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RESEARCH LETTER

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Key Points:

- First nanodust detection by Cassini near 1 AU
- Nanodust flux near 1 AU is determined
- Nanodust flux and variability are consistent with STEREO and models

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Nanodust detection near 1 AU from spectral analysis of Cassini/Radio and Plasma Wave Science data

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Abstract Nanodust grains of a few nanometers in size are produced near the Sun by collisional breakup of larger grains and picked up by the magnetized solar wind. They have so far been detected at 1 AU by only the two STEREO spacecraft. Here we analyze the spectra measured by the radio and plasma wave instrument onboard Cassini during the cruise phase close to Earth orbit; they exhibit bursty signatures similar to those observed by the same instrument in association with nanodust stream impacts on Cassini near Jupiter. The observed wave level and spectral shape reveal impacts of nanoparticles at about 300 km/s, with an average flux compatible with that observed by the radio and plasma wave instrument onboard STEREO and with the interplanetary flux models.

1. Introduction

Nanodust, which lie at the low end of the mass distribution of solar system bodies, bridge the gap between molecules and submicron grains. Their large surface-to-volume ratio implies that most of the atoms lie at the grains' surface, favoring the interactions with the ambient medium, whereas their high charge-to-mass ratio enables them to be picked up by moving magnetized plasmas similar to ions.

Nanodust grains have been observed in situ in a number of environments, such as those of comets [Utterback and Kissel, 1990], Jupiter [Grün *et al.*, 1993; Zook *et al.*, 1996], and Saturn [Kempf *et al.*, 2005; Hsu *et al.*, 2012]. In the interplanetary medium, the presence of nanodust produced in the inner solar system by dust collisional fragmentation [e.g., Grün *et al.*, 1985] and accelerated by the magnetized solar wind to about 300 km/s was predicted by Mann *et al.* [2007] and discovered aboard the Solar Terrestrial Relations Observatory (STEREO) [Driesman *et al.*, 2008] at 1 AU [Meyer-Vernet *et al.*, 2009a]. The presence of these particles has been suggested to have major consequences, especially in the inner solar system where their trapping [Czechowski and Mann, 2012] may produce high nanodust densities possibly contributing to the diffuse X-ray background [Kharchenko and Lewkow, 2012], whereas their contribution to the inner source of solar wind pickup ions [e.g., Gloeckler and Geiss, 1998] is a disputed question [Wimmer-Schweingruber and Bochsler, 2010; Mann and Czechowski, 2012]. The presence of nanodust in solar system plasmas is therefore of major consequence.

Even though the STEREO preliminary observations, which used the low-frequency receiver of the STEREO/WAVES instrument [Bougeret *et al.*, 2008], have been subsequently confirmed and improved by detailed analyses of data from an independent receiver, the time-domain sampler [Zaslavsky *et al.*, 2012], and by 5 years of data [Le Chat *et al.*, 2013], a confirmation onboard other spacecraft would be of major importance. This is the subject of the present letter. We analyze the power spectral density measured with the radio and plasma wave science (RPWS) instrument onboard Cassini in the solar wind, just after the Earth flyby (18 August 1999), when the instrument was turned on for 1 month. We show that these data reveal impacts on the spacecraft of nanodust streams accelerated by the solar wind, with average properties compatible with STEREO/WAVES observations.

2. Wave Instruments as Dust Detectors

Wave instruments are routinely used in space to measure in situ plasma properties via quasi-thermal noise spectroscopy with great accuracy and an equivalent cross section of detection much larger than traditional detectors [Meyer-Vernet *et al.*, 1998a]. This technique is based on the electric voltage pulses induced on

electric antennas by passing or impacting plasma particles [Meyer-Vernet and Perche, 1989]. Similarly, impact ionization produced by dust grains impinging on the spacecraft or antennas at high speed produces electric pulses that can be detected by wave instruments. This technique, pioneered when the Voyager spacecraft crossed Saturn's dusty rings [Aubier et al., 1983; Gurnett et al., 1983], has been refined [e.g., Meyer-Vernet et al., 1996, 1998b]. With Cassini/RPWS, it has been used to measure fast Jovian nanodust streams [Meyer-Vernet et al., 2009b] simultaneously with the Cosmic dust analyzer (CDA) instrument [Srama et al., 2004; Kempf et al., 2005], and it is currently used to measure microdust in Saturn's magnetosphere [Moncuquet and Schippers, 2013; Ye et al., 2013].

Wave instruments are complementary to dedicated dust detectors [Auer, 2001] because of their high sensitivity due to the effective surface area for dust detection being the whole spacecraft surface, with a 2π steradians acceptance solid angle. This is at the expense of a lack of velocity determination and large uncertainties. However, this technique requires generally two conditions. Since it is based on the detection of voltage pulses produced by the electric charges released by impact ionization, it first requires that the impact speed exceeds a few km/s [Auer, 2001]. Since the main target is the spacecraft surface, which tends to recollect the impact charges of sign opposite to that of its floating potential (i.e., the electrons in the solar wind), voltage levels measured between each antenna arm and the spacecraft (the so-called monopoles) are expected to be similar. It then also requires that the antennas must be connected in monopole mode instead of dipole mode (i.e., measurement of the difference of potential between two antenna arms). Unfortunately, most wave instruments use antennas in dipole mode. This is so because this mode is generally better adapted for wave measurements (yielding a greater and better determined antenna effective length), except for direction finding or polarization determination purposes. In that dipole mode, the dust impact signal is generally much smaller, since a change in spacecraft potential modifies negligibly the antenna potential, so that the detection requires asymmetries of the system [Meyer-Vernet et al., 2014]. This holds except when the constraints imposed by mission priorities impose less adequate antenna mounting geometries as was the case for STEREO [Driesman et al., 2008], for which the antenna location caused them to be frequently immersed in the impact plasma [Zaslavsky et al., 2012].

The difference between monopole and dipole mode for dust detection is well illustrated with Cassini/RPWS, which includes three electric antenna booms, one of which is always used as a monopole while the two others are either used as a dipole (i.e., the "dipole + monopole" mode) or a monopole (i.e., the "three monopole" mode or commonly called "Direction Finding" mode). Impacts of E ring microdust [Moncuquet and Schippers, 2013] and Jovian nanodust [Meyer-Vernet et al., 2009b] were observed to produce similar signals on each monopole and much smaller signals on the dipole [Meyer-Vernet et al., 2014], in contrast to radio and plasma waves which generally produce different voltages on the different monopoles and greater voltages in dipole mode.

A further property of the voltage pulses produced by dust impacts is that the pulse rise time τ_r is of the order of tens of μs . Therefore, the voltage power spectrum has a steep spectral shape, proportional to f^{-4} at frequencies exceeding $1/2\pi\tau_r$, of the order of a few kHz.

3. Dust Impact Identification

During the investigated time period, the Cassini spacecraft was oriented such that the high-gain antenna (HGA) was pointing to the sunward direction and the Huygens probe was put in the spacecraft velocity plane [Matson et al., 2002]. The three antenna booms of the RPWS instrument are connected to a suite of five receivers designed to measure electrostatic and electromagnetic waves in Saturn's magnetosphere. In the present study, we analyze the data from the high-frequency receiver HFR (3.5 kHz–16 MHz) from 20 August (day 232) to 15 September (day 258) of 1999. Figure 1a displays the time frequency electric power spectral density measured by the RPWS/HFR between 6 and 10 September in monopole mode. In addition to solar type III bursts and plasma quasi-thermal noise around the electron plasma frequency (f_{pe}), we observe low-frequency bursty activity characterized by sudden voltage enhancements, below 20 kHz.

Figure 1b displays two spectral cuts on 8 September (day 251), one at 20:19 UT (black solid line) and the other at 20:20 UT (black dashed line). The spectrum at 20:20 UT displays a trend close to a power law in ω^{-2} (blue curve in Figure 1). This signature is typically produced by the shot noise due to impacts of the ambient electrons on the spacecraft body and antennas [Meyer-Vernet, 1983; Meyer-Vernet and Perche, 1989]. The spectrum at 20:19 UT displays a much higher amplitude with a steeper slope, proportional to

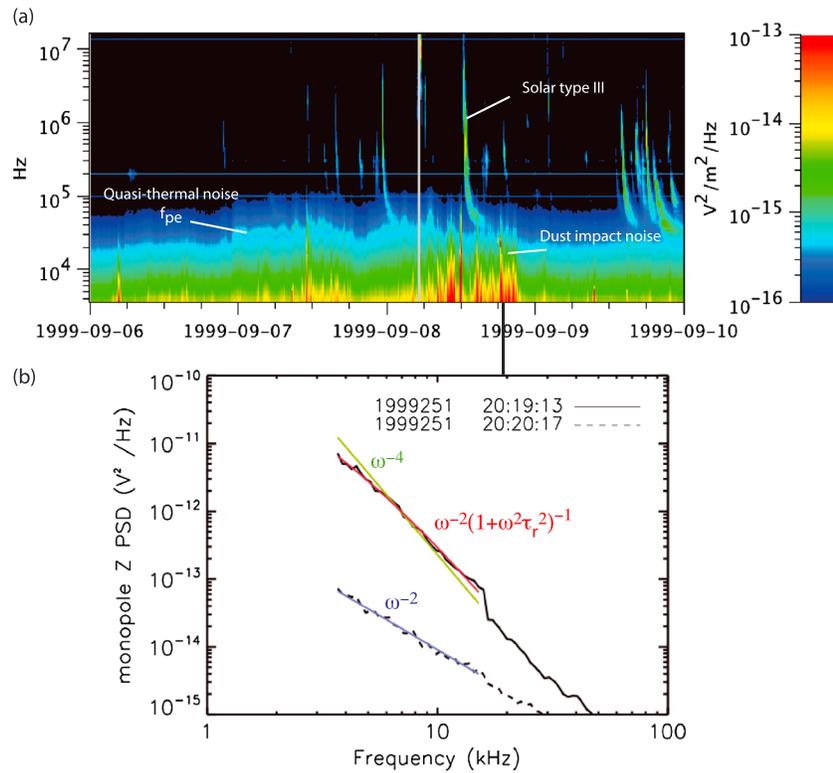


Figure 1. (a) RPWS/HFR dynamic spectrum in electric power spectral density ($V^2/m^2/Hz$) between day 249 (6 September) of 1999 and day 253 (10 September) of 1999 with the antenna z in monopole mode. (b) Voltage power spectral density spectra at 20:19 UT and 20:20 UT on day 251 (8 September) of 1999, in solid and dashed lines respectively. Three power spectral density models are superimposed: (1) $V_f^2 \propto \omega^{-4}$ (in green), (2) $V_f^2 \propto \omega^{-2}$ (in blue), and (3), $V_f^2 \propto \omega^{-2}(1 + \omega^2\tau_r^2)^{-1}$ (in red).

a power law $\omega^{-|n|}$, with index n close to 4. Such a spectral shape is similar to the dust particle impact signature [Meyer-Vernet *et al.*, 1986] and routinely observed on Cassini/RPWS in association with nano [Meyer-Vernet *et al.*, 2009b] and micro [Moncuquet and Schippers, 2013] dust impacts. Indeed, as indicated in section 2, the impact of a dust grain on the spacecraft creates a plasma cloud whose expansion decouples the ion and electrons which are then recollected by the spacecraft surface, depending on the sign of its electric potential. The Fourier transform of the approximate signal induced by one dust particle impact is [Aubier *et al.*, 1983]:

$$V_{\bar{n}}^2 \simeq 2\delta V^2 \omega^{-2}(1 + \omega^2\tau_r^2)^{-1} \tag{1}$$

where δV is the maximum pulse amplitude, τ_r is the pulse rise time, at frequencies $f = \omega/2\pi$ much higher than the inverse of the pulse's decay time τ_d . When $\omega\tau_r \gg 1$, equation (1) simplifies into

$$V_{\bar{n}}^2 \simeq 2(\delta V^2/\tau_r^2)\omega^{-4} \tag{2}$$

Models (1) and (2) have been adjusted to the 20:19 UT spectrum and are displayed in red and green, respectively, in Figure 1b. Model (1) reliably fits the measurement, with $\tau_r \simeq 30 \mu s$.

4. Dust Flux Determination

4.1. MIMI INCA Discharges

To characterize extensively the dust flux profile during the time period of interest, we have to take into account an issue reported by the Magnetospheric Imaging Instrument (MIMI) [Krimigis *et al.*, 2004] team concerning collimator discharges during the early mission. It was reported that with the negative high voltage applied to the Imaging Neutral Camera (INCA) [Krimigis *et al.*, 2004], charged particle rejection plates turned to maximum values, discharges were experienced that disturbed the measurement of the MIMI

instrument itself and might have contaminated the radio measurements of RPWS. The origin of such discharges has not been fully elucidated yet but sunlight shining on the plates and dust hits appear to be responsible for some of them. In order not to use contaminated data, we had to identify and discard the discharge events in our data set. To do so, we used noise indicators observable in a few MIMI/INCA control parameters (the instrument incorporated a discharge monitor for just this possibility). This allowed us to discard a dozen discharge events. Note that the RPWS measurements later in the mission were no more affected by the MIMI/INCA discharges issue because these were significantly diminished after the negative voltage mode was turned off on day 13 of 2001.

4.2. Interpretation of the Voltage Spectra

Let us now check whether the dust signatures identified in Figure 1 are consistent with impacts of the interplanetary nanograins picked up by the solar wind, identified by *Meyer-Vernet et al.* [2009a].

The dust signatures are observed only in monopole mode and are similar on the three monopole antennas. This indicates that the dust is detected via charge recollection by the spacecraft (since the spacecraft is positively charged in the solar wind, these charges are electrons.) Such a detection mechanism is similar to that by which nanodust was detected near Jupiter by Cassini/RPWS [*Meyer-Vernet et al.*, 2009b].

The maximum voltage δV produced by a dust grain impact on the spacecraft and measured by each monopole antenna is:

$$\delta V \simeq \Gamma Q/C \quad (3)$$

where Q is the charge released, C is the spacecraft capacitance (200 pF), and Γ is the antenna gain $\simeq 0.4$ [*Gurnett et al.*, 2004]. The impact generated charge Q strongly depends on the grain speed and can be approximated by [*McBride and McDonnell*, 1999]:

$$Q = 0.7mv^{3.5} \quad (4)$$

with Q (Cb), the grain mass m (kg) and v (km/s). Nano-sized grains picked up by the solar wind can be accelerated up to a speed $\simeq 300$ km/s near 1 AU provided that their mass is smaller than about 5×10^{-20} kg [*Mann et al.*, 2010].

We determine the flux of nanograins by equating the theoretical equation (2) and measured power spectra V_f^2 at $f = 10$ kHz since at and above this frequency, the spectrum varies approximately as f^{-4} . The theoretical power spectral density V_f^2 induced by a distribution of grains with flux $F(m)$ is

$$V_f^2 \simeq S \int_{m_{\min}}^{m_{\max}} dm \frac{dF(m)}{dm} V_f^2(m) \quad (5)$$

where S is the effective spacecraft surface area ($\simeq 15$ m²), and m_{\min} and m_{\max} are respectively the grain minimum- and maximum-detected mass. We assume that

1. the cumulative flux is of the form

$$F(m) = F_0 m^{-5/6} \quad (6)$$

according to the interplanetary dust distribution model by *Grün et al.* [1985] for masses below 10^{-18} kg.

2. the spectral density induced by one grain V_f^2 is defined by equation (2) where δV is given by equation (3) so that

$$V_f^2 \propto F_0 m_{\max}^{7/6} / \omega^4 \quad (7)$$

since m_{\min} is much lower than m_{\max} .

The maximum mass m_{\max} is the smallest between (i) the mass m_0 ($\simeq 5 \times 10^{-20}$ kg) above which the grains are no longer significantly accelerated by the solar wind and ii) the greatest mass that can impact the spacecraft during the integration time $\Delta t \simeq 0.15$ s, i.e., such that $F(m_{\max})S\Delta t \simeq 1/e$. Hence,

$$m_{\max} = \min[m_0, (eS\Delta t F_0)^{6/5}] \quad (8)$$

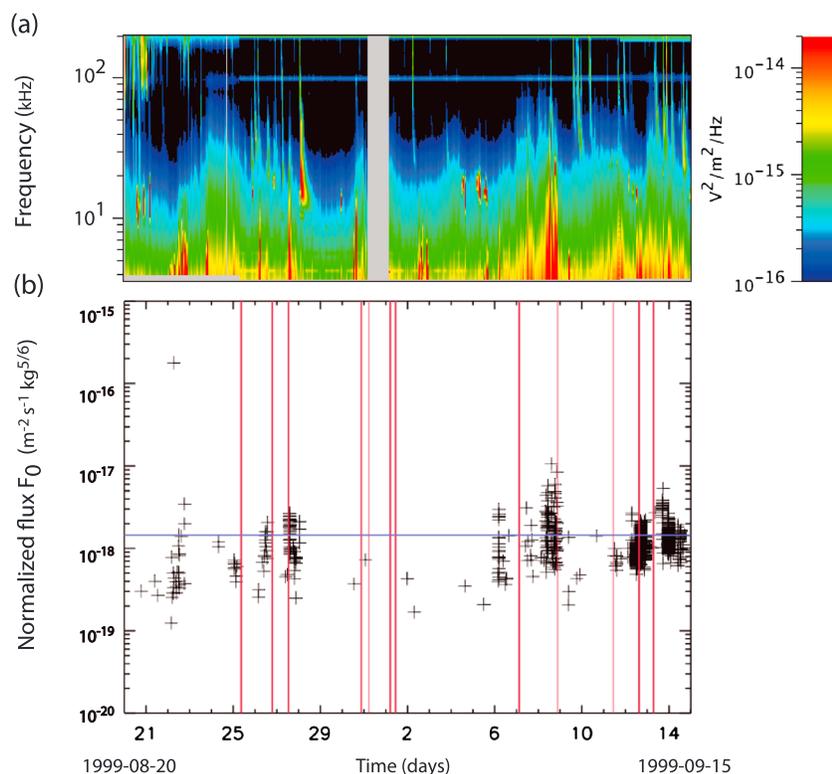


Figure 2. (a) RPWS/HFR dynamic spectrum in electric power spectral density ($V^2/m^2/Hz$) below 200 kHz, between day 232 (20 August) of 1999 and day 258 (9 September) of 1999. (b) Coefficient F_0 determined from our analysis in function of time. The horizontal blue line represents the average value of F_0 calculated over the whole time interval. The red vertical lines indicate the times when MIMI/INCA discharges were identified.

Figure 2 displays the electric power spectral density measured by RPWS/HFR between 3 and 200 kHz (Figure 2a) and the normalized flux F_0 (Figure 2b) deduced for the time period from 20 August (day 232) to 15 September (day 258) of 1999.

In order to eliminate the contributions of discharges, radio and plasma emissions, and plasma quasi-thermal noise, we have carefully selected the times when

- (1) the receiver does not display signatures due to MIMI/INCA discharges, according to section 3.1 (red vertical lines on Figure 2b indicate the times when discharges were identified),
- (2) the average index of the power law adjusted to the measured spectrum lies between -2.2 and -4 ,
- (3) the measurements of the three monopoles (u , v , w) are similar (within 50%) when the instrument is in direction finding mode [Meyer-Vernet *et al.*, 2009b], and
- (4) the ratio between the measurement of monopole w and the dipole is greater than a factor of 3. As discussed in section 2, conditions (3) and (4) enable us to eliminate contributions from plasma wave electric fields.

Figure 2b shows that most of the low-frequency electric power density enhancements are identified as dust signatures according to our criteria. The normalized flux values F_0 we derived oscillate from 10^{-19} and $10^{-17} m^{-2} s^{-1} kg^{5/6}$ during the whole time period. We note that the strong criteria may underestimate the number of dust detections. Relaxing this selection criteria would increase by 35% the number of detections while including outliers (i.e., F_0 bigger than $10^{-16} m^{-2} s^{-1} kg^{5/6}$). We note then that our data selection does not change the order of magnitude of the results.

Figure 3 displays the cumulative flux (ϕ) (in yellow) calculated from the RPWS/HFR during the time interval displayed in Figure 1a. The minimum, maximum, and average flux are displayed in red. Cumulative flux derived from the low-frequency receiver (LFR) [Meyer-Vernet *et al.*, 2009a] and the waveform Time Domain Sampler (TDS) [Zaslavsky *et al.*, 2012] of STEREO/WAVES instrument are superimposed with black

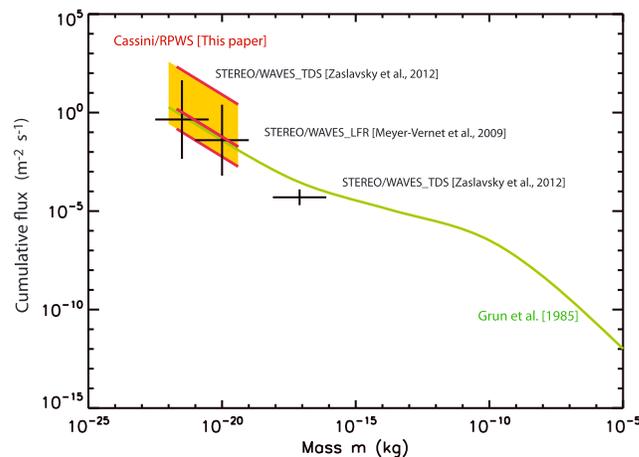


Figure 3. Cumulative flux ($\text{m}^{-2} \text{s}^{-1}$) as function of the mass (kg). Our results using the form $F = F_0 m^{-5/6}$ is displayed with a thick red line. STEREO results from Meyer-Vernet et al. [2009a] and Zaslavsky et al. [2012] are displayed with black crosses. Grün et al. [1985] model is displayed with a green heavy line.

crosses as well as the interplanetary dust distribution model [Grün et al., 1985] (green curve). As noted above, since the values displayed correspond to selected data, the minimum flux indicated is not the actual minimum flux during the period considered, but the minimum flux when nanodust signatures are observed without any ambiguity, which represents a small fraction of this period. With this proviso, the Cassini results are consistent with the previous interplanetary nanodust detection. The flux is also consistent with the most likely value of the flux of particles of mass greater than 10^{-20} kg derived from the statistical survey from Le Chat et al. [2013] based on 5 years (from 2007 to 2011) of STEREO/WAVES/LFR data [Le Chat et al., 2013, Figure 5].

5. Discussion

We analyzed the high-frequency radio data measured onboard Cassini spacecraft during its cruise phase in the solar wind near 1 AU and identified a bursty low-frequency noise which is consistent with the impacts of nano-sized grains on the spacecraft surface. The present analysis, based on Cassini/RPWS data, supports and confirms the presence of the nanograins in the solar wind near 1 AU as previously identified by Meyer-Vernet et al. [2009a] and Zaslavsky et al. [2012] from STEREO/WAVES data analysis and their bursty nature.

The observed variability with burst-like features is not surprising and was also observed on STEREO [Meyer-Vernet et al., 2009a; Zaslavsky et al., 2012; Le Chat et al., 2013]. First of all, because of equations (7) and (8), the power density varies very fast with F_0 . Indeed, $V_f^2 \propto F_0^{12/5}$ when m_{max} is determined by the right-hand side term in the bracket of equation (8), which occurs most of the time. Hence, a small variation in flux produces a large variation in power spectral density. Because of the short transit time from the inner solar system to 1 AU, the intrinsic flux variability may be produced by variations in nanodust trapping near the Sun due to magnetic field changes in the inner solar system [Czechowski and Mann, 2012], as well as to changes in dust collisional rates [Mann and Czechowski, 2012]. Furthermore, the Lorentz force driving nanodust trajectories varies in permanence at virtually all scales due to variations in both solar wind speed and magnetic field, producing variability in nanodust flux and arrival direction [Mann and Czechowski, 2012; Juhász and Horányi, 2013].

Although not designed for dust detection, the high-frequency receiver of Cassini/RPWS has demonstrated its capability to sound nanodust in the interplanetary medium. Similar signatures in a region close to the asteroid belt at 2.7 AU are now under study.

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