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Do we detect interplanetary dust with Faraday cups?

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ABSTRACT

Transient clouds of a plasma generated by hypervelocity dust particles impacting onto the spacecraft were observed *in-situ* by many experiments over the last 20 years. The reported observations analyze sensitive measurements of plasma waves that are transmitted to the Earth with a sufficient time resolution. The detection is based on a fact that hypervelocity impacts generate plumes of the ionized gas expanding into a space. The present paper analyzes five years of the operation of the Bright Monitor of the Solar Wind (BMSW) onboard the Spektr-R spacecraft with a motivation to demonstrate that such type of the instruments is capable to observe the dust impacts into its detectors. The results of analysis are compared with Wind electric field measurements used for a detection of hypervelocity dust impacts.

1. Introduction

Microparticles known as dust are one of important components of the space environment. Their observation and investigation is a complex problem due to their small sizes and a high impact speeds. Moreover, their characteristics like a shape (often irregular), composition, porosity (ranging from fluffy to compact), density, and surface charge are different and depend on their origin, path from the origin to the observing spacecraft and on the surrounding environment.

Dust grains detected by the Earth-orbiting spacecraft can come from two sources. Interstellar dust with sizes from nanometers to centimeters recorded by the Ulysses spacecraft (Grün et al., 1993) originates in the local interstellar cloud beyond the asteroid belt (Frisch et al., 1999; Mann, 2010; Sterken et al., 2012). They enter the solar system with a relative velocity given by the Sun motion with respect to the interstellar environment ($\approx$ 26 km/s according to Mann (2010)). These grains create an important dust component along orbits of the giant planets (Mann et al., 2010) but can be also identified in the near-Earth orbit (Altobelli et al., 2006).

On the other hand, interplanetary dust originates within the solar system by fragmentation of larger bodies mainly due to mutual collisions or by bombardment of larger objects without an atmosphere like, for example, the Moon. According to Mann (2010), the solid objects within the solar system can be classified as meteoroids, zodiacal dust, β-meteoroids, and nanodust, depending on their mass. The approximate mass intervals are: $m > 10^{-8}$ kg for meteoroids, $m \approx 10^{-15}$–10^{-8} kg for zodiacal dust, $m \approx 10^{-18}$–10^{-15} kg for β-meteoroids, and $m < 10^{-18}$ kg for nanodust Mann (2010); Mann et al. (2010). Due to various masses (or sizes), their trajectories within the solar system can be affected by different forces (solar gravity, radiation pressure, and, for small charged grains, the Lorentz force connected with the interplanetary magnetic field (e.g., Mann, 2010; Sterken et al., 2012; Slavin et al., 2012)).

Information about dust in the heliosphere comes mainly from dedicated space detectors (e.g., Srama et al., 2004). For example, the Cassini-Huygens Cosmic Dust Analyzer (CDA) provided direct observations of dust grains with masses between 10^{-19} and 10^{-9} kg in interplanetary space and in the Jovian and Saturnian systems with the motivation to study their interaction with the rings, satellites and magnetospheres (Kempf et al., 2004; Srama et al., 2004; Spahn et al., 2006).

Another technique was demonstrated when the Voyager spacecraft passed through the Saturn ring plane. When a dust grain at high speeds impacts a spacecraft surface, a plasma cloud is generated. This transient cloud consists of vaporized and ionized grains as well as surface material (impact plasma) and it expands and interacts with spacecraft surface components. These effects are manifested as correlated intense pulse signals registered by electric field detectors and space plasma instruments. These voltage spikes originally interpreted as glitches or response to a spacecraft system were later attributed to a micron-sized cosmic dust impacting a spacecraft body (Scarf et al., 1982; Aubier et al., 1983; Gurnett et al., 1983). Later, micron-sized particle impacts of both interplanetary and interstellar origin were identified by the Plasma Wave Instrument during the Voyager flyby of Uranus (Meyer-Vernet et al., 1986a; Gurnett et al., 1987). The dust was detected in cometary environments by Vega or Giacobini-Zinner missions (e.g., Oberc, 1995;

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Meyer-Vernet et al., 1986b), in the Saturn's E ring with the Cassini Radio and Plasma Wave Instrument (Kurth et al., 2006; Ye et al., 2014) and in the solar wind at 1 AU with STEREO (e.g., Zaslavsky et al., 2012; Belheouane et al., 2012) and Wind WAVES instruments (Malaspina et al., 2014; Wood et al., 2015; Malaspina and Wilson, 2016; Kellogg et al., 2016). The technique was extended to measure fast dust in Jovian nanodust streams with Cassini (Meyer-Vernet et al., 2009a) and its application leaded to the discovery by STEREO of interplanetary nanodust picked up by the solar wind (Meyer-Vernet et al., 2009b; Zaslavsky et al., 2012; Le Chat et al., 2015).

The interpretation of antenna data is not simple due to several effects that include, for example, the details of the impact charge generation and properties of the spacecraft materials and near-spacecraft plasma environment. Using present knowledge on the impact plume generation and recollection of the impact charge, Malaspina and Wilson (2016) prepared a large database of micrometer sized interplanetary and interstellar dust detected by the Wind spacecraft. The present paper introduces a set of Faraday cups (FCs) of the Bright Monitor of the Solar Wind (BMSW) instrument onboard the Spektr-R mission that registered voltage spikes during high-time (≈ 30 ms) resolution measurements of the ion flux. We demonstrate a possibility to detect hypervelocity impacts of dust grains by such instruments and we compare the results with Wind dust impact detection. Furthermore, we discuss the opportunities for the grain detection in course of future missions and/or projects in the inner heliosphere such as Solar Probe Plus, THOR, and Luna-Resurs that are planned to be equipped with Faraday cup instruments.

2. BMSW instrument

The BMSW (Bright Monitor of the Solar Wind) instrument located onboard the Spektr-R spacecraft launched in August 2011 is dedicated to fast measurements of the moments of the ion energy distribution by a set of FCs. The orbital parameters are appropriate for solar wind monitoring because the orbital period is ≈ 8.5 days, with apogee of 333,570 km, and perigee of 576 km, thus the spacecraft is usually located in the solar wind for 7–8 days per orbit. BMSW was designed predominantly for very fast measurements of the solar wind parameters with a time resolution ranging from seconds to 31 ms and it is mounted on a solar panel to ensure its permanent orientation toward the Sun. It works in two basic modes that differ in time resolution and are used over parts of the orbit. Nevertheless, the ion current is registered each 31 ms regardless the working mode. The instrument itself and methods of its data processing are described in (Šafránková et al., 2013; Zastenker et al., 2013), thus we will mention only briefly the features important for the dust impact determination.

2.1. Experimental setup

BMSW measurements are based on simultaneous monitoring of collector currents from six FCs. Three of them point towards the Sun, the other three are inclined by 20° from the sunward direction. A presence of 6 FCs is the key feature because while the detector area is additive, an analysis of multiple separated channels can distinguish between dust events and larger plasma blobs.

A schematics of the FC design is shown in Fig. 1. The FC is equipped with four grids: grounded grids cover outer and inner diaphragms that define the angular characteristics, a positive control grid is placed at an equidistance from outer and inner diaphragms, and a suppressor grid lies between the inner diaphragm and the collector. The grounded grids are used for an elimination of the internal electric field outside FC. The positive control grid is connected to a tunable HV source and thus only the ions with the velocity sufficient to overcome the grid potential can reach the collector. The suppressor grid is powered by a negative potential of ≈ −300 V. This potential returns back photoelectrons emitted from the collector by the solar UV radiation as well as solar wind electrons. The value of the suppressor grid potential is sufficient for precise measurements in a plasma with the electron temperature up to ≈ 100 eV. The electron component of the collector current caused by photoelectrons from the suppressor grid should be subtracted from the total measured current. A geometry of an individual FC should provide a measurable ion current for all possible angles of incidence and in a full range of expected plasma parameters in the solar wind. BMSW itself is oriented toward the Sun with an accuracy of 10° but its real orientation is known with a 1° precision.

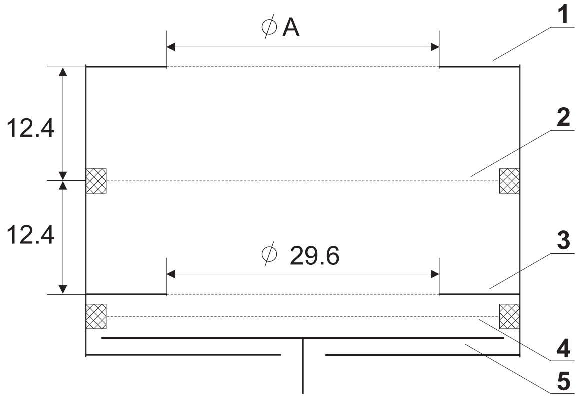

Fig. 1. A design of the Faraday cup: (1) and (3) are outer and inner diaphragms with grounded grids, respectively; (2) a positive control grid, (4) a suppressor grid, (5) a collector. Diameters of the entrance windows are $A = 20$ mm for the FCs pointing toward the Sun and A = 32 mm for three inclined FCs.

The voltages applied on control grids of two of the six FCs that are dedicated for the speed and temperature determination can change abruptly and thus we do not use these FCs in our search for possible dust impacts. The total collection area of the remaining four FCs is about 27 cm^2. The detection of the dust impacts relies on the fact that the dust particle generates impact plume of the evaporated and ionized material.

A dust grain entering a FC via the entrance window could either impact the FC walls in the space between outer (1) and inner (3) diaphragms or they can pass a grid covering the inner diaphragm. We do not consider the possibility of the impact onto the grid wires because the probability of such impact is very low (15 μm wires, 1.0 mm spacing). There is no electric field in the space between inner and outer diaphragm, thus an evolution of the impact plume would be analogous to that described, for example, by Collette et al. (2016) for the dust impact onto a spacecraft body. Fast electrons would leave the plume first but they cannot reach the FC collector due to a large negative potential of the suppressor grid. The plume ions (accelerated by the ambipolar electric field) reaching the grid covering the inner diaphragm are accelerated toward the suppressor grid but the modeling of possible trajectories using the SIMION software package (Ion and Electron Optics Simulator, http://simion.com/) shows that a portion of them would reach the collector and create a positive impulse. The number of the ions reaching the collector would strongly depend on the impact location because such ions should have a significant velocity component directed along the FC axis when reaching the grid covering the inner diaphragm.

The positive impulses could also result from ion impact plumes generated outside a FC near its entrance window. Consequently, the direction of the dust velocity is highly uncertain, the collection area is not well defined, and the relation of the pulse amplitude to the impact parameters (mass, velocity) is very weak. On the other and, dust grains passing the both diaphragms should come from a cone with an angle ±40° centered around the FC axis, where the collection area is given by the entrance window. Moreover, such grains should impact the collector due to the FC geometry. The energy of a 1 μm grain with the velocity ≈ 30 km/s is of the order of 10^{12} eV and its charge hardly exceeds 10^4