeds model by factor of 10000 !!

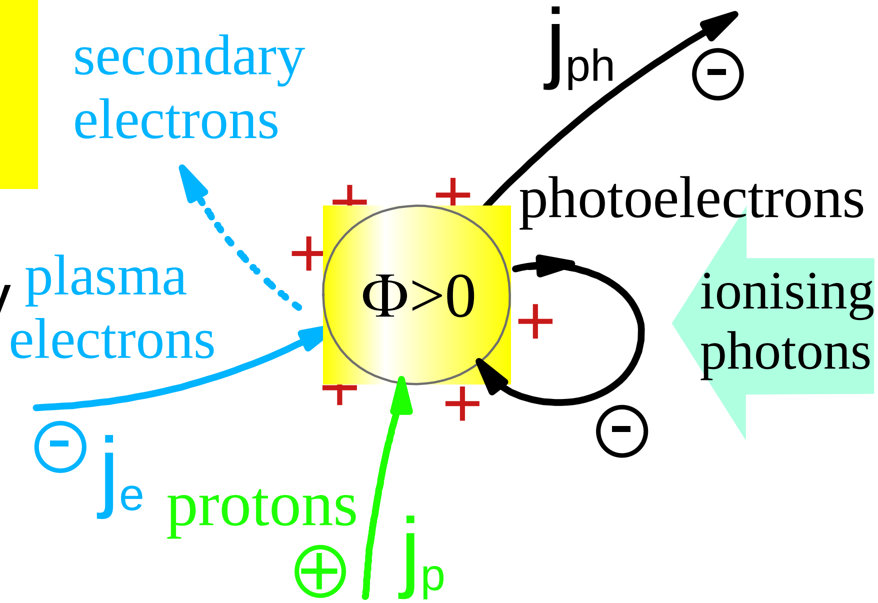
SOLUTION

Same signal with smaller mass IF PARTICLES ARE FAST



1) The importance of being fast

Interplanetary nano dust: large charge-to-mass ratio



- Dust grain potential Φ determined by balance of currents

on uncharged grain: $j_{ph} >> j_e >> j_p$

$\Rightarrow$ charges until Φ binds photoelectrons sufficiently to yield $j_{ph} \sim j_e$

photoelectron energy ~ a few eV ➡ $\Phi \sim + 5\text{-}10$ V

- Dust grain of radius a carries electric charge $q \sim 4\pi\varepsilon_0 a\Phi$

➡ For a ~10 nm, q ~ 70 e $\Rightarrow$ charge-to-mass ratio $q/m \sim 10^{-5}\ e/m_p$

$\propto a^{-2} \propto m^{-2/3}$

Interplanetary nano dust: move fast (Mann et al. 2007)

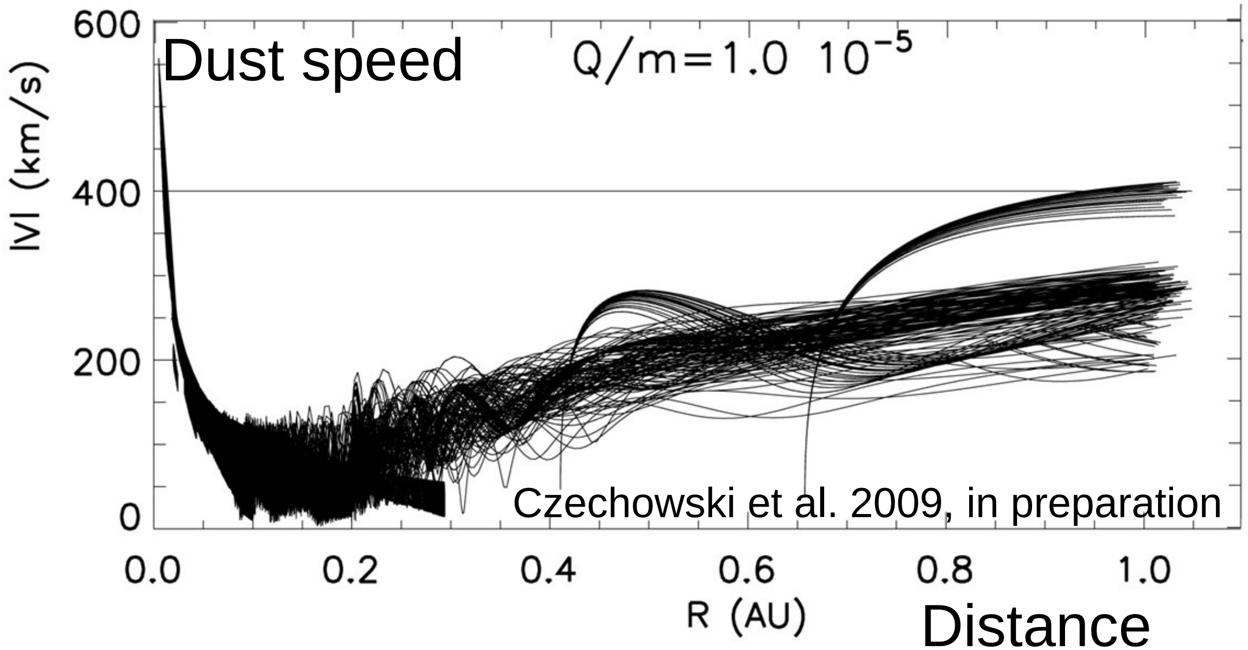
- Lorentz force: $F_L = q(V_{SW} - v_{dust})X B_{SW}$ >> gravitational force F_G

Larmor frequency: $\Omega_L = qB_{SW}/m$ >> Kepler frequency: $\Omega_G = (M_\odot G/d^3)^{1/2}$

For a ~10 nm: $F_L/F_G \sim 200\ d_{AU}$

$\Omega_L/\Omega_G \sim 20$ at 1 AU

- Nano dust grains accelerated to ~ V_{SW} if released farther than ~ 0.15 AU



Distance

How can wave instruments detect nano dust ?

1) The importance of being fast

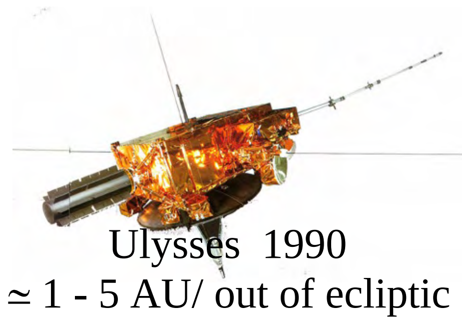
2) Measuring fast dust grains with a wave instrument

Measuring fast dust grains with a wave instrument

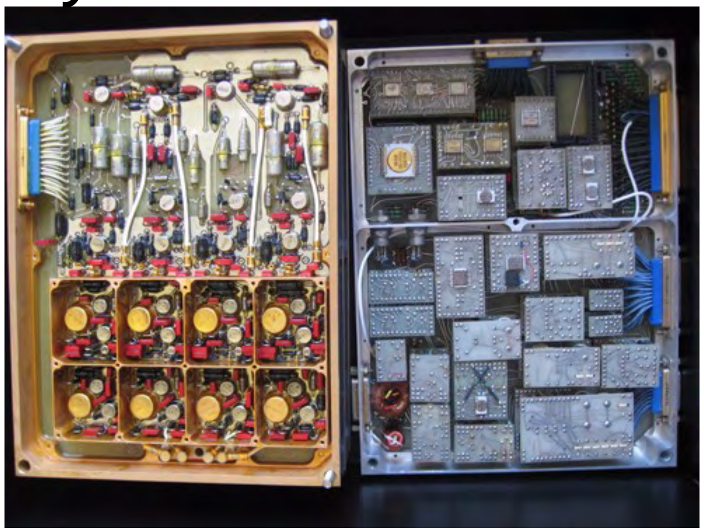
Ultrasensitive radio receivers developed for space missions

ISEE1, 2, 3 (ICE), Ulysses, Cluster, Wind, Cassini, STEREO, Bepi-Columbo, ...

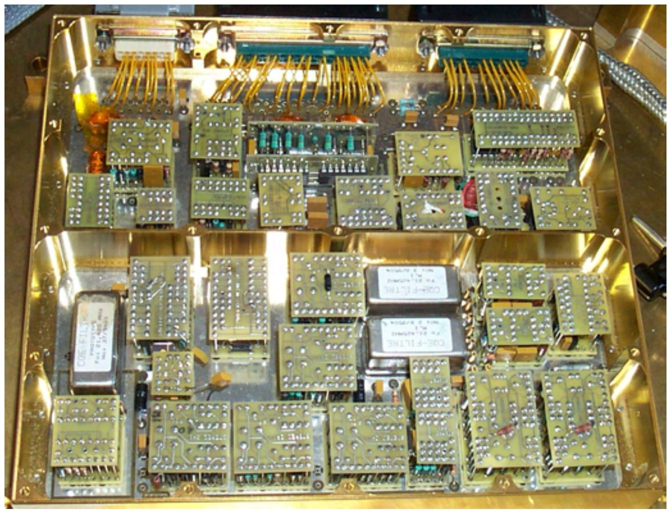
sensitivity: a few nV/Hz$^{1/2}$



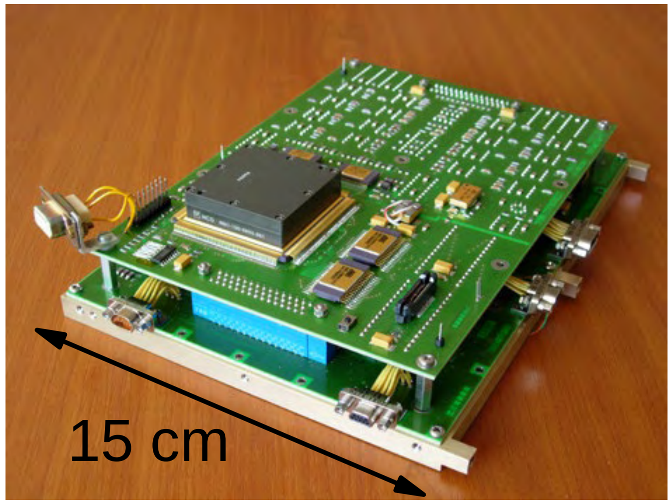
Ulysses/URAP <1990



STEREO 2005



Bepi-Colombo/SORBET 2009



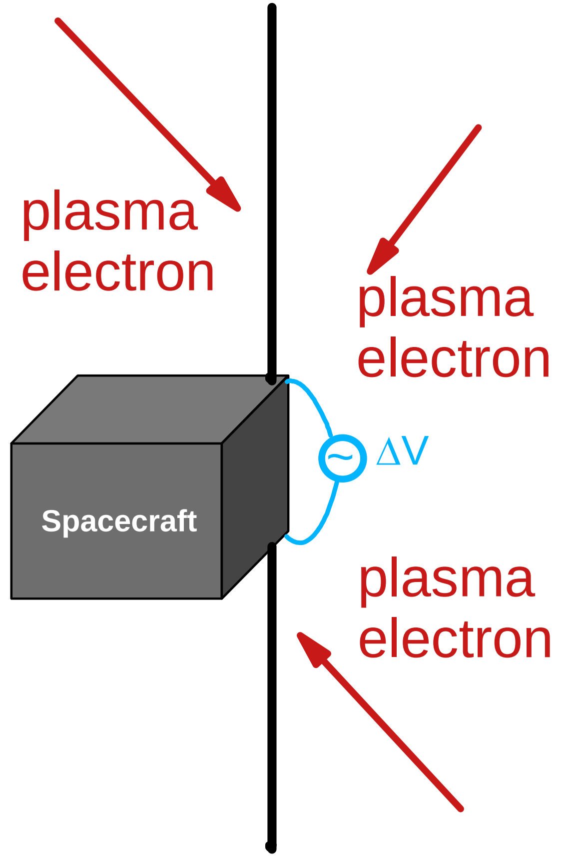
Measuring fast dust grains with a wave instrument

Radio receivers on space missions designed to measure:

- ➡ radioemissions (EM waves)
- ➡ plasma waves

➡ in situ plasma measurement via spectroscopy of plasma quasi-thermal noise [Meyer-Vernet & Perche 1989, Meyer-Vernet et al. 1998]

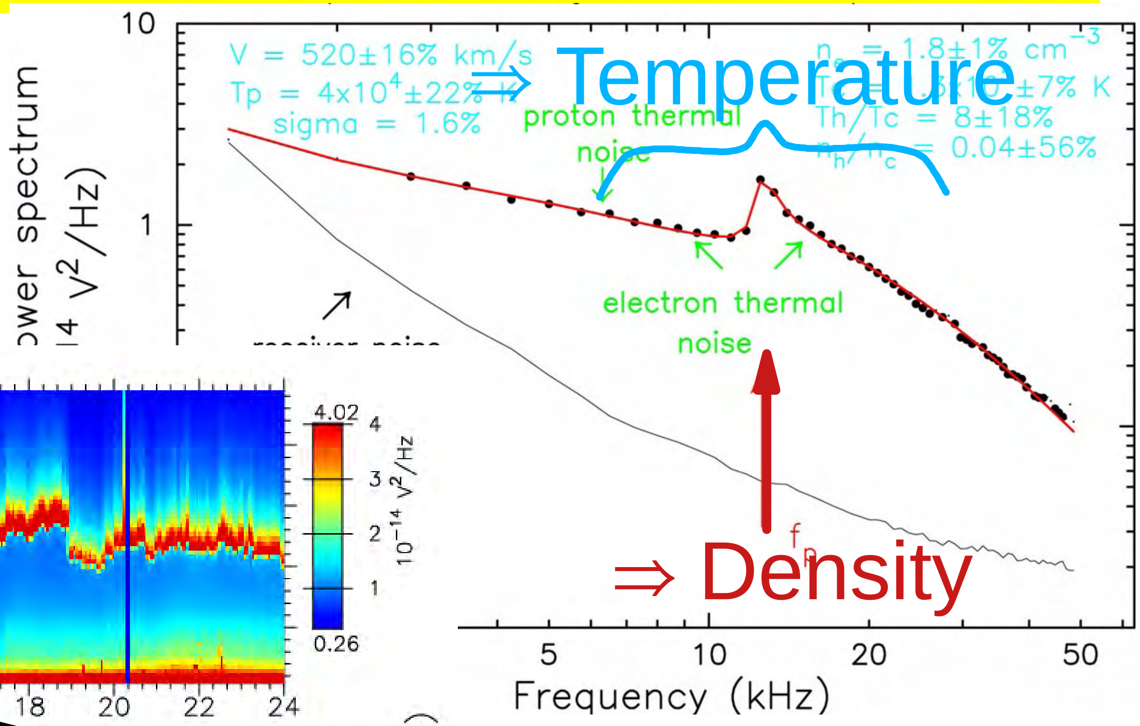
equivalent cross-section of detector
>> physical cross-section

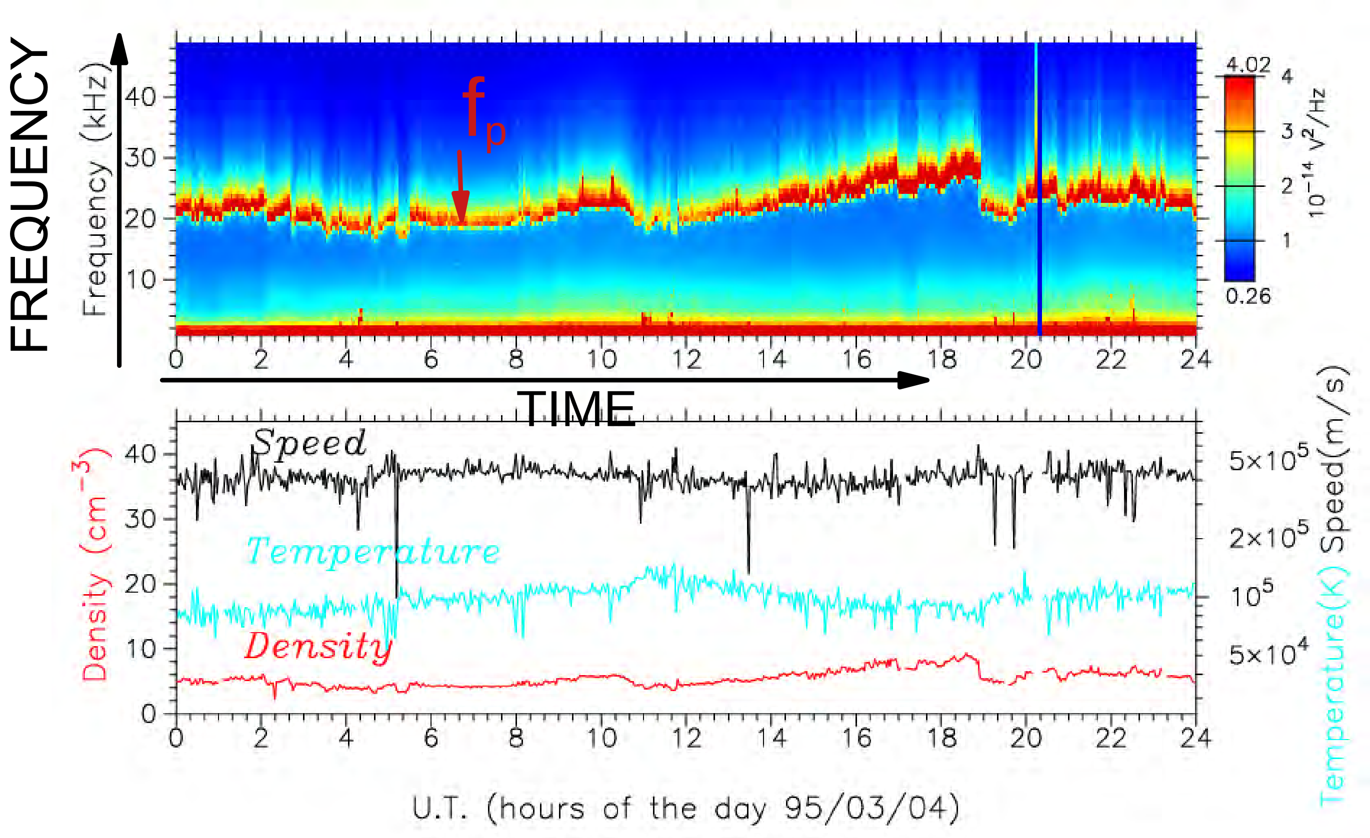


- great sensitivity & accuracy (calibrates other devices)
- only device capable of measuring density & temperature of cold plasmas (comets, rings..)

Example: solar wind electron measurements in routine on Ulysses/URAP

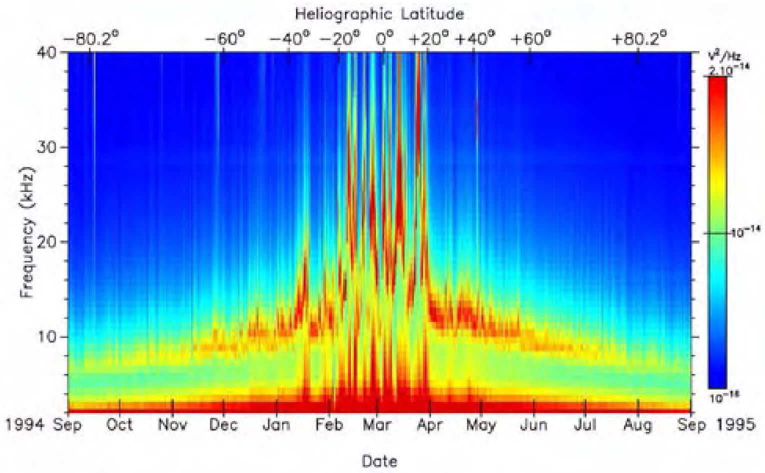
Data points and best fit with 6 plasma parameters (electron density & core temperature, speed, suprathermal electron density & temperature)



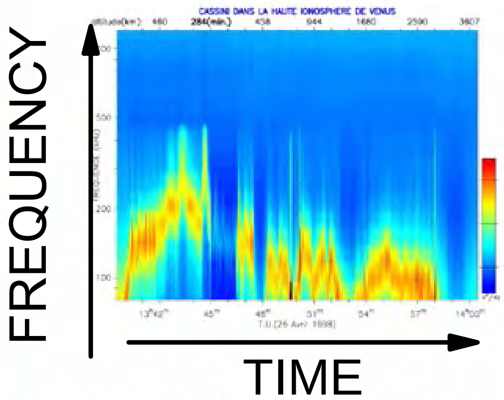


BRUIT QUASI-THERMIQUE DU PLASMA

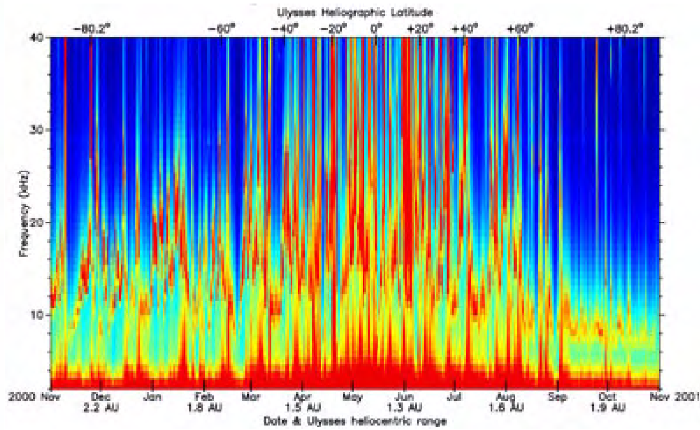
not magnetised



[Issautier & al. 1998] 1995
Vent solaire pole à pole (Ulysse)

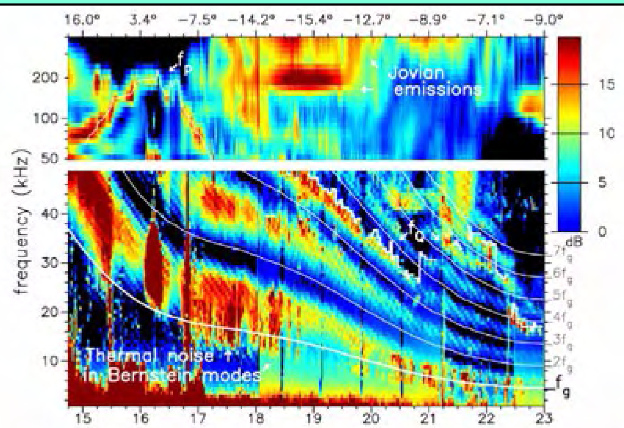


Ionosphère de Vénus
(Cassini) 1999

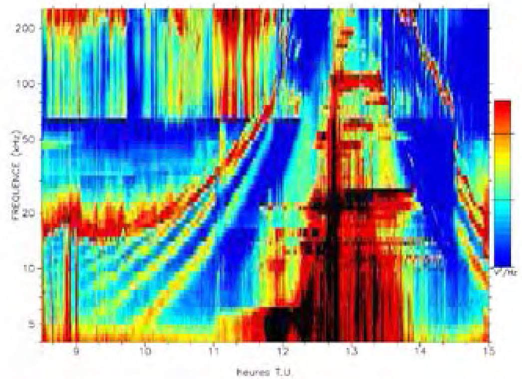


Vent solaire pole à pole (Ulysse)
[Issautier & al. 2001] 2001

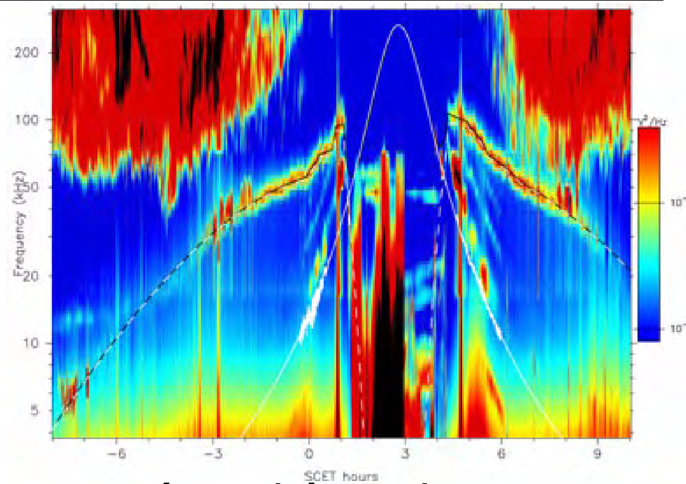
magnetised



Magnétosphère de Jupiter
(Ulysse) 1992
[Meyer-Vernet & al. 1992]

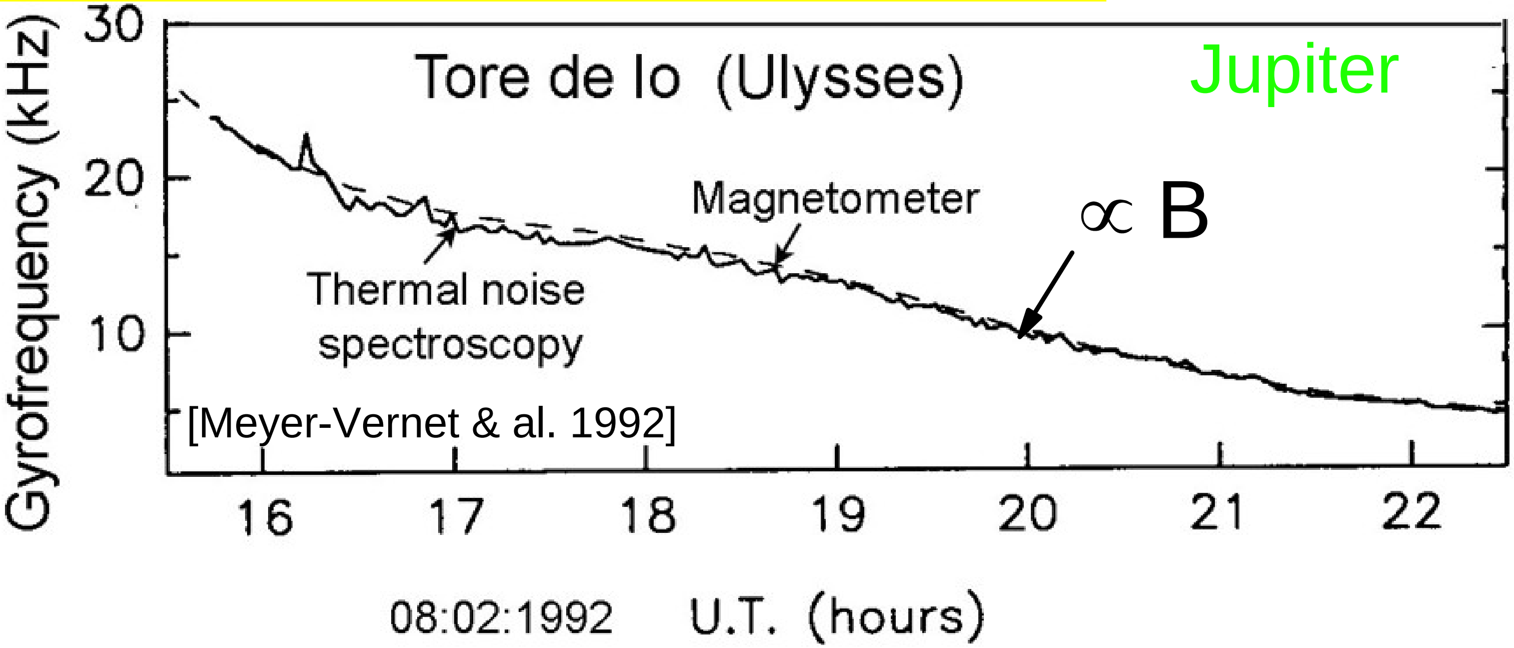


Magnétosphère de la Terre
(Wind) 1998



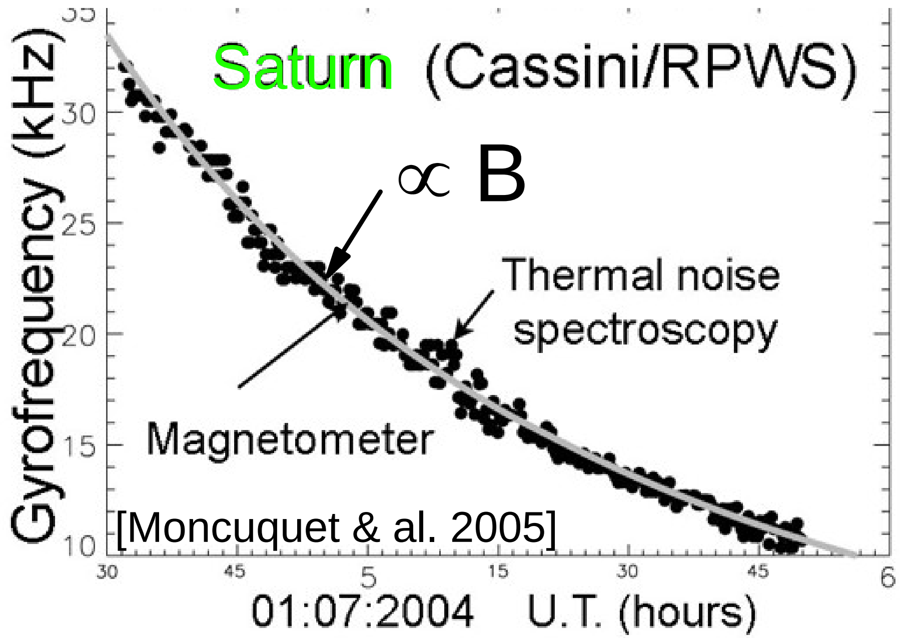
Magnétosphère de Saturne
(Cassini) 2004
[Moncuquet & al. 2005]

PLASMA QUASI-THERMAL NOISE



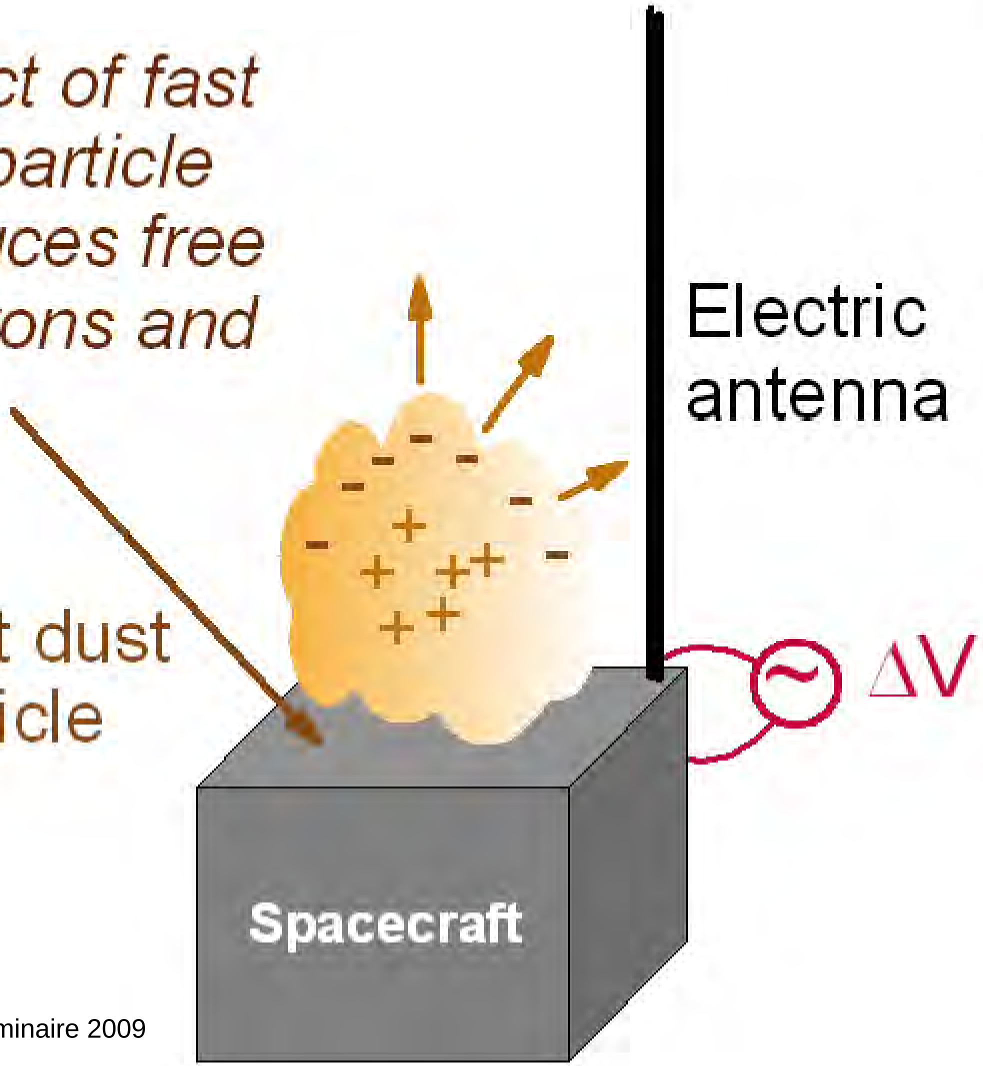
Measure:

- electron density
- electron temperature
- magnetic field B



Measuring fast dust grains with a wave instrument

- **Micro**: impact speed V ~20 km/s kinetic energy/molecule (A=20): ~ 40 eV
- **Nano**:impact speed V ~300 km/s kinetic energy/molecule (A=20): ~ 10 keV



Charge separation and/or recollection produces an electric field detected by the electric antenna

Measuring fast dust grains with a wave instrument

Impact ionisation   Amplitude:

Extrapolation of laboratory measurements:

Detected electric charge upon impact: $Q \propto m\, v^{3.5}$

⇒ increases fast with speed

grain mass (m)   grain speed (v)

Nanoparticle:

radius r ~ 10 nm, mass m ~10^{-20} kg, speed v ~ 400 km/s

yields same Q as:

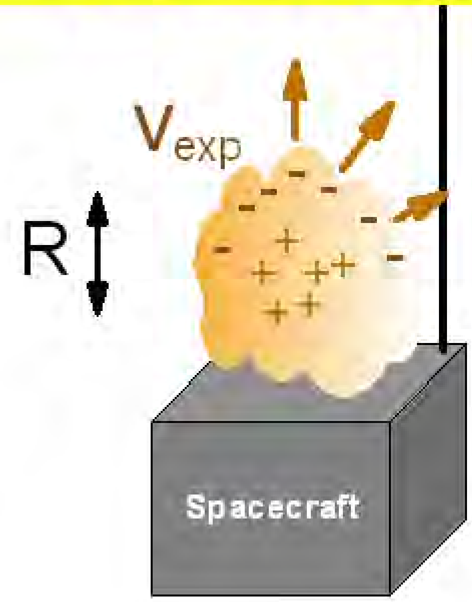
submicron particle:

radius r ~ 0.3 μm, mass m ~10^{-15} kg, speed v ~ 20 km/s

Nanoparticles produce large electric signals

Measuring fast dust grains with a wave instrument

Impact ionisation | Time scale:



- Expanding plasma cloud

radius of cloud: $R \sim v_{exp}\, t \;\Rightarrow\;$ density $n \propto t^{-3}$

- **Detection requires:**
  - charge separation
  - cloud denser than ambient plasma

$$R < R_{MAX} \sim [Q/(\pi e n_a)]^{1/3}$$

$$t < \tau \sim [Q/(\pi e n_a)]^{1/3}/v_{exp} \sim 30\ \mu s \text{ at } 1\ AU$$

↑ Pulse rise time

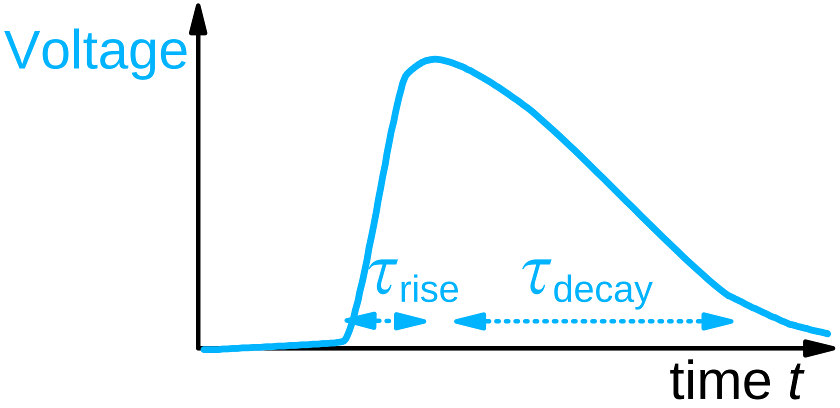
Measuring fast dust grains with a wave instrument

Impact ionisation **Time scale:**

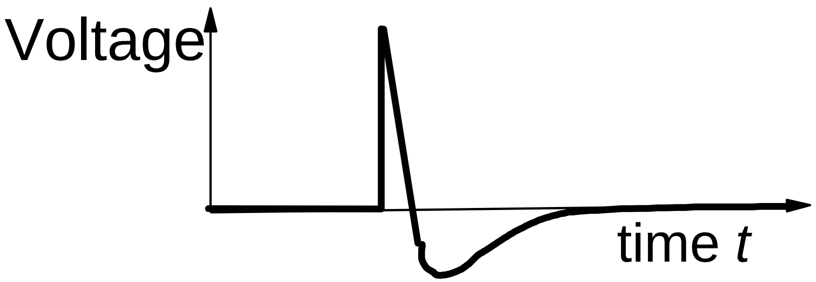
Waveform (time domain sampler)

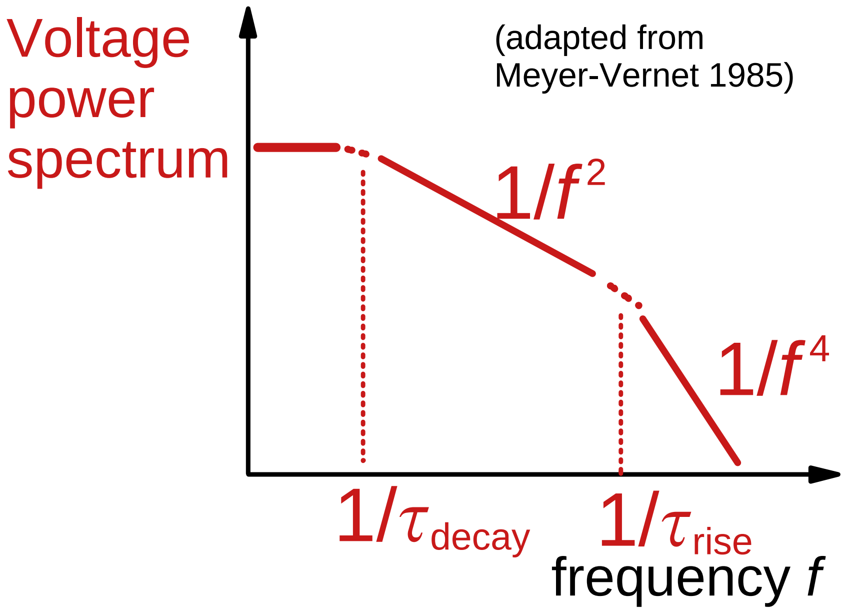
Measurement: and/or

Power spectral density (frequency receiver)



Instrumental filtering



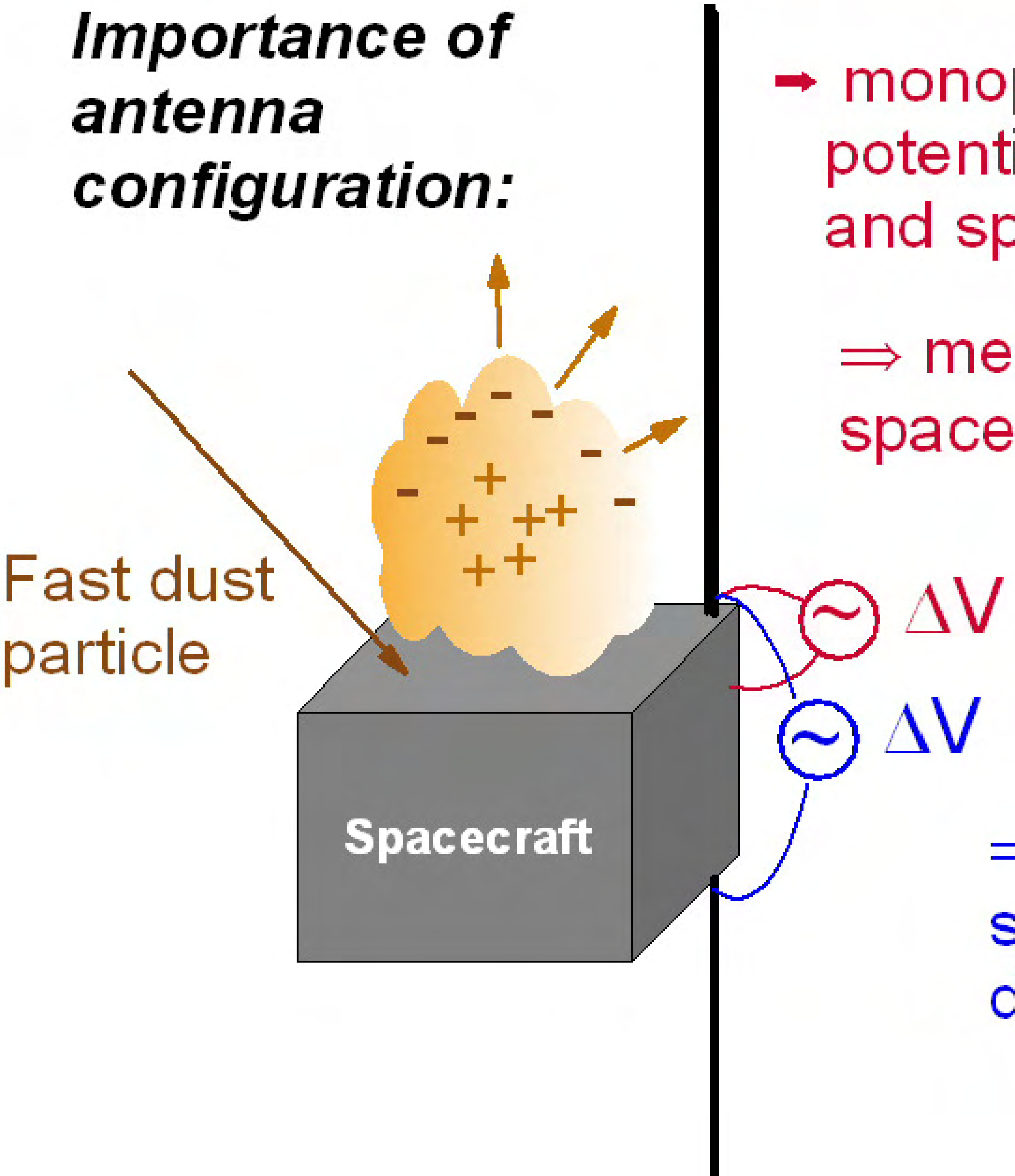


Frequency of observation

$$\sim 1/(2\pi\tau) \sim 5 \text{ kHz} \propto d_{AU}^{-2/3}$$

Measuring fast dust grains with a wave instrument

Importance of antenna configuration:



➡ monopole antenna: measures potential between antenna boom and spacecraft

⇒ measures variations in spacecraft potential

➡ dipole antenna: measures potential between two booms

⇒ measures variations in spacecraft potential only via disymmetries

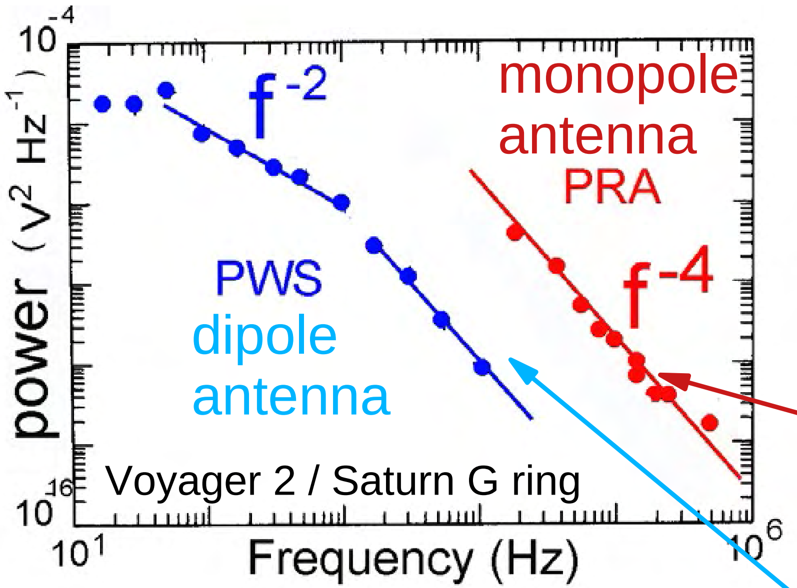
- Nanoparticules
- Nano-poussières dans l'héliosphère
- Principe de détection avec un instrument "ondes"
  - Detection plasma
  - Detection micro
  - Detection nano rapides
- Detections
- Perspectives

Measuring fast dust grains with a wave instrument

First (serendipitous) dust detection with wave instruments

Voyager in Saturn G ring (micro-dust)

- ➡ Dust impacts produce voltage pulses on plasma wave instrument (Gurnett et al 1983)
- ➡ and Voltage power spectrum (Aubier et al. 1983)



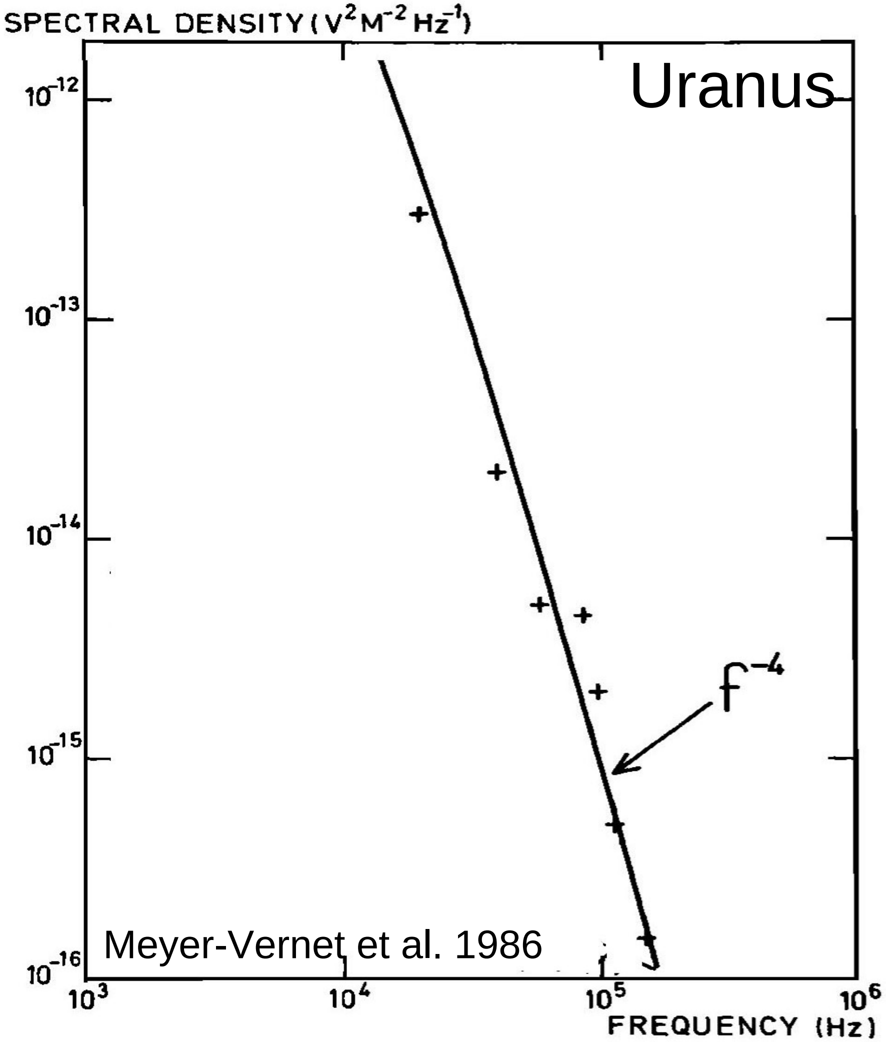
PWS:
Gurnett & al. 1983
Tsintikidis & al. 1994

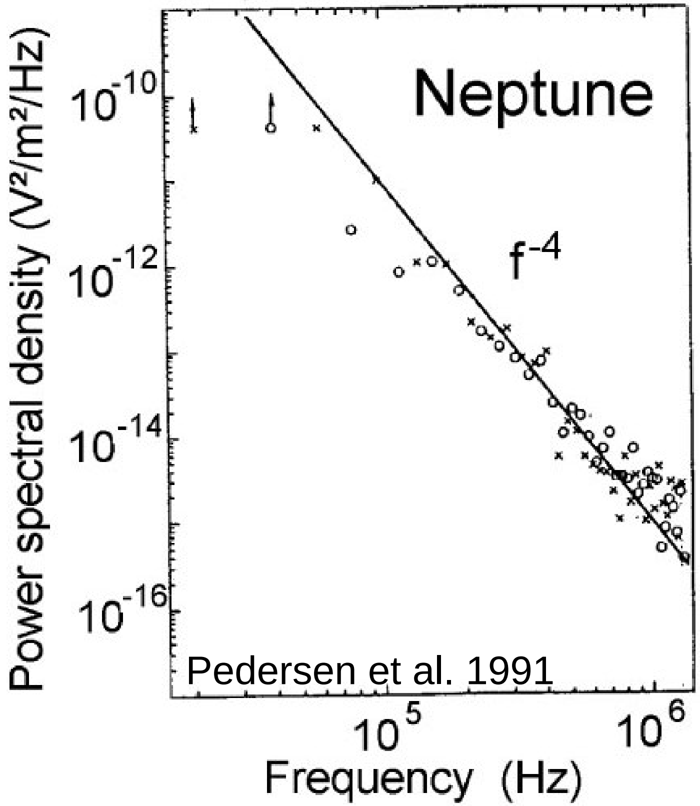
PRA:
Aubier & al. 1983
Meyer-Vernet & al. 1998

- monopole antenna: measures spacecraft potential
- dipole antenna: (measures potential between two booms)
- Signal on monopole much greater than signal on dipole
- and better calibrated
- Signal on dipole depends on dust via dissymetries of antennas

Voyager in Uranus & Neptune rings detects micro dust

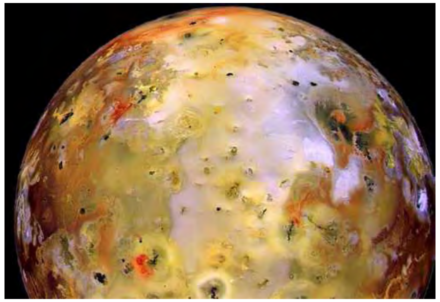
Voyager/PRA (Planetary Radioastronomy instrument)



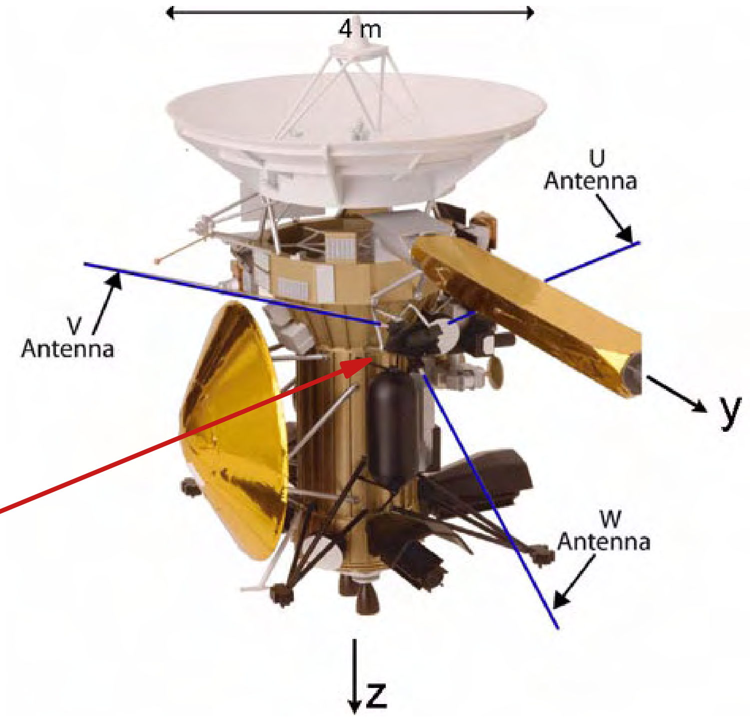


Cassini in solar wind near Jupiter detects nano dust

- Io ejects nano dust
- Nano dust is ejected by Jupiter corotation electric field



- Nanodust is accelerated by solar wind

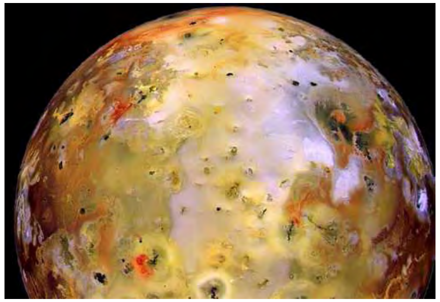


Dust analyser not calibrated for nanodust

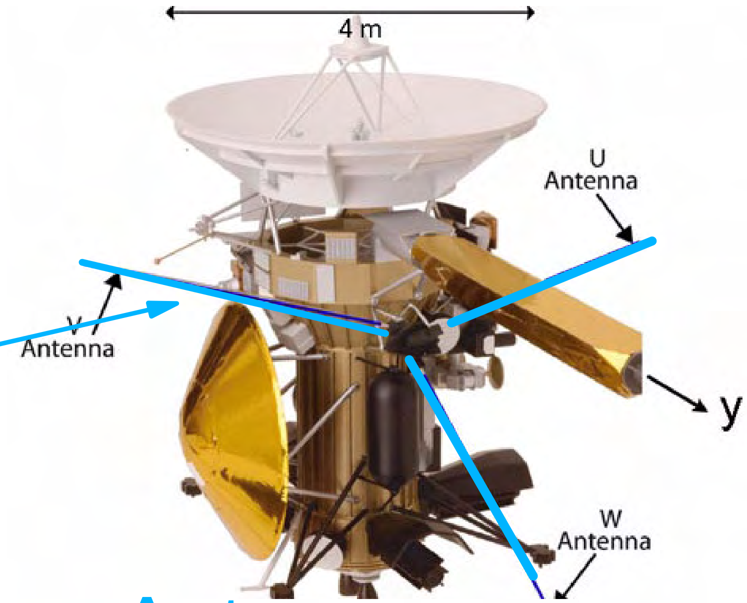
But detected small signals explained by fast nano dust

Cassini in solar wind near Jupiter detects nano dust

- Io ejects nano dust
- Nano dust is ejected by Jupiter corotation electric field



- Nanodust is accelerated by solar wind

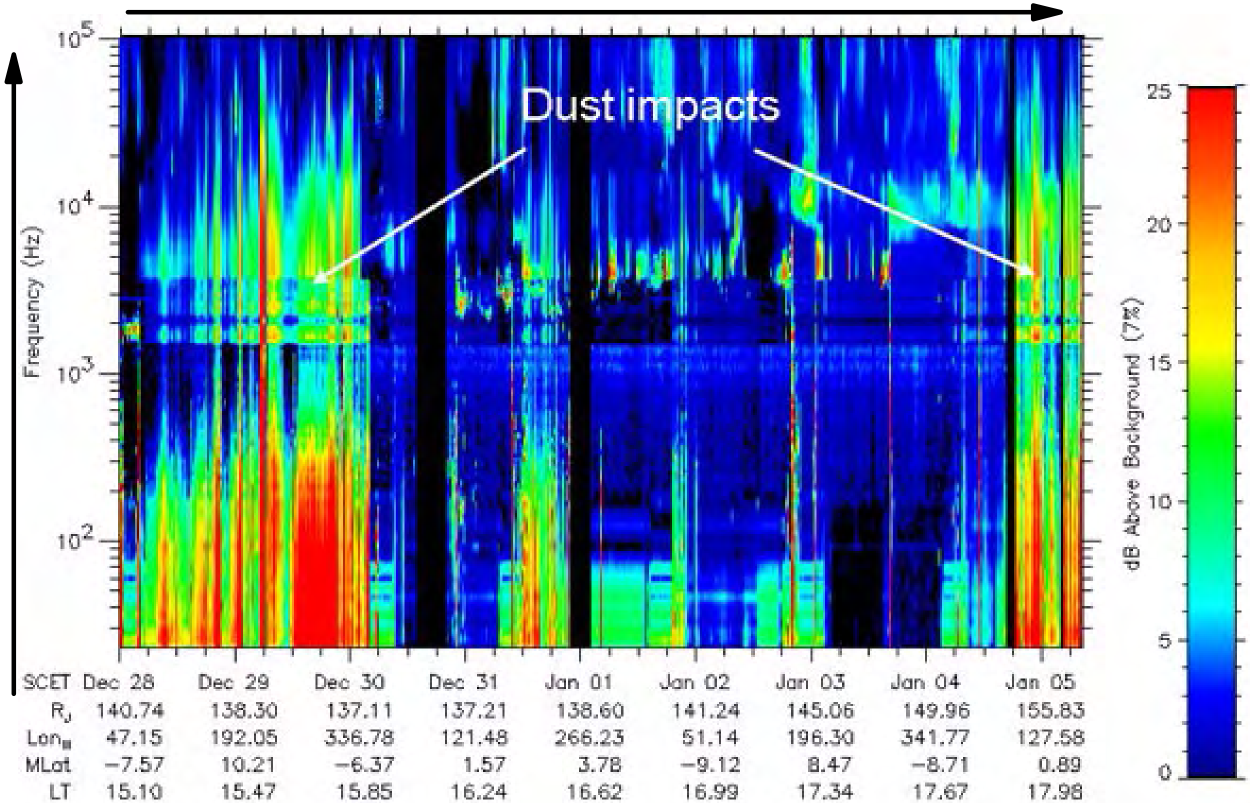


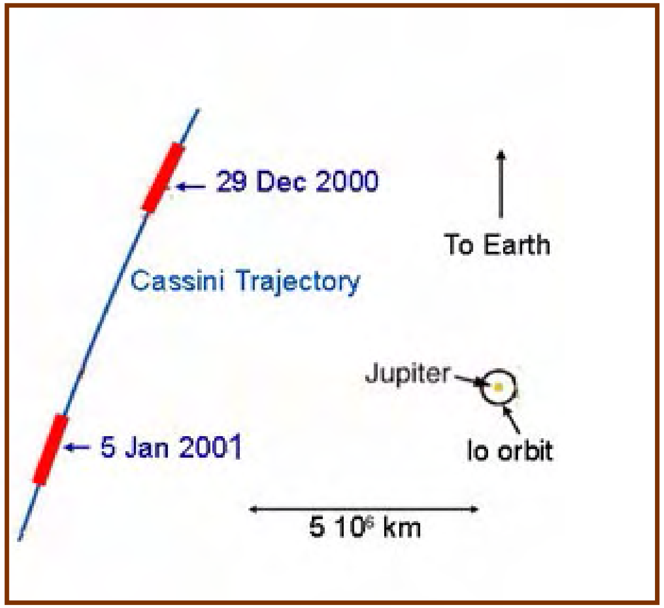
Antennas

RPWS

TIME

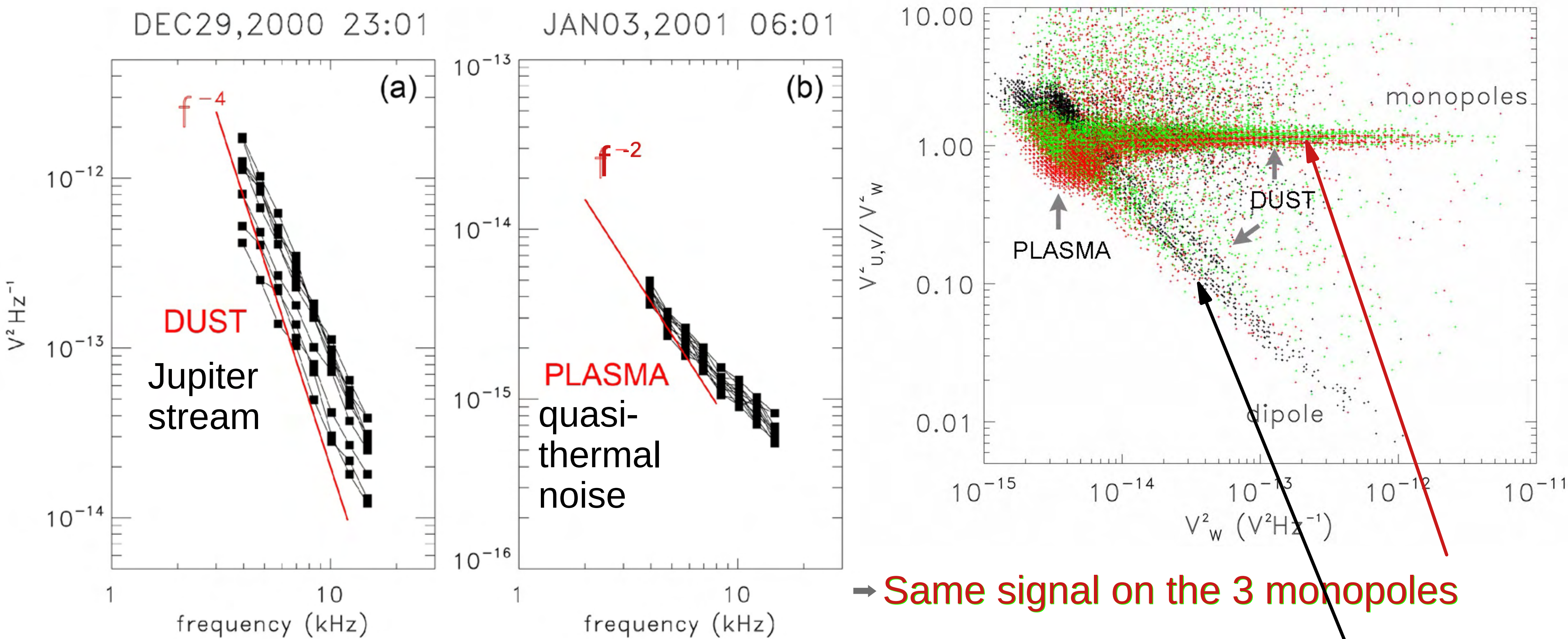
FREQUENCY





Cassini in solar wind near Jupiter detects nano dust

RPWS

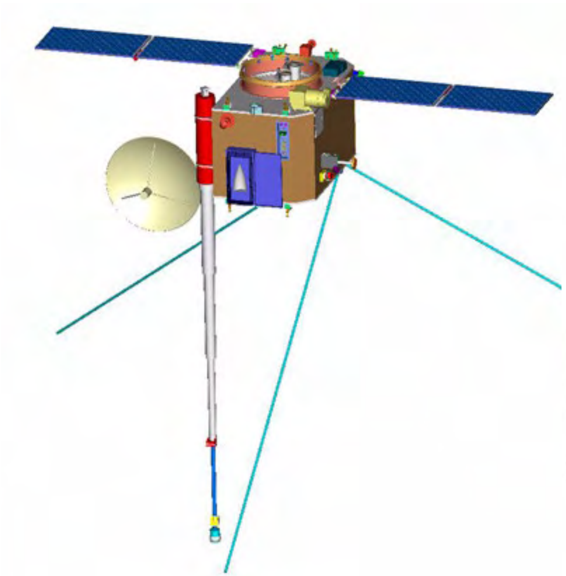


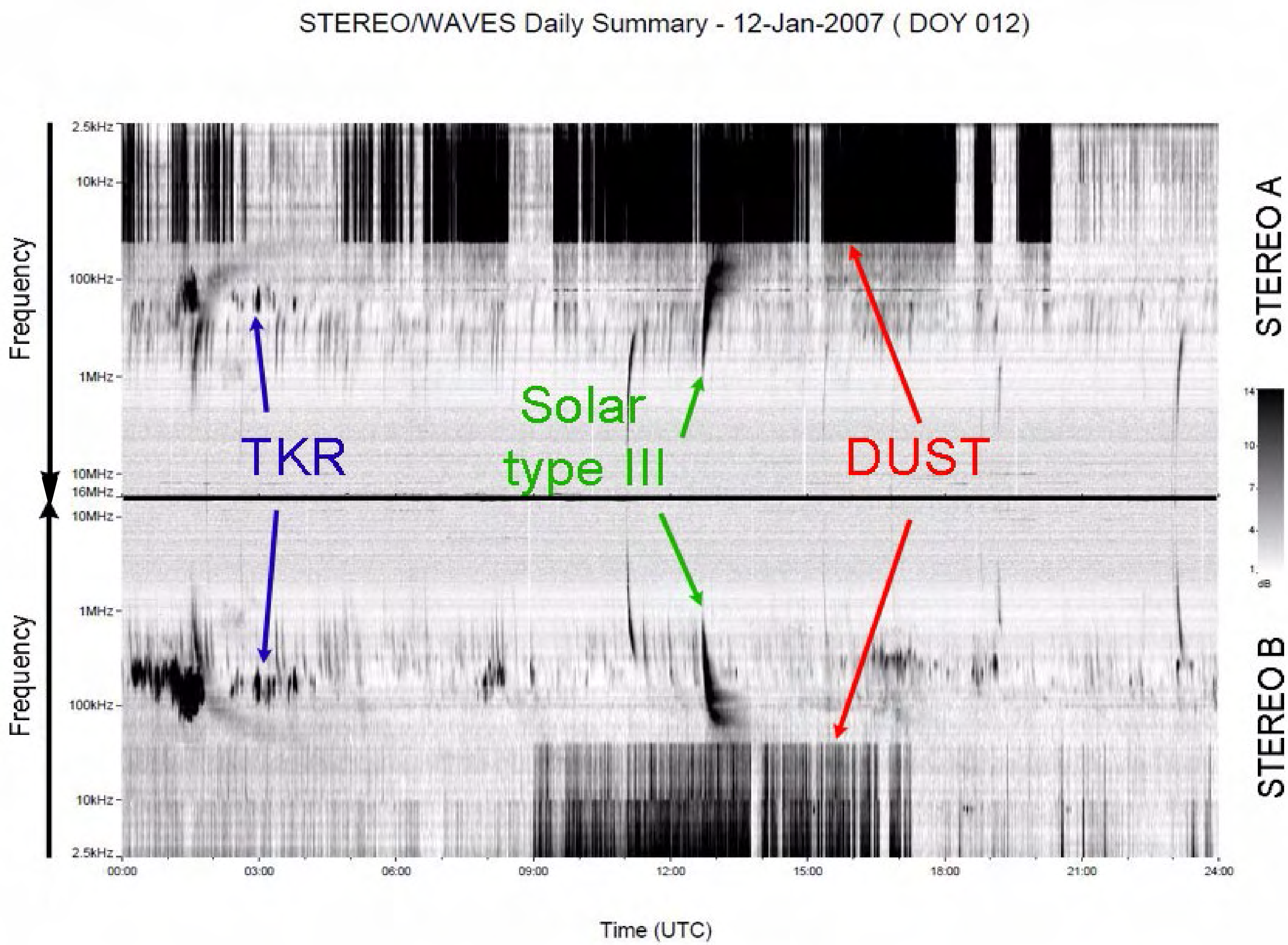
- Same signal on the 3 monopoles
- Signal on dipole is much smaller

Flux of nanodust deduced from wave instrument similar to simultaneous measurement with conventional dust detector

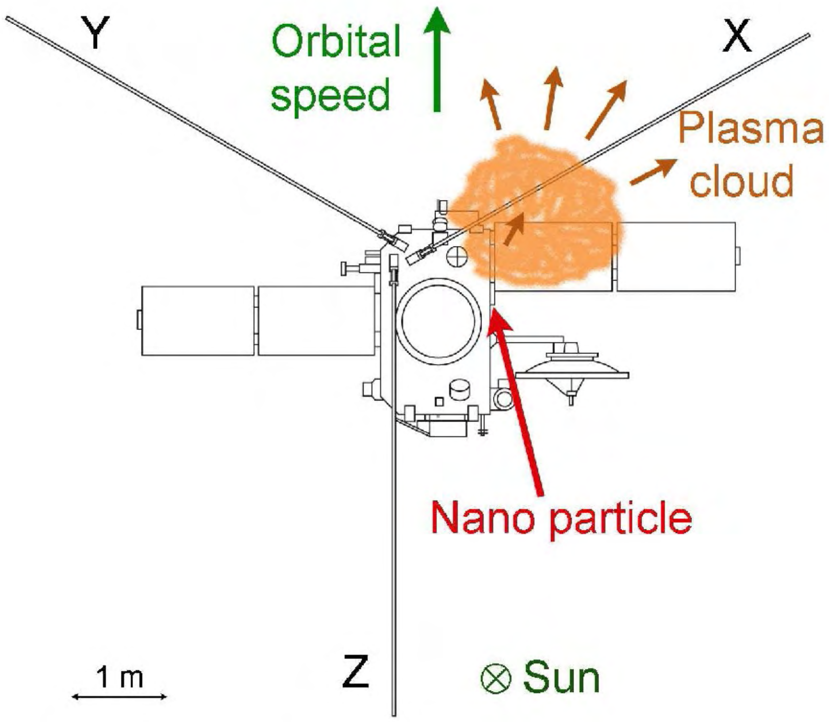
Meyer-Vernet, Lecacheux & al., Geophys. Res. Lett. 36, L03103 (2009)

STEREO in solar wind at 1 AU detects nano dust



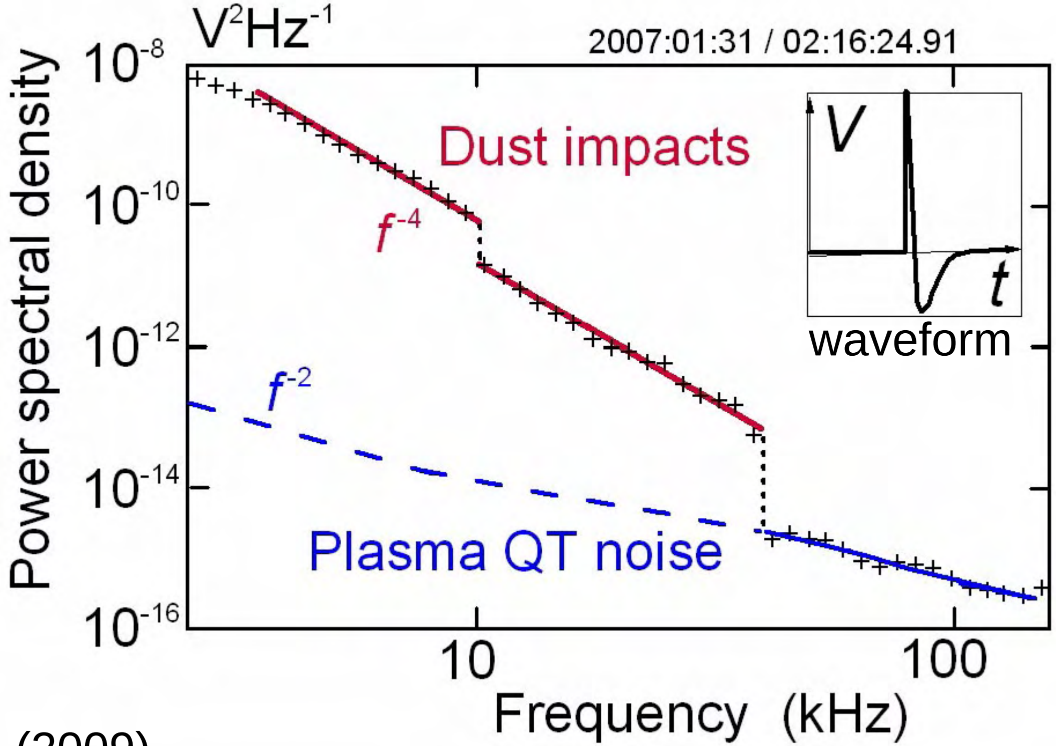


STEREO in solar wind at 1 AU detects nano dust



WAVES

Voltage power spectrum



Meyer-Vernet et al., Solar Phys. 256, 463 (2009)

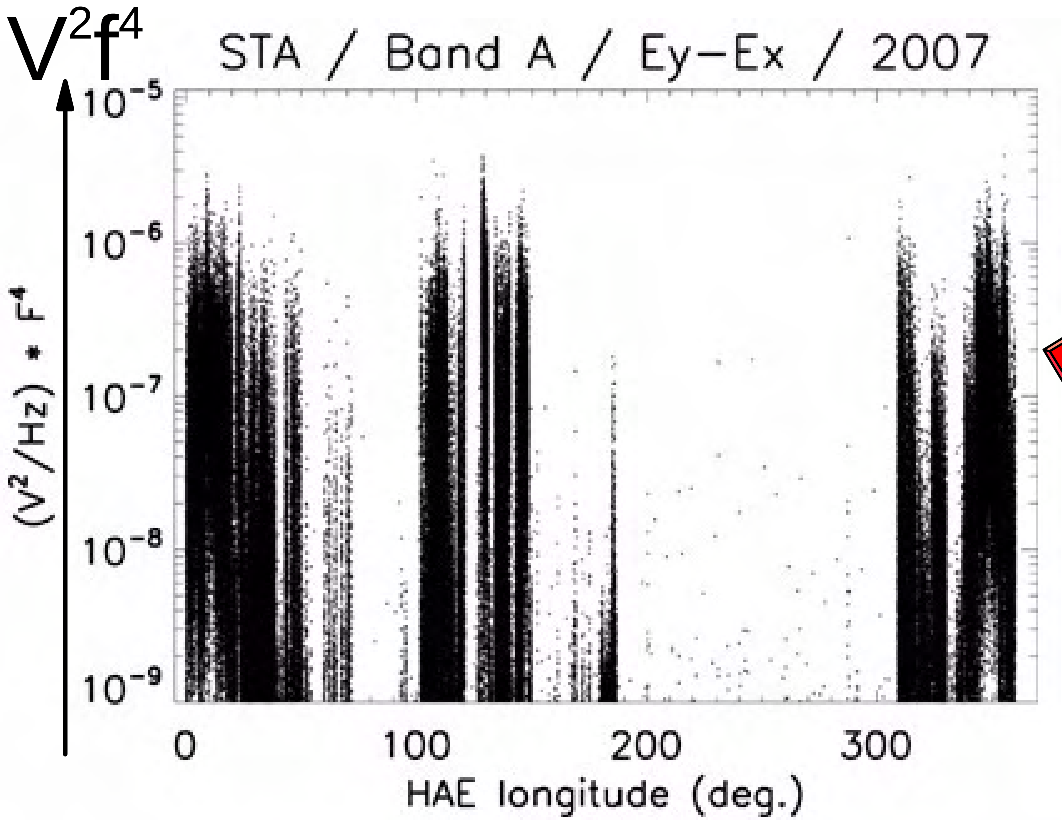
STEREO in solar wind at 1 AU detects nano dust

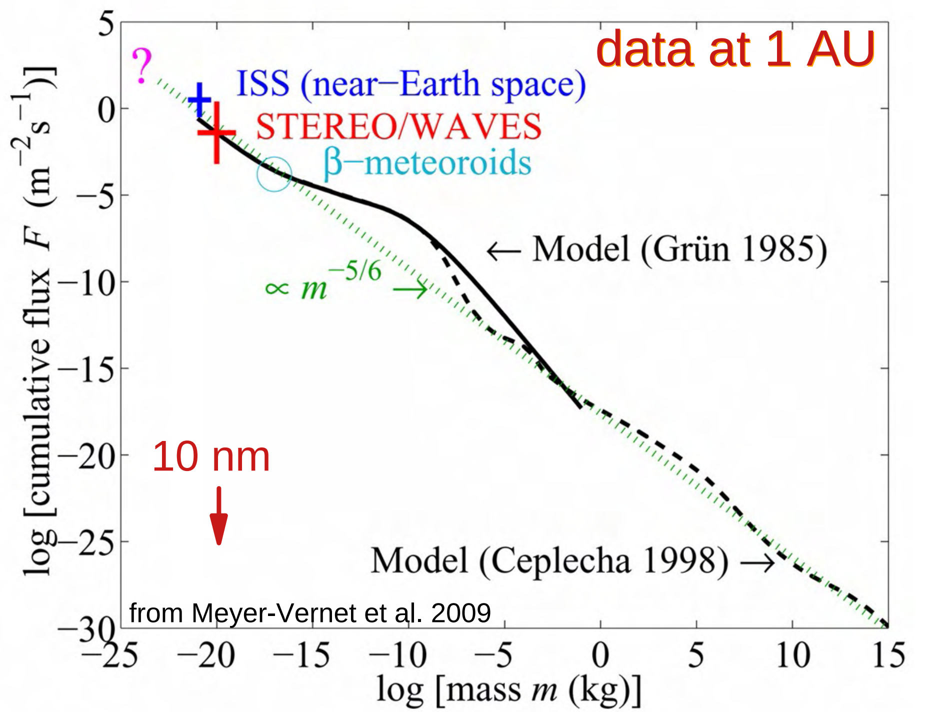
hf voltage power spectrum:

$$V^2 \sim 2\Gamma^2 \langle SF(\Delta V/\tau)^2 \rangle / \omega^4 \leftarrow 2\pi f$$

- Γ: receiver gain
- S: surface of target $\sim R_{MAX}^2$
- F: Flux
- $(\Delta V/\tau)$: from v(m) (dust dynamics)

<..> = average during receiver acquisition time ~0.15 sec





- Nanoparticules
- Nano-poussières
  dans l'héliosphère
- Principe de détection avec
  un instrument "ondes"
  - Detection plasma
  - Detection micro
  - Detection nano rapides
- Detections
- Perspectives

Questions and perspectives

3 years

- Detailed analysis of STEREO data

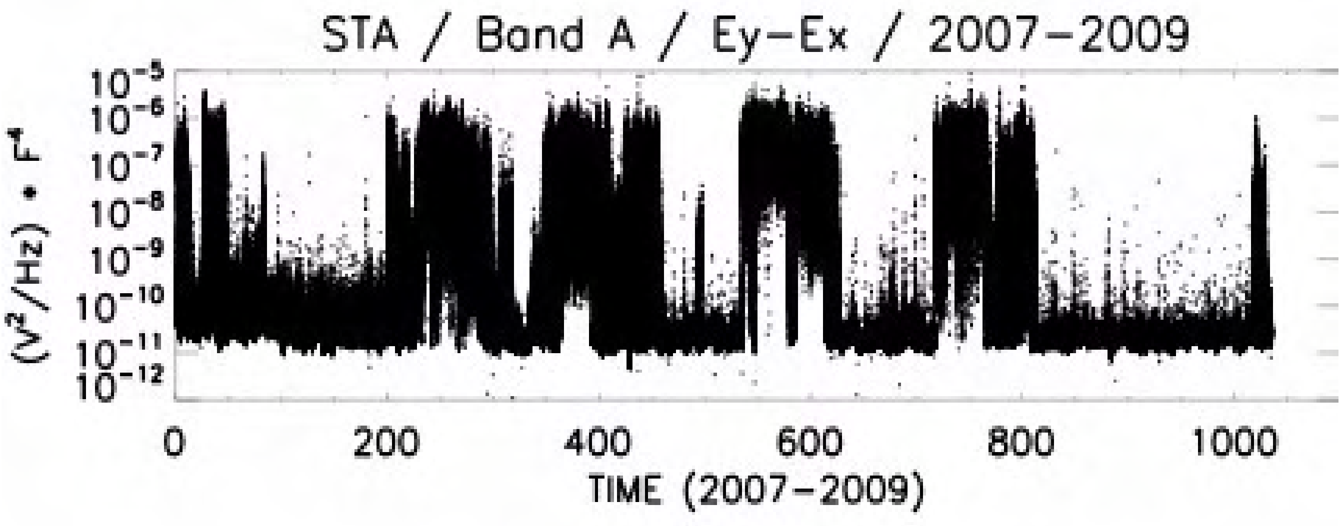


Fig. K. Issautier & M. Maksimovic

- Detailed analysis of Cassini data

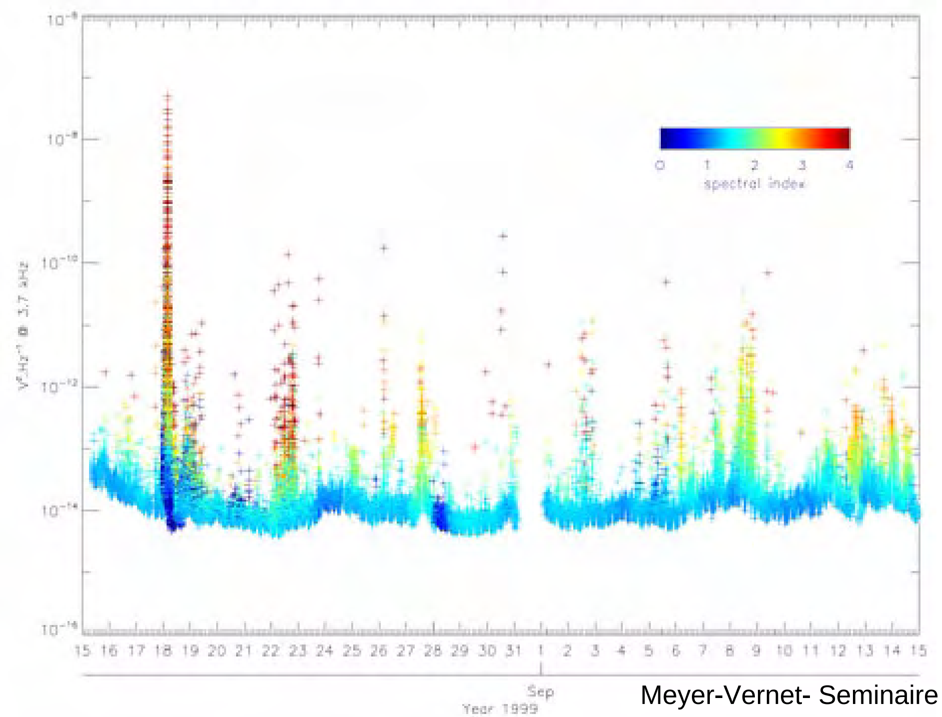


Fig. A. Lecacheux

Questions and perspectives

- **Detection method**
  - ☛ simulation of impact plasma & electric signal [Pantellini & Landi in progress]
  - ☛ response of wave receiver
- **Origin of particles**
  - ► interplanetary dust cloud
  - ► planets, ...
- **Composition, shape ...**
- **Interaction with solar wind**
  - ★ electric charge of nanodust (transition dust/molecules)
  - ★ dynamics [Czechowski et al. in progress]
  - ★ size limit? (Coulomb explosion? since q>0 not limited by field emission)
  - ★ effects on solar wind ("inner source" ...)

ISSI international team

Nano Dust in the Solar System: Formation, Interactions & Detection

http://www.issibern.ch/teams/formationsolar/

Questions and perspectives

- **Other detections**

☛ Via radiation ?

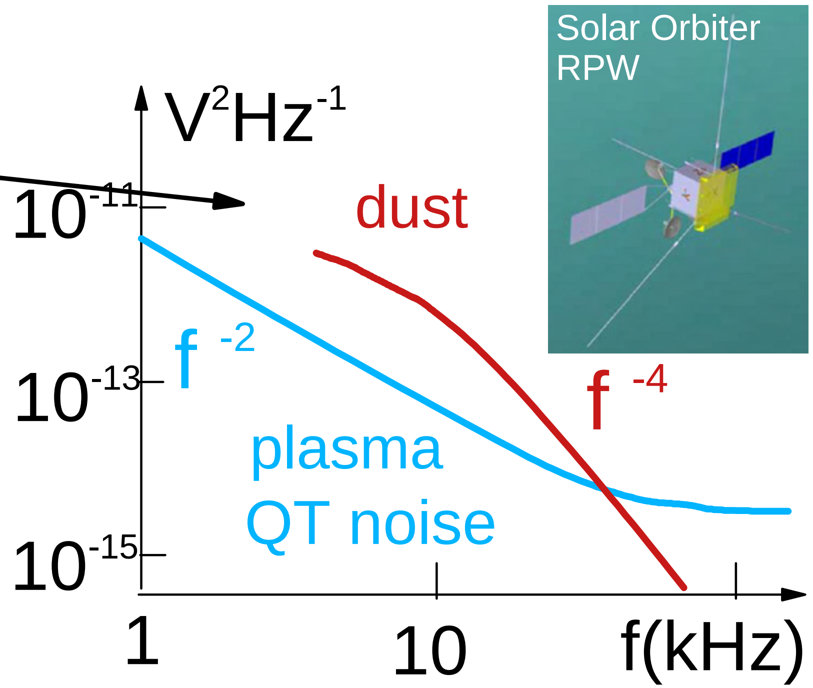
☛ Reanalysis of past detections (impacts from fast nano possibly misinterpreted as bigger & slower grains?)

☛ Wave detection of nanodust on future space missions

☛ dipole antennas: quasi-thermal plasma noise

⇒ electron density & temperature

☛ monopole antennas: fast nano dust



Complementary to conventional dust detectors

- large collecting area (whole spacecraft)
- not reliant on specific spacecraft attitude
- requires few resources (by-product of wave instrument)