

# Effect of the Interplanetary Medium on Nanodust Observations by the *Solar Terrestrial Relations Observatory*

G. Le Chat<sup>1,2,3</sup> · K. Issautier<sup>1</sup> · A. Zaslavsky<sup>1</sup> ·  
F. Pantellini<sup>1</sup> · N. Meyer-Vernet<sup>1</sup> · S. Belheouane<sup>1</sup> ·  
M. Maksimovic<sup>1</sup>

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**Abstract** Dust particles provide an important part of the matter composing the interplanetary medium; their mass flux at 1 AU is similar to that of the solar wind. Dust grains of nanometer size-scale can be detected using radio and plasma wave instruments because they move at roughly the solar wind speed. The high-velocity impact of a dust particle generates a small crater on the spacecraft: the dust particle and the crater material are vaporized. This produces a plasma cloud whose associated electrical charge induces an electric pulse measured with radio and plasma instruments. Since their first detection in the interplanetary medium, nanodust particles have been routinely measured using the *Solar Terrestrial Relations Observatory*/WAVES experiment [S/WAVES]. We present the nanodust properties measured using S/WAVES/*Low Frequency Receiver* [LFR] observations between 2007 and 2013, and for the first time present evidence of coronal mass ejection interaction with the nanodust, leading to a higher nanodust flux measured at 1 AU. Finally, possible influences of the inner planets on the nanodust flux are presented and discussed.

**Keywords** Interplanetary dust · Nanodust · In situ dust detection · Radio antennas · STEREO/WAVES · Solar wind · Coronal mass ejections

## 1. Introduction

Interplanetary nanodust has been detected at 1 astronomical unit [AU] (Meyer-Vernet *et al.*, 2009; Zaslavsky *et al.*, 2012; Le Chat *et al.*, 2013) by a radio- and plasma-wave instrument, the *Solar Terrestrial Relations Observatory*/WAVES experiment [S/WAVES] (Bougeret *et al.*, 2008). This detection has recently been confirmed using the *Cassini/Radio and*

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✉ G. Le Chat  
gaetan.lechat@obsmp.fr

<sup>1</sup> LESIA-Observatoire de Paris, CNRS, UPMC Univ. Paris 6, Univ. Paris Diderot, 5 Place Jules Janssen, 92195 Meudon, France

<sup>2</sup> NASA Lunar Science Institute, Moffet Field, CA, USA

<sup>3</sup> Harvard-Smithsonian Center for Astrophysics, Cambridge, USA

*Plasma Wave Science* [RPWS] instrument (Schippers *et al.*, 2014). This detection is made possible by the interaction between nanodust and the interplanetary plasma and magnetic field, which accelerate the particles to solar wind speed because of their relatively high charge-over-mass ratio (Mann *et al.*, 2010). The amplitude of the signal induced by a dust grain impacting a spacecraft grows much faster with speed than with the mass of the dust particle (McBride and McDonnell, 1999). As a result, nanodust can produce a strong signal, despite their low mass (Zaslavsky *et al.*, 2012; Pantellini *et al.*, 2013).

Interactions between magnetized plasma and nanodust determine the dynamics of the nanoparticles, which enabled detecting the nanodust and allows these particles to escape solar gravity (Czechowski and Mann, 2010; Mann *et al.*, 2010; Juhász and Horányi, 2013; Belheouane, 2014). Concepts of probing the interplanetary magnetic field using nanodust stream particles in the magnetosphere of Saturn have also been proposed (Hsu *et al.*, 2011, 2013).

After describing nanodust observations and providing a statistical analysis of the nanodust flux measured by *S/WAVES Low Frequency Receiver* [LFR] between 2007 and 2013 (see Section 2), we here study the effects of transient events in the solar wind on nanodust fluxes. We show for the first time that coronal mass ejections can interact with interplanetary nanodust, which leads to a higher nanodust flux measured at 1 AU (Section 3). Finally, we show evidence that the inner planets affect the observed nanodust flux and discuss the ramifications of this (Section 4).

## 2. Nanodust Observations

Although the radio experiment on STEREO was not designed to measure dust, nanodust particles are observed by two of the *S/WAVES* instruments: i) the *Low Frequency Receiver* [LFR], which is a spectrum analysis receiver observing from 2.5 kHz to 160 kHz designed to measure the ubiquitous plasma thermal noise and solar radio bursts; ii) the *Time Domain Sampler* [TDS], which produces high-rate samples of waveforms primarily to study Langmuir waves (Bougeret *et al.*, 2008). Detailed analyses of nanodust measurements were made by Le Chat *et al.* (2013) using LFR and by Zaslavsky *et al.* (2012) using TDS.

When nanodust is observed on STEREO-A, the impact zone is close to the X-antenna, producing a voltage pulse that typically is 20 times higher than in the two other antenna booms, as shown by the TDS measurements (Zaslavsky *et al.*, 2012). The voltage pulse on the X-antenna is given by Pantellini *et al.* (2013)

$$\delta V_X = \Gamma \frac{Q_a(l)}{C_a}, \quad (1)$$

with

$$Q_a(l) \approx j_{\text{ph},1\text{AU}} 2r_0 l \tau, \quad (2)$$

the charge of photoelectrons emitted during a time  $\tau$  by a boom of length  $l$  and radius  $r_0$ , with  $j_{\text{ph},1\text{AU}}$  the photoelectron current density at 1 AU.  $\Gamma \approx 0.5$  and  $C_a = 60$  pF are the antenna gain and capacitance (Bale *et al.*, 2008). Assuming equipartition between the average potential energy of the photoelectrons bound to a boom of length  $l$  (and total charge  $Q_a(l)$ ) and their thermal energy, Equation (1) can be simplified to

$$\delta V_X \approx \frac{\Gamma T l}{L}, \quad (3)$$

where  $L = 6$  m is the antenna length (Bale *et al.*, 2008),  $l$  is the length of the antenna within the plasma cloud, and  $T = 2.5$  eV is an effective temperature given in eV, which is of the order of the photoelectron temperature (Zaslavsky *et al.*, 2012; Pantellini *et al.*, 2012, 2013; Le Chat *et al.*, 2013). The parameter  $l$  in Equations (2) and (3) implies that there is a critical radius  $R_C$  up to which the antenna is affected by the plasma cloud created by the impact. The existence of  $R_C$  has been extensively demonstrated in Zaslavsky *et al.* (2012). The critical radius  $R_C$  can be interpreted as the radius for which the electron number density of the ambient plasma is large enough to screen the charge created by the impact, whose electric field perturbs the antenna photoelectrons (Pantellini *et al.*, 2013).  $R_C$  is given by  $R_C \approx (3Q/4\pi en_a)^{1/3}$ , where  $Q$  is the charge of the cloud created by the dust impact on the spacecraft, and  $n_a$  is the ambient electron density.  $Q$  is given with a large uncertainty by (McBride and McDonnell, 1999)

$$Q \approx 0.7mv^{3.5}. \tag{4}$$

Le Chat *et al.* (2013) have shown that the rise time  $[\tau]$  and the amplitude  $[\langle N\delta V^2 \rangle]$  (where  $N$  is the number of impacts per time unit) obtained from the fitting of the LFR spectra of STEREO-A allow inferring the nanodust flux observed at 1 AU from the relation

$$\langle N\delta V^2/\tau^2 \rangle \approx f_0\pi K^4 m_{R_{SC}}^{-\gamma+7/3} \left( \frac{\Gamma T}{L\tau} \right)^2, \tag{5}$$

where  $K = R_C/m^{1/3} \approx (3 \times 0.7v^{3.5}/4\pi n_a e)^{1/3}$ .  $m_{R_{SC}} = (R_{SC}/K)^3$  is the mass of the impacting dust for which  $R_C = R_{SC} = 0.84$  m, with  $R_{SC}$  the effective size of the spacecraft (Zaslavsky *et al.*, 2012; Le Chat *et al.*, 2013). The flux of particles of mass between  $m$  and  $m + dm$  is given by  $f(m)dm = f_0 m^{-\gamma} dm$ , where  $\gamma$  is assumed to be equal to 11/6, which corresponds to collisional equilibrium. While assuming a value for  $\gamma$  is necessary to obtain numerical values of the nanodust flux measured by STEREO-A/WAVES LFR, deviation from collisional equilibrium can be expected.

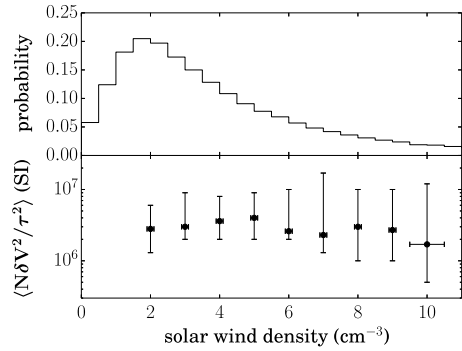
In Equation (5), both  $K$  and  $m_{R_{SC}}$  are functions of the ambient electron density  $[n_a]$ . This leads to the following relation between LFR dust signals  $[\langle N\delta V^2/\tau^2 \rangle]$  and  $n_a$ :

$$\begin{aligned} \langle N\delta V^2/\tau^2 \rangle &\approx f_0\pi k^{3(\gamma-1)} R_{SC}^{7-3\gamma} \left( \frac{\Gamma T}{L\tau} \right)^2 n_a^{1-\gamma} \\ &\approx f_0\pi k^{5/2} R_{SC}^{3/2} \left( \frac{\Gamma T}{L\tau} \right)^2 n_a^{-5/6}, \quad \text{for } \gamma = 11/6, \end{aligned} \tag{6}$$

with  $k \approx (3 \times 0.7v^{3.5}/4\pi e)^{1/3} \approx 8 \times 10^8$  for a typical value of the impact speed  $v = 300$  km s<sup>-1</sup>. Two electron populations contribute to the ambient density  $[n_a]$ : the spacecraft photoelectrons and the solar wind plasma. Because of the anti-sunward position of the antenna on the STEREO spacecraft (Bougeret *et al.*, 2008; Bale *et al.*, 2008), the expansion of the cloud away from the spacecraft surface, and the absence of direct measurements, we cannot estimate  $n_a$  precisely.

Figure 1 (bottom) shows the value of  $\langle N\delta V^2/\tau^2 \rangle$  observed by STEREO-A/WAVES LFR from January 2007 to December 2013 as a function of the solar wind density measured by PLASTIC. The values plotted are the most probable value [mode] and the full width at half maximum [FWHM] observed for a given solar wind density. The large FWHM is primarily due to the variable nature of the nanodust flux seen by STEREO-A in the interplanetary medium (Zaslavsky *et al.*, 2012; Le Chat *et al.*, 2013), with variations spanning three orders of magnitude, with a very asymmetric distribution. Figure 1 (top) also provides the histogram of the solar wind density to illustrate the increasing statistical error of the mode of

**Figure 1** Histogram of the solar wind density measured by STEREO-A/PLASTIC (top) and the mode and full width at half maximum of dust signals observed by STEREO-A/WAVES LFR *versus* solar wind density (bottom).



**Table 1** Flux of nanodust observed at 1 AU by STEREO-A/WAVES LFR. The systematic errors correspond to the worst cases (see text).

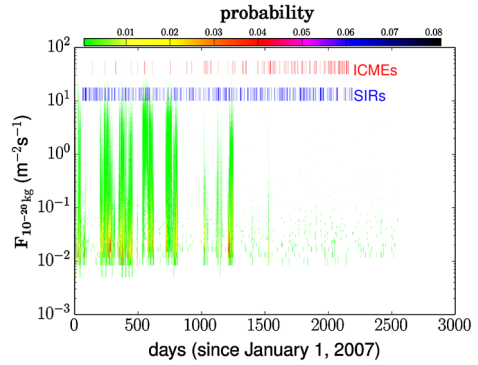
	$f_0$ [kg <sup>-1</sup> m <sup>-2</sup> s <sup>-1</sup> ]	$F_{10-20 \text{ kg}}$ [m <sup>-2</sup> s <sup>-1</sup> ]
Mean (lower limit)	$2.9 \times 10^{-18}$	0.16
Mean (upper limit)	$2.4 \times 10^{-17}$	1.34
Standard deviation	$3.6 \times 10^{-17}$	2
Mode	$2.5 \times 10^{-19}$	$1.4 \times 10^{-2}$
FWHM	[ $1.42 \times 10^{-19}$ ; $1.1 \times 10^{-18}$ ]	[ $8 \times 10^{-3}$ ; $5 \times 10^{-2}$ ]
Systematic error (underestimation)	$1.1 \times 10^{-16}$	6.2
Systematic error (overestimation)	$-2 \times 10^{-19}$	$-1.1 \times 10^{-2}$

$\langle N\delta V^2/\tau^2 \rangle$  as density increases as a result of the lack of measurements at high solar wind density. Figure 1 shows that the observed signal does not vary as expected with the solar wind density. Neither the value of  $n_a$  nor its variations could be precisely estimated, and as in our previous study, we here take  $n_a = 5 \text{ cm}^{-3}$  but assume that it may increase to ten times more while estimating the error of the measurements given in Table 1.

Table 1 provides statistical values (means, standard deviation, mode, and full width at half maximum [FWHM]) of the flux of nanodust obtained using STEREO-A/WAVES LFR measurements. However, because of the sporadic behavior of the STEREO-A/WAVES nanodust measurements (Zaslavsky *et al.*, 2012; Le Chat *et al.*, 2013), it is only possible to calculate two extreme values for the mean. The upper value is obtained by only considering the 651 246 spectra with dust measurements. The lower value is obtained by assuming that there is no nanodust when not measured by STEREO-A, *i.e.* assuming  $f_0 = 0$  for the 4779 857 spectra without dust signals observed between January 2007 and December 2013. The upper value must be an overestimate since, as stated by Le Chat *et al.* (2013), LFR cannot observe individual nanodust impacts or values of  $\langle N\delta V^2/\tau^2 \rangle$  lower than the quasi-thermal noise of the solar wind plasma. On the other hand, the lower value may be an underestimate due to the effect of the spacecraft geometry and of the dynamic properties of the nanodust, which in some interplanetary field configurations defocused the nanodust away from the ecliptic plane on which STEREO-A is orbiting (Belheouane, 2014; Juhász and Horányi, 2013).

In Equation (6), the parameter  $k$ , the effective temperature  $T$ , and the density  $n_a$  are not measured but estimated to be at a constant value. This leads to systematic errors on the flux measurements, for which two worst cases can be calculated and are given in Table 1. These

**Figure 2** Variation with time of the cumulative flux of particles of mass greater than  $10^{-20}$  kg measured by STEREO-A/WAVES LFR between 2007 and 2013. Red vertical bars correspond to the time periods when STEREO-A encounters ICMEs, while blue ones indicate SIR events.



errors can be directly added to the values of the upper limit mean, mode, and FWHM, but must be multiplied by the ratio of dust measurements over the number of spectra (*i.e.* 0.12) before being added to the lower limit mean. The largest underestimation of the nanodust fluxes is obtained using the lowest possible value of  $k$  and  $T$  and the highest density  $n_a$ . The largest overestimation is obtained with the highest value of  $k$  and  $T$  and the lowest possible ambient density. These errors are dominated by the uncertainty of the value of the parameter  $k$ . The error on the parameter  $k$  can be estimated to be an order of magnitude and comes from both the uncertainty on the charge  $Q$  created by the impacting dust (Equation (4)) and of the relative speed of the dust relative to the spacecraft due to changes in the direction of the dust speed. It is noteworthy that this latter uncertainty also plays a significant role in the observed standard deviation.

### 3. Effect of Transient Events on Dust Measurements

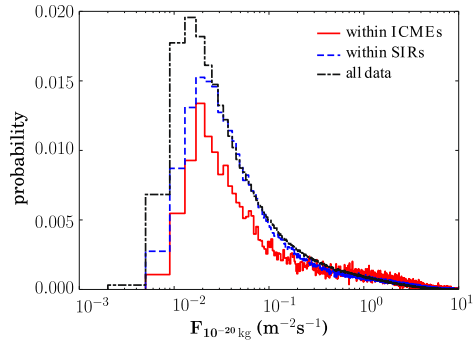
Transient events in the solar wind, such as interplanetary coronal mass ejections [ICME] and stream interaction regions [SIR], locally change the solar wind and interplanetary magnetic field properties. These modifications would change the dynamic behavior of already released nanodust, or might allow part of the trapped nanodust below 0.2 AU from the Sun to be accelerated outwards (Czechowski and Mann, 2010; Mann *et al.*, 2010). We have determined the transient events observed by STEREO-A using the detection mechanism for ICMEs and SIRs given by Jian *et al.* (2006a, 2006b, 2013).

Figure 2 compares periods when STEREO-A was within transients to the cumulative flux of particles heavier than  $10^{-20}$  kg: red vertical bars correspond to the time periods when STEREO-A encounters ICMEs, while blue ones indicate SIR events. No time correlation between either ICMEs or SIR events and the observed flux of nanodust is observed. During solar activity maximum, when the number of observed ICMEs increased in STEREO-A data, the number of spectra with nanodust signatures decreased significantly, but studies of the dynamics of the nanodust suggest that this is due to the defocusing configuration of the interplanetary magnetic field, which pushes the nanodust released in the inner heliosphere away from the ecliptic (Juhász and Horányi, 2013).

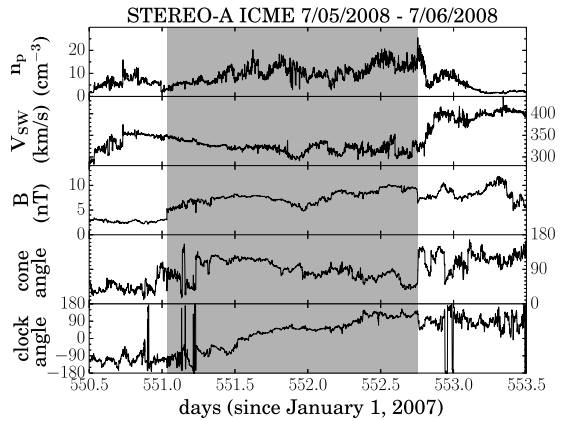
Figure 3 shows histograms of  $F_{10^{-20}\text{kg}}$  measured by STEREO-A within ICMEs (red solid line), within SIRs (blue dashed line), and for all dust measurements (black dashed-dotted line).

The distribution of the measurements within SIRs has a mode at  $F_{10^{-20}\text{kg}} = 1.8 \times 10^{-2} \text{ m}^{-2} \text{ s}^{-1}$ , compared to the one of the whole dataset at  $F_{10^{-20}\text{kg}} = 1.3 \times 10^{-2} \text{ m}^{-2} \text{ s}^{-1}$ .

**Figure 3** Histogram of the cumulative flux of particles heavier than  $10^{-20}$  kg for all dust measurements (black dashed-dotted line) compared to measurements within ICMEs (red solid line) and within SIRs (blue dashed line). Note the log-scale on the X-axis.



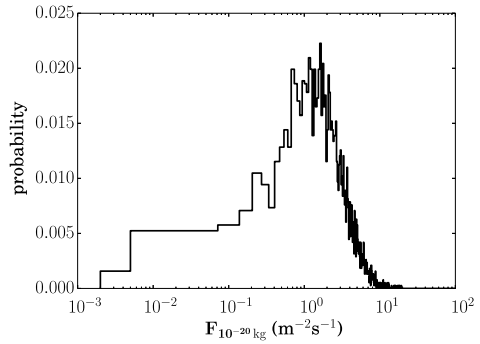
**Figure 4** Density, bulk speed, magnetic field strength, magnetic cone angle, and magnetic clock angle measured by STEREO-A during the ICME on July 5–6, 2008 (gray area).



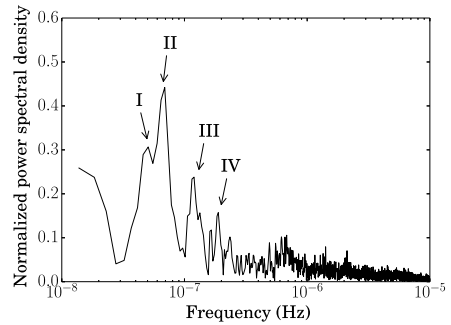
The nanodust flux within SIRs is slightly higher than for the whole dataset; but the distribution of the flux higher than  $3 \times 10^{-2} \text{ m}^{-2} \text{ s}^{-1}$  is similar to the one obtained for the whole S/WAVES LFR dataset.

A bimodal distribution appears for nanodust measurements within ICMEs, the first mode at  $F_{10^{-20} \text{ kg}} = 1.8 \times 10^{-2} \text{ m}^{-2} \text{ s}^{-1}$  and the second at  $F_{10^{-20} \text{ kg}} = 2 \text{ m}^{-2} \text{ s}^{-1}$ . The values of both modes of the cumulative fluxes are higher than the value observed for the whole dataset. Furthermore, the proportion of measurements corresponding to fluxes higher than  $1 \text{ m}^{-2} \text{ s}^{-1}$  is larger for the measurements within ICMEs than for either the whole dataset or the measurements within SIRs. The second peak of the distribution comes from four ICMEs with plasma and magnetic field properties similar to those represented in Figure 4 for the ICME detected by STEREO-A on July 5–6, 2008. The distribution of the nanodust cumulative flux within these four ICMEs has similar properties to the distribution plotted in Figure 5, which corresponds to the July 5–6, 2008 ICME. These four ICMEs have the following common plasma properties: i) a bulk speed between  $300$  and  $400 \text{ km s}^{-1}$ ; ii) a magnetic clock angle in RTN coordinates varying from  $-90^\circ$  or slightly lower (*i.e.* mainly aligned with the normal direction pointing southward) to  $90^\circ$  or slightly higher (*i.e.* mainly aligned with the normal direction pointing northward), as seen in the bottom panel of Figure 4. No influence of the magnetic field strength within the ICMEs has been found. The six other ICMEs, observed by STEREO-A while measuring nanodust, show a distribution of the cumulative flux with only one mode around  $F_{10^{-20} \text{ kg}} = 1.8 \times 10^{-2} \text{ m}^{-2} \text{ s}^{-1}$ , have typical speeds higher than

**Figure 5** Histogram of the cumulative flux of particles heavier than  $10^{-20}$  kg within the ICME detected by STEREO-A on July 5–6, 2008. Note the log-scale on the X-axis.



**Figure 6** Periodogram of the cumulative flux of particles heavier than  $10^{-20}$  kg measured by STEREO-A/WAVES LFR. The labeled peaks of the normalized spectral power density are discussed in Section 4. Note the log-scale on the X-axis.



$400 \text{ km s}^{-1}$ , and do not show the magnetic field rotation within the  $T$ – $N$  plane from  $-90^\circ$  to  $90^\circ$  observed in the four others.

While the physical process at the origin of the higher nanodust fluxes observed within these ten ICMEs is not yet understood, our hypothesis is the following: first, nanodust is accelerated by a focusing interplanetary magnetic field [IMF] to a speed close to that of the ICMEs, allowing the dust to interact with the plasma and magnetic field of the ICMEs. For the ICMEs whose inner magnetic field is in a focusing configuration, the interacting nanodust is trapped within the ICME, leading to the observed higher nanodust fluxes. This process also explains the absence of nanodust observed within ICMEs outside a focusing IMF configuration. This is for instance illustrated in Figure 2 between 2011 and 2013 where the number of ICMEs increased while nanodust observations nearly disappeared as a result of the large-scale configuration of the IMF.

#### 4. Effect of the Inner Planets on the Dust Flux Measured by STEREO-A

As one can see on Figure 2 and in Zaslavsky *et al.* (2012) and Le Chat *et al.* (2013), the nanodust flux observed by STEREO-A/WAVES LFR is highly variable and some periodic patterns can be seen. Figure 6 is the periodogram of the cumulative flux of particles heavier than  $10^{-20}$  kg. Because of the uneven temporal sampling of S/WAVES LFR, the periodogram has been computed using a Lomb–Scargle periodogram algorithm (Lomb, 1976; Scargle, 1982; Townsend, 2010). Four significant frequencies appear in the periodogram, labeled from I to IV from lowest to highest frequency in Figure 6.

The most significant peak, labeled II in Figure 6, appears at a frequency of  $(6.9 \pm 0.3) \times 10^{-8}$  Hz. This frequency corresponds to the inverse of half the orbital period of STEREO-A.



It can be explained by the dynamic behavior of the nanodust and the large-scale IMF focusing configuration between 2007 and 2010. During this time, the spacecraft has crossed the large-scale neutral line every half-rotation, as expected based on simulations of the dynamics of the interplanetary nanodust in the inner solar system (Juhász and Horányi, 2013; Belheouane, 2014; Mann, Meyer-Vernet, and Czechowski, 2014).

Three other peaks, labeled I, III and IV, appear at the following frequencies:  $(5.1 \pm 0.3) \times 10^{-8}$  Hz,  $(1.20 \pm 0.03) \times 10^{-7}$  Hz, and  $(1.90 \pm 0.03) \times 10^{-7}$  Hz. Peak I is close to the inverse of Venus' orbital period ( $5.15 \times 10^{-8}$  Hz), peak III is close to the inverse of Mercury's orbital period ( $1.32 \times 10^{-7}$  Hz), and peak IV is close to the inverse of Mercury's rotation period ( $1.97 \times 10^{-7}$  Hz). While it is possible that these are coincidental, they may also represent clues of either interaction between the inner planets and the nanodust (or the dust particles responsible for the observed nanodust) or that these planetary bodies are sources of interplanetary nanodust. It is noteworthy that these frequencies are related to the planets' orbital period and not to the synodic periods from the point of view of STEREO-A (whose frequencies would be  $1.8 \times 10^{-8}$  Hz and  $9.8 \times 10^{-8}$  Hz for Venus and Mercury, respectively). This implies that STEREO-A does not observe nanodust streams coming from these two planets, unlike the ones observed near outer planets (see Hsu, Krüger, and Postberg 2012 and references therein), but that both Venus and Mercury increased the number of nanodust in the interplanetary medium around a fixed point on their respective orbits. A simple explanation could be the perturbation of cometary trails crossing these planets' orbits, which leads to a higher local collision rate, which in turn produces more nanoparticles. The last peak corresponds to the Mercury rotation period and may be due to a hot spot on the surface of Mercury releasing dust into the interplanetary medium when illuminated by the Sun.

## 5. Conclusions

A main result of the work presented here is the observation of the effect of ICMEs on the flux of nanodust measured at 1 AU (see Section 3). This effect is another example of the dynamical influence of the magnetized solar wind on nanodust particles, which includes the acceleration of the nanodust to speeds close to the solar wind speed (Czechowski and Mann, 2010; Mann *et al.*, 2010; Juhász and Horányi, 2013; Belheouane, 2014), and the increase of the nanodust stream flux ejected by Saturn's magnetosphere (Hsu *et al.*, 2011, 2013; Hsu, Krüger, and Postberg, 2012). Our analysis showed that ICMEs can trap nanodust that has already been accelerated, but their trapped nanodust may not be detected at 1 AU with STEREO-A when the large-scale interplanetary magnetic field is in the defocusing configuration (Juhász and Horányi, 2013). Future nanodust dynamic simulations coupled with semi-empirical full-MHD simulations of the solar corona and solar wind will provide significant insight into the interaction between the nanoparticles and the interplanetary medium. This will allow investigating the effect of the ICMEs observed in our study and testing the process suggested in Section 3.

In addition to the interaction with the plasma and magnetic field of the interplanetary medium, the nanodust flux observed by STEREO-A at 1 AU may be influenced by Venus and Mercury (see Section 4). Our result indicates that both planets increase the number of nanoparticles in the interplanetary medium as the planetary bodies encounter regions of higher interplanetary dust density, such as cometary trails.

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