WAVES FOR PLASMA
PLASMAS FOR WAVES

Monopole and dipole electrical signatures of near-solar hypervelocity dust impacts recorded with Solar Orbiter

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Abstract/Résumé

A deeper understanding of interplanetary dust dynamics is desirable, as it holds significance for heliospheric and planetary space science. Operating within 1 AU, Solar Orbiter (SolO) and Parker Solar Probe (PSP) venture as close as <0.3 AU and <0.05 AU from the Sun, respectively. Despite lacking dedicated dust detectors, both spacecraft detect dust in-situ upon impact through rapid measurements facilitated by their electrical antenna suites.

Our investigation focuses on analyzing SolO's antennas' response to individual dust impacts on a statistical basis, as this instrument provides both monopole (antenna to spacecraft) and dipole (antenna to antenna) electrical measurements, as opposed to PSP, which mostly performs dipole measurements. The primary objective is to attain understanding of how the hypervelocity impacts produce signals on the antennas, which enables the examination of high-level data from both spacecraft. Specifically, we present a study of SolO's monopole time-domain data, providing insights into the impact process, particularly in relation to monopole and dipole data acquisition. This understanding is then used for the analysis of PSP's data.

1 Introduction

A lot remains unknown about the interplanetary dust dynamics, especially in the vicinity of the Sun: the location and the properties of the near-solar dust free zone, the particulars of the collisional griding process in the interplanetary dust cloud (also known as zodiacal cloud), and the dynamics of dust much smaller than the visible light wavelength (also known as nanodust), to mention a few. Near-solar in-situ measurements are therefore priceless for answering the open questions [1].

Solar Orbiter (SolO) and Parker Solar Probe (PSP) both orbit the Sun in inner heliosphere, that is <1AU. Neither of these is equipped with a dedicated dust detector, but both allow for in-situ on-collision dust detection, recording the plasma effects that accompany the hypervelocity impacts with their respective antenna instruments. The process of impact onto a positively charged spacecraft has been studied extensively previously (e.g. [2, 3]), yet the understanding is still limited to simple cases. While both spacecraft provide dust detection capability in the dipole (antenna-antenna) mode, only SolO provides monopole (antenna-body) mode, which is much easier to interpret. Given the similarities between the spacecraft, we study the difference between monopole and dipole dust detection capabilities of SolO, to use the knowledge for PSP data interpretation.

2 Dust impact process

A dust grain colliding with a solid object at high relative speed, that is ≥km/s, is destroyed and at least partially vaporized and ionized due to great energies present on impact [7]. Consider a hit on the spacecraft's body (as opposed to less likely, yet possible hit on the spacecraft's electrical antenna). Should the spacecraft be on an electrical potential different from the local plasma potential, such as if illuminated by the sunlight, the local electric field acts to separate the impact-generated charge plume, which in turn creates a disturbance, which is possibly picked up by the electrical measurements. There are several possible scenarios for the disturbance, depending on the spacecraft's state and the impact location, angle, etc.

The impact happens on the surface of the body; therefore, the generated plume is initially coupled to the spacecraft body. Since the plume is quasi-neutral, the generation of the plume is not observed per se in the first order. As some of the charges escape from the vicinity of the spacecraft due to the present electrical field, the change in the spacecraft's potential is induced. Should the impact happen on a positively charged spacecraft, which is the typical scenario if the spacecraft is illuminated by the sunlight, then the electrons in the impact plume with energy insufficient to escape are retained by the spacecraft, while virtually all the ions are repelled. Given the difference in the time scale, electrons with sufficient energy escape first, then the ions escape. Once the process is over and all the impact charges are collected by the spacecraft or have escaped, the spacecraft's body is left on a different potential than before, hence out of equilibrium. Now the ambient plasma currents act to equalize this potential on a timescale slower than the timescale of the charge separation process described in this paragraph.

There are two typical measurement arrangements for the electrical antennas: monopole and dipole. In the monopole configuration, the antennas measure voltage with respect to a common ground, that is the body of the spacecraft. In the dipole arrangement, two antennas measure with respect to each other, see Fig. 1. The monopole configuration is therefore the sole one that is sensitive to the changes in the spacecraft body's potential. The typical evolution of the electric potential of the spacecraft body upon a dust impact is shown in Fig. 2. Note that in the typical monopole measurement, the voltage is measured with respect to the body (antenna - body), therefore the signature would have shown reversed in the measured waveforms, hence predominantly positive.

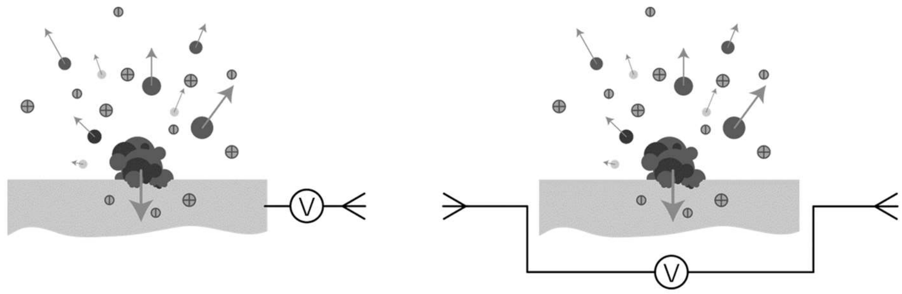

Figure 1: Monopole (left) and dipole (right) configuration of the electrical antennas. Only the monopole configuration is sensitive to the changes in the spacecraft body's potential in the first order.

The photoelectron sheath is present near the illuminated metallic surfaces of the spacecraft. It is the result of the trajectories of the photoelectrons, most of which do not have energy sufficient to escape the potential well of the spacecraft, yet they reach the extent comparable with the size of the spacecraft before they return to the body of origin. They are an important complication for the understating of the process, since they are believed to shield the much slower escaping ions [2]. They were however used to explain the hard to understand single-hits observed with STEREO spacecraft [3].

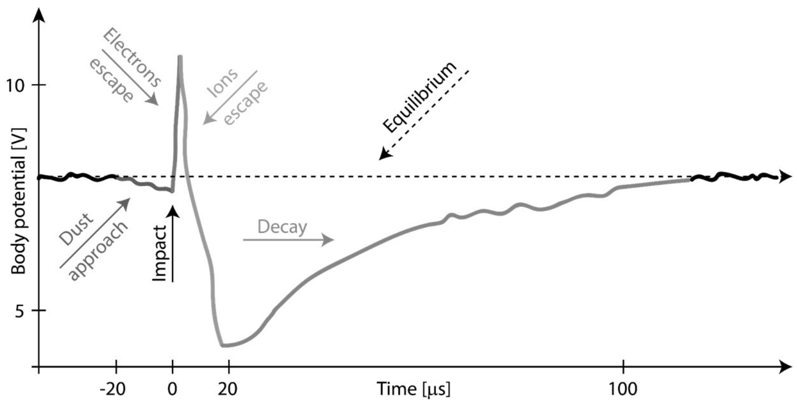

Figure 2: The typical spacecraft body's electrical potential evolution as a result of a dust impact. The time scales approximate those of Solar Orbiter and the amplitudes are much larger than usually observed.

3 Impact signatures at Solar Orbiter

The monopole (antenna - body) impact signature is a positive peak caused by ions escaping from the impact site, as explained in the previous section. Upon inspection of high-resolution SolO/RPW electrical data, a previously unobserved feature was found: a secondary positive peak, decidedly delayed after the main positive peak, intermittently present in one or several channels [4,5]. It was concluded that this peak comes as a result of ions interfering with the antennas, mostly due to the delay of ≈100ms behind the main peak, and due to the strong asymmetry with respect to the three channels. Fig. 3 shows a clear example of such event, which only shows strong in the third channel. We note that the negative peak of escaping electrons is not pronounced in this event.

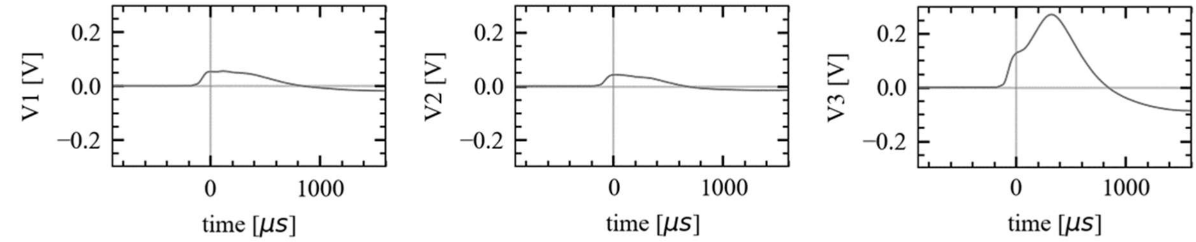

Figure 3: Three monopole electrical channels, as measured with SolO's RPW, produces by the time domain sampler.

A mechanism for generation of secondary positive peaks, compatible with our observations, was proposed previously as a means of explanation of certain features observed with Waves instrument onboard Solar Terrestrial Relations Observatory (STEREO) [6]. The newly observed features in SolO data are explained using this approach [4]. The mechanism relies on the assumption that the impact plume generated electric field is capable of liberating some of the otherwise bonded photoelectrons from the photosheath and therefore enhances the photocurrent for a short time. For detail, the reader is referred to [3,4]. Some of the specifics of SolO necessary for this phenomenon to occur are present at PSP, while other are not.

Importantly, the secondary peak's amplitude is not a linear function of the primary peak's amplitude and is very random, present intermittently. See the comparison between the well-understood primary peak and the newly reported secondary peak in Fig. 4.

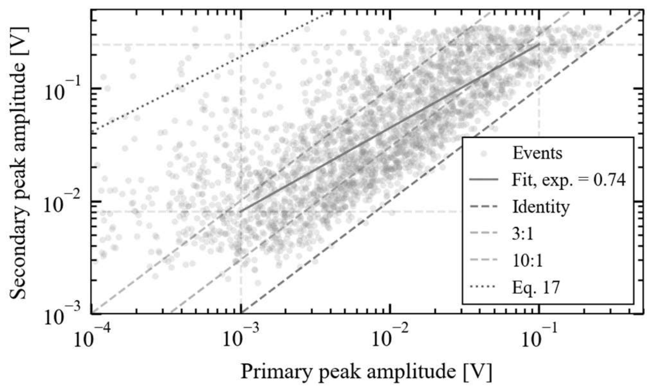

Figure 4: Three monopole electrical channels, as measured with SolO/RPW, produces by the time domain sampler.

4 Monopole vs. dipole effects

Generally speaking, monopole antenna configuration is favorable for dust detection, since in the first order approximation, the impact influences the spacecraft's body. Hence, measurements of antenna voltage against the body allow for detection of this effect [5]. Since PSP mostly records the peak values of electrical waveforms in dipole (antenna - antenna) configuration, it is of interest to study how much do the statistics of these differ from much better understood statistics of the monopole signals. It is of interest to study the response of Solar Orbiter in order to interpret the statistics obtained in the analysis correctly.

The secondary peak found in the Solar Orbiter data and described in the previous section is a dipole feature, since it doesn't show in all of the channels. It is the typical choice to focus on the amplitude measured in the channel which shows the strongest peak. It is however not the strongest peak, but the chronologically first peak, which is the better understood and the statistics of which can be therefore used to infer the properties of the impacting grains and the impact process. One should not assume the strongest peak to be the well understood monopole response.

Fig. 5 compares the peak voltage distribution evaluated in two distinct ways: 1. the solid line shows the histogram of the main positive peak in the monopole signal, specifically the smallest of the three recorded monopole peaks, which we consider to correspond to the primary peak reasonably well and therefore to be the best measure of the monopole response. 2. the dashed line shows the histogram of the highest observed maxima for each impact, specifically the maximum of the three monopole maxima detected during the impact. It is easily observed that the average amplitude obtained in the first way is lower and with a lower variance, compared to the amplitude obtained in the second way. Even more importantly, the amplitude obtained in the second way does not scale proportionally to the amount of the impact charge generated on impact.

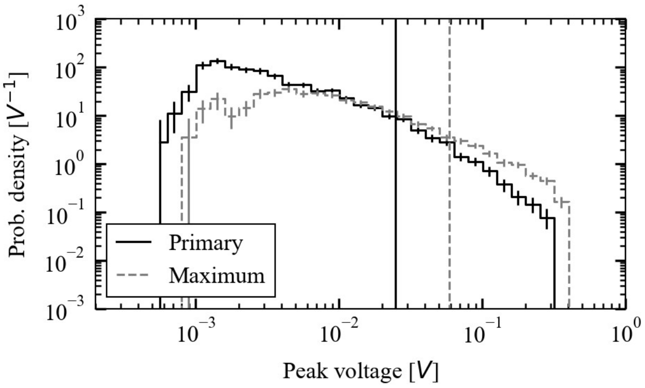

Figure 5: The primary peaks and the highest max amplitude histogram of all the SolO/RPW dust hits. The vertical lines show the mean value.

5 Parker solar probe and Solar Orbiter

The database of dust impacts recorded with PSP/Waves was recently published [6]. Thanks to Solar Orbiter, we have an opportunity to study a bias present in the PSP data. Since there is, generally speaking, a single monopole channel recording in PSP, the amplitudes of the peaks cannot be compared across several channels. We now assume the waveforms to be the same as with Solar Orbiter. This is a very crude assumption, given the different construction and the region of operation of PSP. Assuming this, we can however study what bias does this bring to the statistics of the impacts on PSP. We chose the solar Orbiter antenna number 2, which corresponds best to the PSP antenna V2 in terms of its orientation with respect to the Sun and ram directions. The histogram of the amplitudes collected in this way is shown in Fig. 6. This measure is comparable to the dust data which are provided for PSP/FIELDS [6], as these measurements also provide one monopole. We see that the bias is present, as the Antenna 2 does not report the same statistics as the primary peak, but the approximation is much better than it would have been in the case of analyzing the strongest of the three peaks.

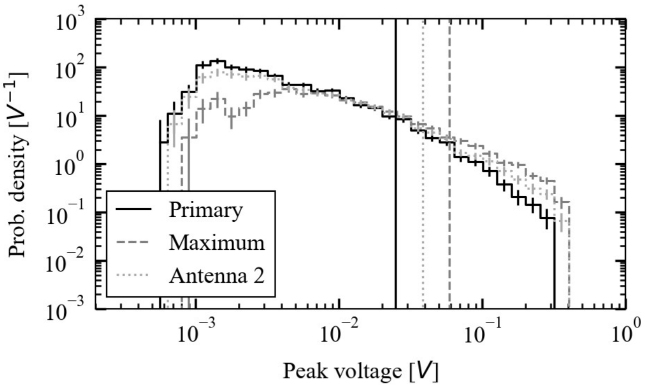

Figure 6: The same as in Fig. 5, but showing one more histogram: the histogram of the amplitudes as recorded if the same antenna is studied for all the impacts.

6 Conclusions

It was shown before by other authors and in the present work that the electrical antennas are sensitive to dust impacts onto spacecraft surfaces. With proper configuration and with the understanding of the limitations, properties of both the individual dust grains and the solar system dust cloud can be analyzed.

A double peak structure was found in Solar Orbiter electrical waveform data recently. The primary peak is well understood and linked to the alteration of the spacecraft potential due to the impact, while the secondary peak is of dipole quality, since it is different in each channel, usually showing prominently in a single channel. When approaching the statistical analysis of the properties such as the amplitude, rise and decay time, it is very important to sensitively distinguish between the primary and the secondary peaks. The highest of the present peaks should not be assumed proportional to the amount of impact-produced charge.

Making use of the three monopole channels available for Solar Orbiter, we studied the influence of the wrong choice of the amplitude measure. The bias is greatly reduced, when one analyzes a single given antenna rather than the maximum of the available antennas. This has relevance for PSP, where only one dipole is usually available, although the electronic process for PSP is different due to different construction and environment. This also has relevance for future analyses of the Solar Orbiter data, since Solar Orbiter has recently lost the electrical antenna 3. When interested in the amount of impact-generated charge, it is recommended to assume it proportional to the smaller of the two recorded amplitudes.

References

[1] Mann, Ingrid, et al. "Dust observations with antenna measurements and its prospects for observations with Parker Solar Probe and Solar Orbiter." Annales Geophysicae. Vol. 37. No. 6. Copernicus GmbH, 2019.

[2] Meyer-Vernet, Nicole, et al. "Frequency range of dust detection in space with radio and plasma wave receivers: Theory and application to interplanetary nanodust impacts on Cassini." Journal of Geophysical Research: Space Physics 122.1 (2017): 8-22.

[3] Pantellini, Filippo, et al. "Nano dust impacts on spacecraft and boom antenna charging." Astrophysics and Space Science 341 (2012): 309-314.

[4] Kočiščák, Samuel, et al. "Impact Ionization Double Peaks Analyzed in High Temporal Resolution on Solar Orbiter." EGUsphere 2023 (2023): 1-39.

[5] Kvammen, Andreas, et al. "Machine learning detection of dust impact signals observed by the Solar Orbiter." Annales Geophysicae. Vol. 41. No. 1. Copernicus GmbH, 2023.

[6] Malaspina, David M., et al. "A Dust Detection Database for the Inner Heliosphere Using the Parker Solar Probe Spacecraft." The Astrophysical Journal Supplement Series 266.2 (2023): 21.

[7] Friichtenicht, J. F. "Micrometeoroid simulation using nuclear accelerator techniques." Nuclear Instruments and Methods 28.1 (1964): 70-78.