Detection of fast nanoparticles in the solar wind

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Abstract. Dust grains in the nanometer range bridge the gap between atoms and larger grains made of bulk material. Their small size embodies them with special properties. Due to their high relative surface area, they have a high charge-to-mass ratio, so that the Lorentz force in the solar wind magnetic field exceeds the gravitational force and other forces by a large amount, and they are accelerated to a speed of the order of magnitude of the solar wind speed. When such fast nanoparticles impact a spacecraft, they produce craters whose matter vaporises and ionises, yielding transient voltages as high as do much larger grains of smaller speed. These properties are at the origin of their recent detection at 1 AU in the solar wind. We discuss the detection of fast nanoparticles by wave instruments of different configurations, with applications to the recent detections on STEREO/WAVES and CASSINI/RPWS. Finally we discuss the opportunities for nanoparticle detection by wave instruments on future missions and/or projects in the inner heliosphere such as Bepi-Colombo and Solar Orbiter.

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NANO-DUST IN THE SOLAR WIND

Nanoparticles lie at the frontier between two well-studied solar wind populations: ions and dust grains. Such particles have been inferred a long time ago in the interstellar medium ([5] and refs. therein). More recently, nanoparticles produced in the heliosphere have been suggested to be accelerated to speeds of the order of magnitude of the solar wind speed by the solar wind motional electric field [7]. Nevertheless, there is still no instrument dedicated to their measurement onboard interplanetary space probes.

Indeed, cosmic dust analyzers in space have not been calibrated to measure dust grains moving faster than 100 km/s, so that the serendipitous discovery on Ulysses of nanoparticles expelled by Jupiter required a theoretical modelling of dust dynamics [18]. Such nanoparticles were subsequently confirmed from dust detector data on other spacecraft, outside their calibration ranges, and recently with the wave (RPWS) instrument on Cassini [15].

The recent first detection by STEREO/WAVES in the interplanetary medium at 1 AU, of fast nanoparticles presumably produced in the inner heliosphere, opens new perspectives. This detection was serendipitous, too, due to favourable configuration of the electric antennas [14].

CHARGE AND SPEED OF INTERPLANETARY DUST

The charging of bodies in interplanetary space is mainly governed by photoelectron emission and by collection of ambient electrons. For most materials, photoemission is largely dominant, so that the surfaces are charged to a potential which binds sufficiently the photoelectrons to make their escaping flux balance that of incoming electrons, i.e. to several Volts positive since the photoelectron "temperature" $\sim$1-3 eV [10]. For nanoparticles of size smaller than the photon attenuation length and comparable to the photoelectron escape length, the yield is enhanced [2], still increasing the positive potential.

For a given potential, the grain charge is roughly proportional to its size, so that a three-dimensional grain has a charge-to-mass ratio q/m inversely proportional to its surface area. For a grain of radius 10 nm (mass $m \sim 10^{-20} kg$), $q/m \simeq 10^{-5} e/m_p$. With such a high charge-to-mass ratio, the Lorentz force in the solar wind magnetic field is much greater than the solar gravitational attraction and other forces, and the Larmor frequency is much greater than the orbital Keplerian frequency, so that grains produced farther than about 0.15 AU can reach at 1 AU a speed of the order of magnitude of the solar wind speed [7]. Figure 1 shows the speed as a function of heliocentric distance for a sample of nu-

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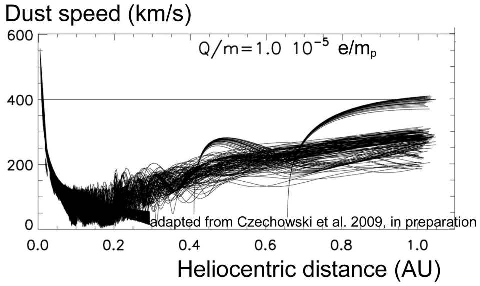

FIGURE 1. Speed of nanoparticles of charge-to-mass ratio $q/m = 10^{-5} e/m_p$ as a function of heliocentric distance with a simple model of the interplanetary dust cloud and of the solar wind [1].

merically calculated trajectories of nanograins [1], assuming a simple solar wind model, with the particles produced by collisions in the interplanetary dust cloud within 1 AU at initial positions distributed over this region [6]. Smaller grains, which have a greater q/m ratio, reach similar speeds, whereas larger grains (smaller q/m), reach smaller speeds.

MEASURING FAST DUST GRAINS WITH A WAVE INSTRUMENT

When a grain impacts a spacecraft at a high speed, the energy dissipated vaporises and partly ionises the grain as well as a part of the target's material [3]. This produces an expanding plasma cloud whose residual charge induces an electric pulse which can be detected by the antennas (Fig.2) as soon as the Debye length in the cloud exceeds the cloud size. This process is akin to that used by grain mass spectrometers in space [4].

Dust impact ionisation involves complex processes not fully included in laboratory simulations and theory at present, so that the impact generated charge Q is determined semiempirically with a large uncertainty. It varies with the grain's mass and speed approximately as $Q \simeq 0.7\, m\, v^{3.5}$ with Q in Cb, m in kg, v in km s^{-1} [8]. Since the above coefficients depend on mass, speed, angle of incidence, as well as grain and target composition, Q may differ from this relationship by one order of magnitude. In the absence of laboratory measurement with fast nanoparticles, we make the bold assumption that this relationship also holds for them, within limits set by energy conservation [14]. For interplanetary nanoparticles at 1 AU that are moving at about 300 km/s for $m \leq 10^{-20}$ kg, we find $Q \sim 10^{8} \times m$ in this mass range. Since larger grains cannot reach high speeds, Q no longer increases with m for $m > 10^{-20}$ kg, so that the maximum charge is $Q \sim 10^{-12}$ Cb.

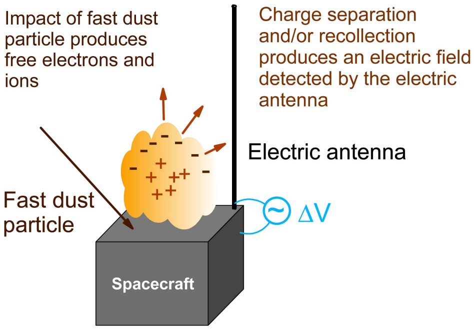

FIGURE 2. Basics of the electric detection of a fast grain impinging on a spacecraft

The time scale of the electric pulses is set by the time τ at which the cloud expansion at speed V_{exp} has reduced its plasma density to the ambient level n_a, i.e., $\tau \sim R_{max}/V_{exp}$ where the maximum cloud size is $R_{max} \sim (Q/en_a)^{1/3}$. This sets the order of magnitude of the pulse rise time, $\tau_{\text{rise}} \sim \tau$, whereas the decay time, generally determined by filtering, is much longer. For pulses of rate N, maximum amplitude δV, and rise time τ, the power spectrum is [11]

$$V_f^2 \simeq 2 < N \delta V^2 \omega^{-2} (1 + \omega^2 \tau^2)^{-1} > \qquad (1)$$

at frequencies $f = \omega / 2\pi$ much greater than the pulses' inverse decay time, where the angular brackets stand for averaging over the pulses detected during the receiver acquisition time. This produces a power spectrum varying as f^{-4} at frequencies greater than $1/2\pi\tau$ (Fig.3).

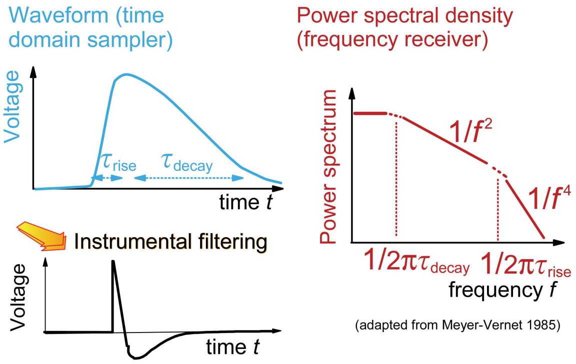

FIGURE 3. Typical pulse produced grain impact ionisation (top left), result after instrumental filtering (bottom left), and power spectral density in different frequency ranges (right).

The amplitude of the individual pulses produced by impact ionisation of nanodust, and of the corresponding voltage power spectrum, depends on the antenna configuration.

With long antennas extending far from the spacecraft - the usual configuration - the voltage is generally due to the variation Q in spacecraft charge upon a grain impact, making the spacecraft potential (with capacitance C) vary by $\delta V_1 \sim Q/C$. In that case, each antenna boom in monopole mode (where one measures the difference in voltage between the boom and the spacecraft) detects simultaneously a pulse $-\delta V_1$, and the whole spacecraft area can serve as a target. However, the detected voltage is much smaller in dipole mode (where one measures the difference in voltage between two booms), since the spacecraft voltage pulses are then detected only via inbalances in the antenna/receiver system.

Such observations have been made recently on Cassini/RPWS (Figure 4, left) near Jupiter, when the data from the on-board dust detector, together with Galileo observations and calculations of particle dynamics, indicated impacts of nanoparticles on the spacecraft. The RPWS voltage produced by nanodust impacts was detected only in monopole mode, with the three booms detecting simultaneously the same signal. Even though the individual pulses are of very small amplitude, the power spectrum is not, because the target area for impacts can be the whole spacecraft. Comparing the observations with the spectrum (1), with $\delta V \sim -\delta V_1$ and the above expressions of Q and $\tau \propto Q^{1/3}$, yields results consistent with those of the dust detector [15]. Note that with a grain mass distribution $dn_G/dm \propto m^{-11/6}$, the spectrum (1) is $V_f^2 \propto f^{-4} \int dm\, m^{4/3} dn_G/dm$ at high frequencies, which is proportional to the integrated squared surface area of the particles, and therefore depends (weakly) on the largest particles detected.

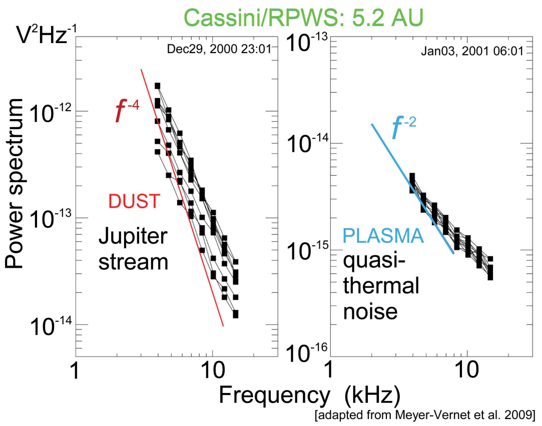

FIGURE 4. Examples of power spectrum measured with the lowest filter of the h.f. receiver on Cassini/RPWS near Jupiter. The left and right spectra are produced respectively by dust impacts and by the ubiquitous plasma quasi-thermal noise.

On STEREO/WAVES, an additional process takes place because the antenna booms extend close to the spacecraft surface, and their length L is not much greater than the maximum cloud size R_{max}. In that case, a significant part of a boom can be immersed in the impact plasma clouds, so that each impact closer to the boom than $\sim R_{max}$, produces on this boom a voltage pulse $\delta V_2 \sim T_{\mathrm{eV}} R_{max}/L$ where T_{eV} is the temperature in the cloud in eV [17]. With $Q \sim 10^{-12}$ Cb and the interplanetary electron density $n_a \sim 5 \times 10^6$ m^{-3} at 1 AU, the maximum cloud size is $R_{max} \sim 1$ m, so that, with a STEREO boom of length $L \sim 6$ m and $T \sim 2$ eV, the pulse amplitude is $\delta V_2 \sim 0.3$ V. Since this holds for impacts on the spacecraft closer to the boom than $\sim R_{max}$, the corresponding target area $\sim R_{max}^2$.

In contrast, with the capacitance $C \sim 200$ pF, the variation in spacecraft potential has the much smaller amplitude $\mid \delta V_1 \mid \sim 5 \times 10^{-3}$ V. This is consistent with the observed STEREO/WAVES detection of the pulses mainly on one boom, in either monopole or dipole mode (voltage pulse $\sim \delta V_2$), whereas the other booms measure simultaneously pulses of much smaller amplitude ($\sim -\delta V_1$).

With the above expressions of Q and $\tau \propto R_{max} \propto Q^{1/3}$, we estimate the voltage power spectrum (1) by integrating the individual pulses $\delta V \sim \delta V_2$ over the grain mass distribution dn_G/dm. Since the impact rate is proportional to the flux times the target surface R_{max}^2, we have $V_f^2 \propto f^{-4} \int dm\, m^{2/3} dn_G/dm$ at high frequencies, which is proportional to the integrated surface area of the nanoparticles. With a mass distribution $\propto m^{-11/6}$ (equivalent to a size distribution $\propto r^{-7/2}$), the high frequency power spectrum level depends (very weakly) on the minimum particle size.

Figure 5 shows an example of power spectrum on STEREO/WAVES in the three l.f. bands, acquired sequentially with an acquisition time decreasing with frequency, so that the upper band has so short an acquisition time that it only sees the ubiquitous plasma quasi-thermal noise [12]. The observations averaged over the year 2007 are compatible with the flux of nanoparticles obtained by extrapolating the interplanetary dust distribution with $dn_G/dm \propto m^{-11/6}$ [14].

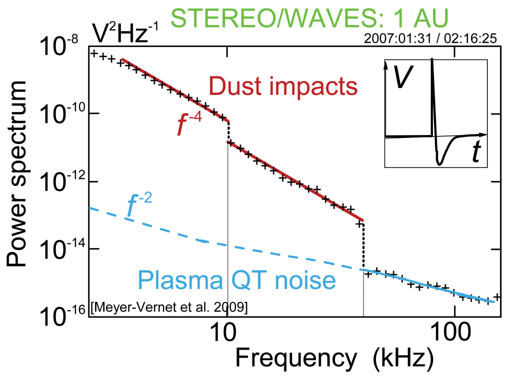

FIGURE 5. Example of power spectrum measured with STEREO/WAVES in the three l.f. bands, with a typical individual waveform inserted. The spectra in the two lower bands are produced by dust impacts; the higher band (of very small acquisition time) detects only the plasma quasi-thermal noise.

IMPLEMENTATION ON FUTURE MISSIONS IN THE INNER HELIOSPHERE

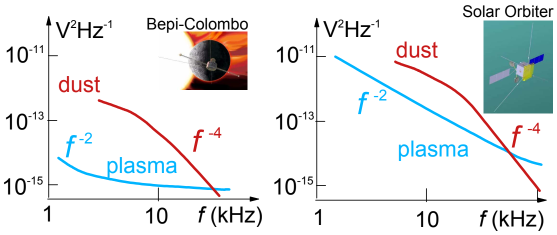

FIGURE 6. Modelled power spectrum from fast nanoparticle impacts on Bepi-Colombo with a 15-m monopole antenna in Mercury magnetospheric cavity (left) and on Solar Orbiter/RPW with a 1-m boom close to the spacecraft (right).

Wave instruments are used in routine on space missions to measure in situ the electron density and temperature, using quasi-thermal noise spectroscopy [13]. This requires dipole electric antennas longer than the ambient Debye length [12]. That wave instruments can also measure dust was realized when both the radio and the plasma wave instruments on Voyager 2 detected serendipitously micro-dust grains near Saturn - opening the way to a novel technique for measuring dust, subsequently applied in various environments [9].

The recent observations in the solar wind by STEREO/WAVES at 1 AU, and by Cassini/RPWS near Jupiter, the latter being simultaneous with observations by the on-board dust detector, showed that wave instruments can also measure fast nanoparticles. Even though wave detection of dust has still to be systematically calibrated, it is complementary to conventional methods because the wave technique has a very large collecting area (which can be the whole spacecraft), and is much less reliant on spacecraft attitude. Furthermore, it requires few additional resources since it is a by-product of the plasma wave instrument - only requiring that the returned data include also the monopole voltage.

Nanoparticles have never been observed in the inner heliosphere closer than 1 AU. Investigating their origin and dynamics, their interaction with the solar wind particles, and their possible contribution to the observed minor ions, is a major goal. We therefore propose to use the wave instruments on Bepi-Colombo, and on the project Solar Orbiter, to measure fast nanoparticles.

Figure 6 shows a simulation of voltage power spectra produced in monopole mode by fast nanoparticles impacting on Bepi-Colombo (left) and Solar Orbiter (right) near 0.3 AU. In both cases, we have estimated the particle flux by extrapolating inward the value detected at 1 AU on STEREO, and estimated the impact charge Q from the dust speed shown in Fig. 1. For Bepi-Colombo, with an antenna of 15-m length extending perpendicular to the spacecraft surface, the voltage pulses are expected to be due to the pulses in spacecraft potential δV_1. Figure 6 (left) shows that below a few tens kHz the power spectrum produced by fast interplanetary nanoparticles is expected to be much greater than the plasma quasi-thermal noise in the Hermean magnetospheric cavity [16].

For Solar Orbiter/RPW, we have assumed a 1-m boom close to the spacecraft, so that the voltage pulses produced by nanodust impacts are due to the pulses in boom potential δV_2, and are therefore of much greater amplitude. The corresponding voltage power spectrum in the solar wind is expected to exceed the plasma quasi-thermal noise at frequencies below a few tens kHz (Fig. 6, right).

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