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Optimization of the Nano-Dust Analyzer (NDA) for operation under solar UV illumination

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ABSTRACT

The performance of the Nano-Dust Analyzer (NDA) instrument is analyzed for close pointing to the Sun, finding the optimal field-of-view (FOV), arrangement of internal baffles and measurement requirements. The laboratory version of the NDA instrument was recently developed (O'Brien et al., 2014) for the detection and elemental composition analysis of nano-dust particles. These particles are generated near the Sun by the collisional breakup of interplanetary dust particles (IDP), and delivered to Earth's orbit through interaction with the magnetic field of the expanding solar wind plasma. NDA is operating on the basis of impact ionization of the particle and collecting the generated ions in a time-of-flight fashion. The challenge in the measurement is that nano-dust particles arrive from a direction close to that of the Sun and thus the instrument is exposed to intense ultraviolet (UV) radiation. The performed optical ray-tracing analysis shows that it is possible to suppress the number of UV photons scattering into NDA's ion detector to levels that allow both high signal-to-noise ratio measurements, and long-term instrument operation. Analysis results show that by avoiding direct illumination of the target, the photon flux reaching the detector is reduced by a factor of about 10^3. Furthermore, by avoiding the target and also implementing a low-reflective coating, as well as an optimized instrument geometry consisting of an internal baffle system and a conical detector housing, the photon flux can be reduced by a factor of 10^6, bringing it well below the operation requirement. The instrument's FOV is optimized for the detection of nano-dust particles, while excluding the Sun. With the Sun in the FOV, the instrument can operate with reduced sensitivity and for a limited duration. The NDA instrument is suitable for future space missions to provide the unambiguous detection of nano-dust particles, to understand the conditions in the inner heliosphere and its temporal variability, and to constrain the chemical differentiation and processing of IDPs.

1. Introduction

The Nano-Dust Analyzer (NDA) instrument is designed for the detection and chemical analysis of nano-sized dust particles originating in the inner heliosphere (O'Brien et al., 2014). Such particles are generated by the collisional break-up of interplanetary dust particles (IDPs) and subsequently accelerated outward by the expanding solar wind (Czechowski and Mann, 2010). Recently, the wave antennas on the two STEREO spacecraft reported the detection of a large number of voltage spikes, which were interpreted as nano-dust particle impacts on the spacecraft and the generated impact plasma signal picked up by the antennas (Meyer-Vernet et al., 2009). The detection and chemical analysis of the nano-dust particles delivered to ~1 AU using a dedicated and calibrated instrument is desired for a number of reasons: (1) It would provide the reliable impact rate and possibly the mass distribution of the detected particles that are difficult to determine from wave instrument measurements. (2) The monitoring of the angular distribution and temporal variability of the dust flux would allow learning about conditions in the inner heliosphere, nano-dust dynamics, and/or the source mechanisms of nano-dust particles. (3) The elemental composition information of nano-dust particles would constrain the chemical differentiation and processing (e.g., loss of volatiles) of interplanetary dust particles slowly spiraling towards the Sun.

The NDA instrument and its characteristics are described in detail by O'Brien et al. (2014). Briefly, the NDA is a linear time-of-flight (TOF) dust analyzer operating on the basis of impact ionization and its design is loosely derived from the Cosmic Dust Analyzer (CDA) instrument operating on the Cassini spacecraft (Srama et al., 2004). In a hypervelocity impact on a solid target, the dust particles evaporate and ionize, with the ion composition bearing the characteristics of the

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dust. The schematic of the instrument is depicted in Fig. 1. The target is 20 cm in diameter and is curved with a radius of 30 cm. The target is electrically biased and the positive ions are accelerated away using a high open area curved grid at ground potential in front of the target. The ions are analyzed in a TOF fashion upon arrival to the ion detector placed at the center point of the target, mounted in a small housing. Due to the linear arrangement, the mass resolution is limited by the initial energy distribution of the generated ions. The laboratory version of the NDA instrument was tested and characterized using the dust accelerator facility operated at the University of Colorado (Shu et al., 2012). The mass resolution is approximately $m/\Delta m = 50$, and shows little variation with the dust impact location (O'Brien et al., 2014).

A numerical study was performed to determine the angular distribution of particles that pass nearby the orbit of the Earth, where they are detectable from a spacecraft operating outside of the magnetosphere. The angular distribution of the incoming particles is a function of the dust size and the configuration of the interplanetary magnetic field (IMF). For more details on the performed simulations and the temporal variability of the nano-dust flux, see, for example, Juhasz and Horanyi (2013). Fig. 2 shows reproduction of the results presented in O'Brien et al. (2014). For small particles, typically below 10 nm in radius, the velocity vector is close to the ecliptic plane with approximately a 20° azimuth angle. Particles larger than 10 nm will arrive either from the southward or northward direction, depending on the IMF orientation in the inner heliosphere. The directions in Fig. 2 are 'as seen' from Earth's orbit about the Sun.

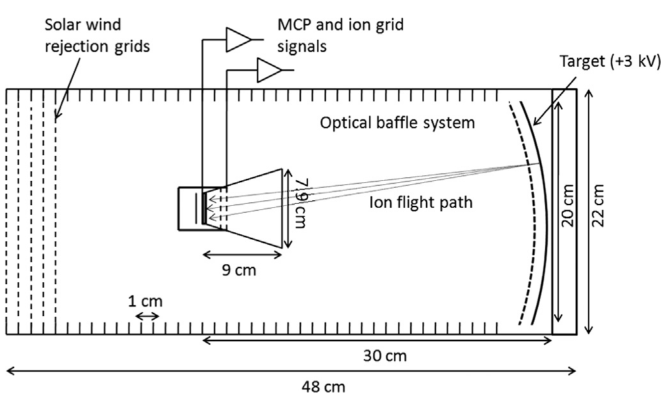

Fig. 1. Schematic drawing of the NDA instrument, optimized for exposure to UV radiation. Incoming dust particles impact the hemispherical target on the right. The generated ions are accelerated onto a detector by an electric field between the target and the curved grid. The aperture of the instrument is covered by a set of high open area grid electrodes that are used to prevent solar wind particles from entering. The optical baffles here are shown in their optimized geometry (see Sections 4 and 6).

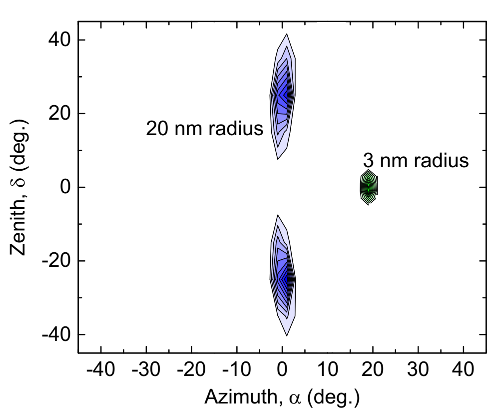

Fig. 2. Contour plot of the angular distribution of the direction of the velocity vector for 3 nm and 20 nm dust particles. Small dust particles are arriving at 1 AU nearly in the ecliptic plane at about 20° azimuth angle (α), while the concentration of larger dust particles exists symmetrically above and below the ecliptic plane at about 20–25° (δ, zenith). The Sun is at $\alpha=\delta=0°$.

The challenge in detecting and analyzing the nano-dust particles is in the pointing requirement of NDA that is close to the Sun's direction (Fig. 2). Some fraction of the solar UV photons entering through the aperture will inevitably scatter into the ion detector. The generated background noise then reduces the signal-to-noise ratio (SNR) of the recorded TOF spectra and also limits the lifetime of the ion detector. The straightforward way to reduce the level of UV background is to limit the field-of-view (FOV) of the instrument and avoid pointing at or near the Sun's direction. This approach, however, is in conflict with a desire of a large FOV instrument capable of detecting the nano-dust particles from all directions simultaneously, including that of the Sun's (Fig. 2). The analysis performed in this article finds the optimum compromise for sensitive detection of nano-dust particles by the NDA instrument in terms of FOV and pointing requirements. The expected UV noise background is analyzed in detail and a combination of low-reflectivity optical coatings and baffles is used to reduce it to acceptable levels. The analysis is performed using the ray-tracing program *Zemax* for Lyman-alpha radiation, which has the most significant effect on the NDA. The analysis shows that only an instrument with a relatively narrow FOV provides a feasible solution. This means that the continuous monitoring of nano-dust particles arriving from all expected directions requires operation from a scanning platform or spinning spacecraft. With the Sun in the FOV, the instrument is still capable of measurements but with reduced sensitivity and for a limited duration.

The sections below are organized as follows. The requirements for acceptable UV background are derived in Section 2. Section 3 discusses the general properties of UV reflection from surfaces and the contribution to noise from Lyman-alpha. Section 4 describes the design of the optical light trap system using baffles. Section 5 describes the performance analysis. Sections 6 and 7 present the results from the analysis and requirements on all optical surfaces that are necessary to reduce the UV effect to the required level and the conclusions, respectively.

2. Operation requirements

For the detection and chemical analysis of nano-dust particles, the generated impact charge and the total amount of ions in the individual TOF mass lines needs to be clearly above the solar UV background level. The charge generated by impact ionization depends on the mass, impact velocity, and target material (e.g., Auer (2001)). A number of laboratory studies were performed to determine the empirical relation between these parameters and find a power-law typically in the form of $Q = \alpha m v^{\beta}$, where Q is the generated impact charge, m is the mass, and v the velocity, while α and β are fitting parameters. Laboratory calibration measurements of the impact charge are limited by the capabilities of dust accelerators to a typical velocity range of 1–50 km/s (Mocker et al., 2011; Shu et al., 2012), though the range was recently reported to extend to 100 km/s. Nano-dust particles, however, arrive to Earth's orbit with velocities considerably higher, up to 300 km/s, depending on their mass (Juhasz and Horanyi (2013), and references therein).

Fig. 3 shows the extrapolations to high velocities of the power-laws for several high-Z materials that are potential target materials for NDA. Rhodium is used in the Cosmic Dust Analyzer (CDA) and Lunar Dust EXperiment (LDEX) instruments due to its resistance to oxidation and good impact ionization properties (Srama et al., 2004; Horanyi et al., 2014). It is beyond the scope of this article to discuss the validity of the extrapolation to high velocities. It is noted, however, that there is an associated uncertainty of several orders of magnitude in the predicted impact charge that the NDA