MEASURING MICRO-DEBRIS IN-SITU WITH THE DESTINY$^+$ DUST ANALYZER

M. Sommer[(1)], Y. Li[(1)], R. Srama[(1)], J. Simolka[(1)], H. Strack[(1)], J. Gläser[(1)], P. Fröhlich[(1)], A. Exle[(1)], S. Ingerl[(1)], M. Bauer[(1)], A. Mocker[(1)], H. Krüger[(2)], P. Strub[(2)], M. Kobayashi[(3)], T. Hirai[(3)], and T. Arai[(3)]

[(1)] University of Stuttgart (Institute of Space Systems), Stuttgart, Germany, Email: sommer@irs.uni-stuttgart.de
[(2)] Max Planck Institute for Solar System Research, Göttingen, Germany
[(3)] Chiba Institute of Technology (Planetary Exploration Research Centre), Chiba, Japan

ABSTRACT

The DESTINY$^+$ Dust Analyzer (DDA) is a planetary science instrument for the JAXA mission DESTINY$^+$. For the first 2 years of the mission, the spacecraft will remain bound to the Earth on highly eccentric orbits, giving DDA the opportunity to sample debris dust, the smallest artificial objects in space. With its ability to analyze composition and dynamics of impacting grains, DDA is able to distinguish natural, interplanetary dust grains from artificial dust in orbit around the Earth. This micro-debris population is thought to stem primarily from solid rocket motor exhaust and poses a hazard to sensitive satellite surfaces. Here we discuss DDA's potential to study micro-debris on the basis of results obtained from ESA's MASTER model, as well as previous in-situ measurements in Earth-orbit.

Keywords: in-situ dust detection; impact ionization; MASTER.

1. INTRODUCTION

The JAXA-led small body science mission DESTINY$^+$, is designated to study the dust environment in near-Earth interplanetary space, as well as the poorly understood active asteroid Phaethon. Set to launch in 2024, the probe carries two cameras to image Phaethon during a flyby, as well as the DESTINY$^+$ Dust Analyzer (DDA), which will sample grains released from Phaethon's surface, as well as interplanetary and interstellar dust during the four years leading up to the Phaethon encounter. The probe will spend the first two years of its mission in Earth-orbit, using its ion-engines to spiral up from a GTO-like initial orbit, and finally escape the Earth-Moon system via a series of Lunar gravity assist manoeuvres. Besides its main science objectives, DDA will thus have the opportunity to study micro-debris at altitudes between LEO and GEO.

DDA is a simplified version of the Dust Telescope envisioned by [14], which combines physical and chemical analysis of grains with an accurate measurement of their

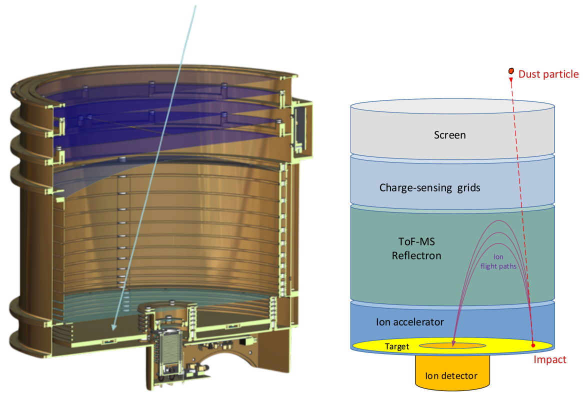


Figure 1. Cut view and schematic view of the DESTINY$^+$ Dust Analyzer (DDA).

trajectory. To reduce complexity, DDA forgoes the high accuracy trajectory sensor —which would require a large number of wire electrodes each connected to a charge-sensitive amplifier (CSA) [2, 24]— and instead uses just four charge-sensing grid electrodes at the instrument entrance to constrain the location at which the particle entered the instrument and thus its approach direction. The grain's velocity is determined via time-of-flight measurement between the passing of the entrance grids and the impact on the gold plate target inside the sensor housing.

For compositional analysis, DDA adopts the working principle of an impact ionization mass spectrometer: The high relative velocity ($> 1\,\mathrm{km\,s^{-1}}$) of cosmic dust causes the grains to decompose into a plasma upon impacting the instrument's high-purity gold target. The plasma's constituents are then analyzed via reflectron-type time-of-flight mass spectrometry, yielding a typical mass resolution of $m/\Delta m \approx 100$. The high mass resolution enabled by the reflectron ion optics, as well as the directional analysis enabled by the segmentation of the charge-sensing entrance grid, pose key advancements over DDA's predecessor, the Cosmic Dust Analyzer (CDA), which flew aboard the Cassini-Huygens mission to study Saturn's dust environment. Furthermore, DDA is mounted on a two-axis pointing mechanism, which allows for some pointing autonomy even

Proc. 2nd NEO and Debris Detection Conference, Darmstadt, Germany, 24-26 January 2023, published by the ESA Space Safety Programme Office
Ed. T. Flohrer, R. Moissl, F. Schmitz (http://conference.sdo.esoc.esa.int, February 2023)

when the spacecraft attitude is determined by operational factors.

Artificial micron-sized dust is known to be generated in large amounts by solid-rocket-motor (SRM) upper stages [e.g., 1]. Generated during combustion, these aluminium-oxide particles are spread widely around the Earth, with a fraction of them remaining over prolonged amounts of time [20, 17]. By analyzing the composition of impactors on retrieved shuttle solar arrays [16] showed that, in LEO, the debris dust flux dominates over the cosmic dust flux. Artificial dust has thus been incorporated into ESA's *Meteoroid And Space debris Terrestrial Environment Reference* (MASTER) model [25]. The results of active dust detectors in orbit around Earth are valuable inputs to the development of such models, offering time- and spatially-resolved flux data compared to retrieved dust collectors and spacecraft surfaces. In that way, the Geostationary Impact Detector (GORID) identified streams of dust, some of which could be connected to specific SRM firings while for others no such explanation could be found [6].

Here we analyze the debris dust environment to be encountered along the DESTINY$^+$ trajectory using the MASTER model. We also discuss DDA's potential to study the stream and cloud phenomena discovered by GORID and other active sensors, for which DDA—as the first active sensor in Earth orbit with composition analyzing capability—is in a unique position to find an explanation.

2. THE EARTH-BOUND MISSION PHASE

DESTINY$^+$ will be launched aboard an *Epsilon S* rocket from Uchinoura Space Center into an eccentric Earth-orbit, that is similar to a geostationary transfer orbit (GTO), with perigee and apogee altitudes at 230 km and 37 000 km, and an inclination of 31°. From there, DESTINY$^+$ uses its ion engines to raise its orbit toward the Moon over the course of 2 years (see Fig. 2). For the first 8 months the engines operate continuously to minimize the time the probe spends within the Earth's radiation belts. Once the most hazardous regions of the radiation belts are passed (altitude $> 20\,000$ km), thrusting occurs in arcs to optimize propellant usage [21].

DDA may begin scientific operation, once the cover of the instrument is opened. This is planned to occur 4 weeks to protect mass analyzer components from contamination due to outgassing of the spacecraft. During passage of high-energy regions of the radiation belts, the instrument's electron multiplier may be operated at decreased gain or switched off entirely to prevent degradation due to electrical breakdown, which may occur upon incidence of corpuscular radiation energetic enough to penetrate the instrument's shielding grids. This measure may impair or disable compositional analysis of impacting dust grains, yet, it does not interfere with the determination of their surface charge, velocity vector, and impact

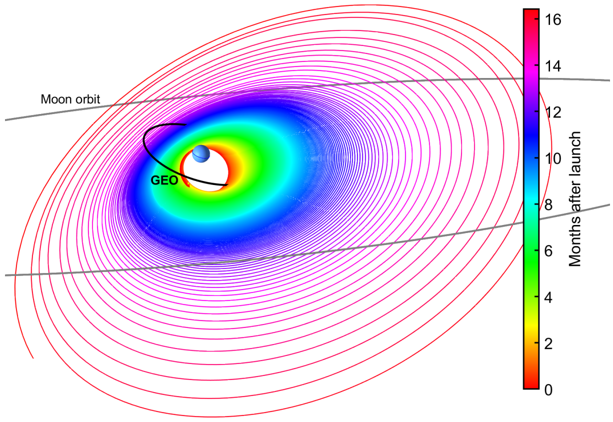


Figure 2. 3D-view of the trajectory of DESTINY$^+$ during the Earth-bound spiralling phase.

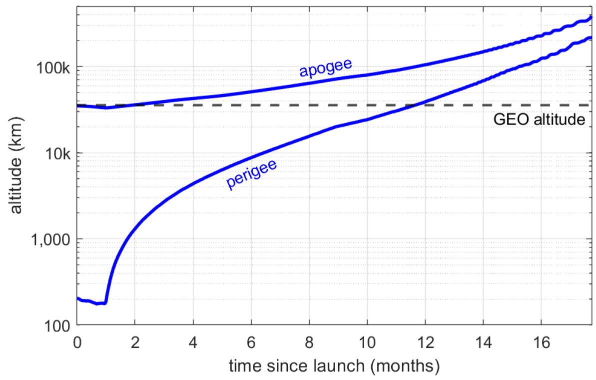


Figure 3. Evolution of orbit altitude during the spiralling phase of DESTINY$^+$.

energy.

During the spiralling phase, the spacecraft attitude is constantly adjusted to maintain a thrusting vector that is parallel with the probe's velocity vector. In addition, the spacecraft's roll angle about its thrust vector is regulated to maximize illumination of the solar panels. DDA's two-axis pointing mechanism grants coverage of $^1/_4$ of the sky (solid angle of 1πsr), that includes the moving direction of the spacecraft under nominal operation (see Fig. 4).

3. MODEL PREDICTIONS

MASTER is ESA's tool for space debris and meteoroid impact risk assessment for Earth-orbiting satellites [4]. While impacts of micron-sized particles are no critical threat to satellites, they may still degrade functional surfaces such as solar arrays and radiators, and can damage exposed sensitive elements, such as the imaging sensors of X-ray space-telescopes [7, 18]. In the case of DDA, of course, dust impacts are primarily considered a scientific objective rather than a hazard. Here we use the MASTER model to understand and estimate the types,

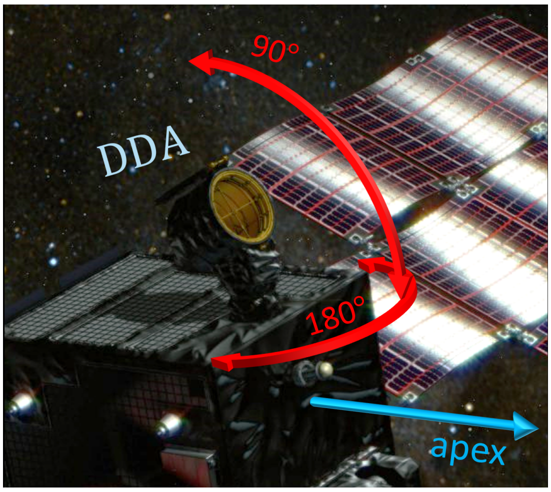


Figure 4. Two-axis pointing mechanism of DDA.

dynamics, and quantities of debris dust that DESTINY$^+$ will encounter.

To get an overview of the spatial distribution of debris dust around the Earth, we first run the *spatial density* mode of MASTER. Fig. 5a shows the simulated spatial density as dependent on altitude and object diameter. Note that only three debris populations appear in this plot. Other debris populations modelled in MASTER produce insufficient densities and are not considered in this study. The relevant populations are **SRM dust**, **ejecta** (surface material of satellites and larger debris excavated by impacts), and **paint flakes** (particles released from degrading spacecraft surfaces). Ejecta particles dominate at altitudes below 2000 km with a peak density at 1000 km. Paint flakes show an altitude profile similar to that of ejecta (consistent with their common origin) although with densities roughly one magnitude lower. SRM dust on the other hand reaches a peak density at around 10 000 km and drops off to zero at 36 000 km, which is the apogee altitude of dust created in GTO apogee motor firings [5]. Fig. 5b shows the spatial density over object diameter profile taken at two different altitudes, 1000 km and 10 000 km. The predominant grain size is in the range of a few microns for SRM dust and ejecta and a few tens of microns for paint flakes. Note that ejecta and paint flakes are not present at 10 000 km. Fig. 6 shows the density distribution of these three populations over altitude-declination bins. For ejecta and paint flakes the density peaks near the poles, hinting at the predominance of sun-synchronous orbits among LEO satellites. The SRM dust distribution at low altitudes appears confined to declinations within $\pm 40°$ but becomes uniformly distributed in declination at altitudes above 3000 km. Also indicated are the paths of the DESTINY$^+$ orbit at three different points in time, showing that the spacecraft will have exposure to the ejecta and paint flakes population only for the first few months after launch. The SRM dust population will be encountered longer, but exposure diminishes once the perigee is raised beyond 20 000 km around the 8th month.

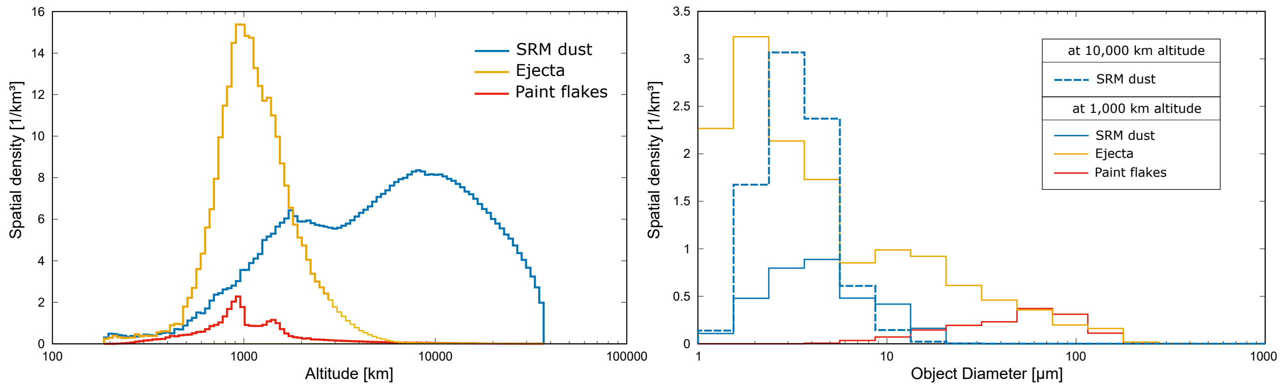
Considering the short time DESTINY$^+$ will spend at LEO altitudes and that the DDA cover will remain closed after launch for several weeks, study of the ejecta and paint flakes population will not be possible with DDA. For the flux analysis along the orbit of DESTINY$^+$, we thus focus on the SRM dust population. As an exemplary case, we use the orbit at four months after launch for this MASTER simulation. Fig. 7 shows the distribution of impact azimuth and elevation along that orbit of DESTINY$^+$, to get a sense of the impact directionality (the underlying coordinate system is the 'Earth-oriented' system used in MASTER). The angular distributions show that the predominant impact direction veers off the spacecraft's (Earth-centred) apex direction, but stays roughly within $\pm 50°$ from the apex in azimuth and $\pm 30°$ from the apex in elevation. We see that the flux is minimal around perigee and grows with increasing altitude, however drops off sharply closer to the apogee, which lies beyond GEO altitude at month four. This is consistent with the density distribution noted earlier, which shows a cut-off at 36 000 km.

To compare the incidence of SRM dust with the meteoroid background, Fig. 8a shows their cumulated fluxes for a plate that is oriented toward the spacecraft apex during the entire orbit. While the simulated flux of interplanetary dust is around 35% higher than the SRM dust flux for grains larger than 1 µm, it is around 30% lower than the SRM dust flux for grains larger than 3 µm. For a rough estimation, the SRM dust plate flux of 450 $m^{-2}yr^{-1}$ can be multiplied with DDA's sensitive area of 0.03 m^2, amounting to an impact rate for DDA of 13.5 yr^{-1}. This, however, assumes all dust influx to be parallel and DDA always pointing in the right direction, and should thus be considered an upper limit. If, instead, we assume the flux to be isotropic—knowing that DDA (with an effective solid angle of 0.55 sr) has a geometric factor of 0.0053 that of a unit plate—we obtain an impact rate of 2.4 yr^{-1}. This, on the other hand, can be considered a lower limit as it ignores that the flux has in fact a predominant directionality, (seen in Fig. 7), which DDA will be able to access with its pointing mechanism. Notwithstanding the fact that the orbit is not stationary, it seems the detection of a few SRM dust grains is during the first eight months of the mission is realistic.

Fig. 8b compares the velocity distribution of that apex-plate flux SRM dust and meteoroid background grains. The different velocity profiles grant would help to distinguish grain origin, in case of an ambiguous grain composition.

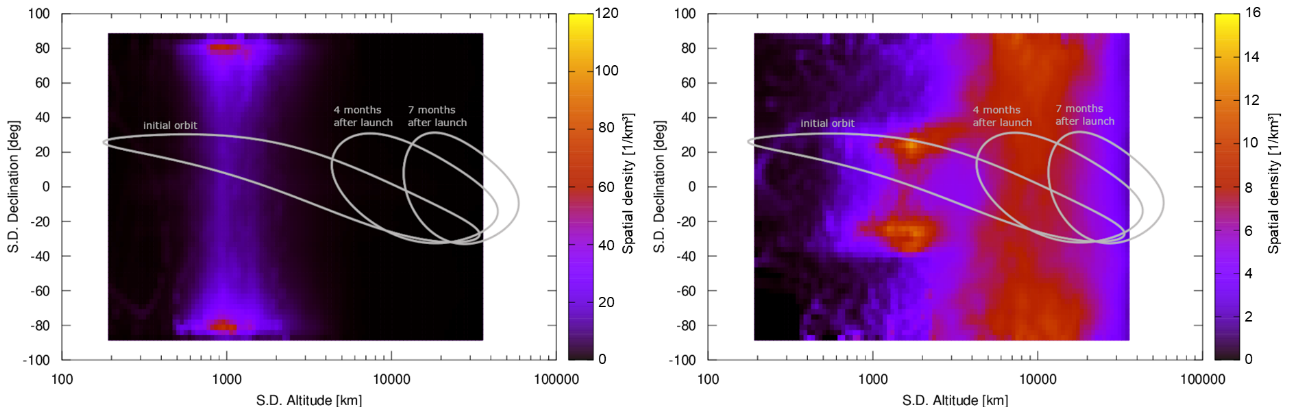
4. PREVIOUS MEASUREMENTS

In addition to the quasi static debris cloud modelled by MASTER there have been repeated detections of clustered impacts by previous active sensors, indicating the existence of clouds or streams around the Earth. Here, we briefly discuss some historic and recent active sensor measurements that are relevant to the near-Earth phase



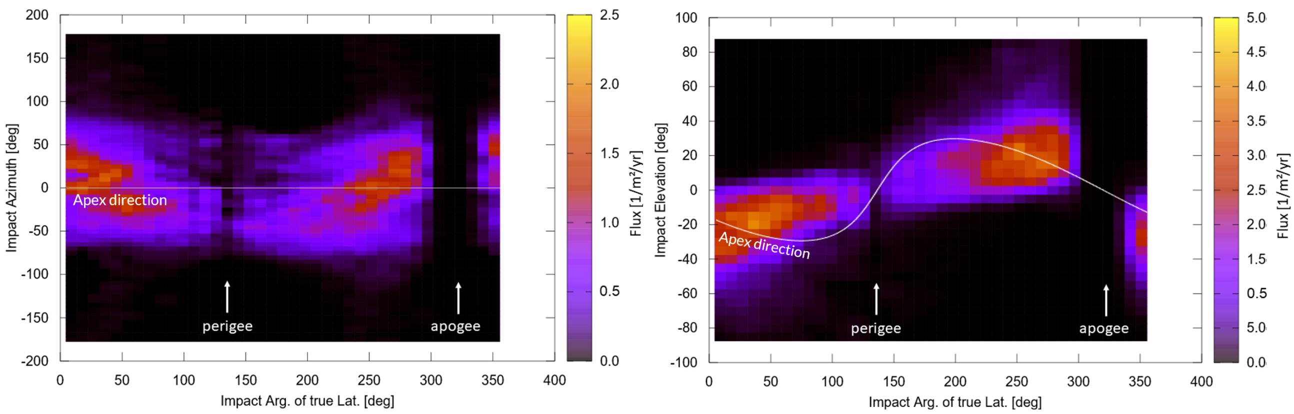
(a) (b)

Figure 5. Density distribution of debris dust populations over altitude (a) and over object diameter taken at two different altitudes (b), modelled with MASTER. Populations other than the ones shown cannot reach significant densities in comparison and have been omitted. At 10 000 km altitude SRM dust is the only significant population density-wise.



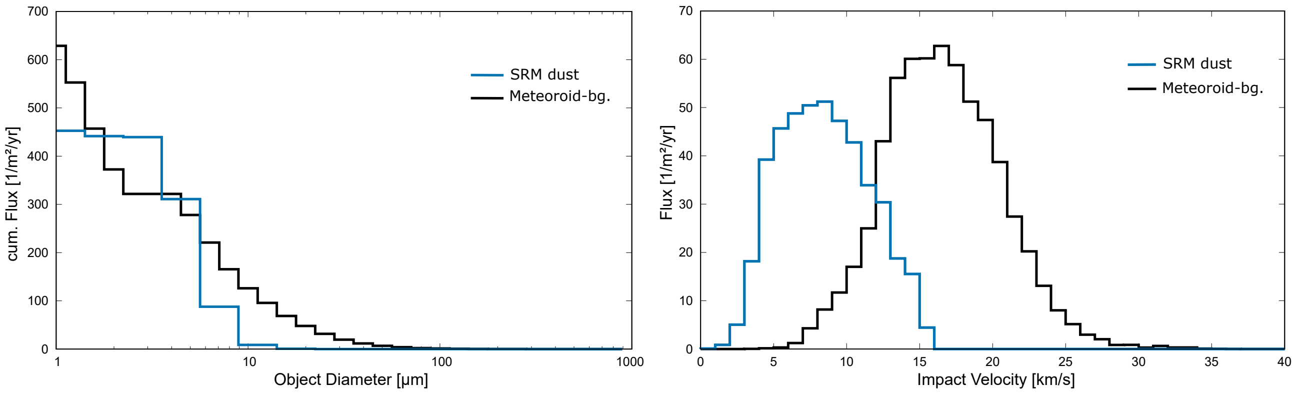
(a) (b)

Figure 6. Spatial density distribution of debris dust as modelled with MASTER. Dust populations shown are (a) ejecta & paint flakes (which are similarly distributed) and (b) SRM dust. The orbit of DESTINY^{+} is shown for three points in time.



(a) (b)

Figure 7. Directional debris flux distribution along DESTINY^{+} orbit, modelled with MASTER. The orbit used to model the flux is that of DESTINY^{+} 4 months after launch. The coordinate system is the 'Earth-oriented' system used in MASTER, where azimuth and elevation are the angular components of the impact direction inside and outside the local horizontal plane. The spacecraft's (Earth-centric) apex direction is indicated by a white line. The gap in the flux around apogee is due to the absence of debris particles in MASTER beyond GEO altitudes.



(a) (b)

Figure 8. Flux and velocity comparison of SRM dust and meteoroid-background dust along DESTINY$^+$ orbit, modelled with MASTER. For the meteoroid environment the Divine-Staubach model within MASTER was chosen. The orbit used to model the flux is that of DESTINY$^+$ 4 months after launch. The Target surface is an apex-facing plate (i.e. surface normal points parallel to the Earth-centric velocity vector of the spacecraft).

of DESTINY$^+$/DDA—that is, especially those that retrieved data from higher altitudes. Among the first to deliver reliable data on the dust abundance around the Earth were the impact ionization detectors aboard the spacecrafts Prospero (launched in 1971 into LEO) and HEOS-2 (launched in 1972 into a highly eccentric orbit with a perigee from 350 km to 3000 km and apogee of 240 000 km. Both reported a significant fraction of the dust flux to occur in 'swarms', that is clusters of impacts spaced in time only by few minutes [3, 12]. HEOS-2 found these 'swarms' to occur only within a distance of 10 Earth radii, causing a significant increase in flux over the interplanetary background flux. Hiten, another spacecraft on a highly eccentric orbit carrying an impact ionization detector, similarly reported a ten-fold increase of flux near Earth (closer than 100 000 km) compared to interplanetary space, as well as the occurrence of clustering [15]. Then the Geostationary Orbit Impact Detector (GORID), a large area impact ionization detector identical to the ones flown with the Ulysses and Galileo missions, was in operation for six years from 1996. Due to its consistent orbit and long operation time, GORID gathered a highly valuable dataset that put the spotlight on debris dust. It, too, encountered particle clouds, some of which repeatedly at certain points along its orbit thus characterized as streams. To some extent, these clouds and streams could be dynamically linked to specific contemporary firings of SRMs [6]. The averaged impact rate for debris particles, distinguished from natural meteoroids by their clustering, determined by GORID was 2.46 d^{-1} [8]. With DDA having a geometric factor of roughly one tenth that of GORID, this would translate to an impact rate of 0.25 d^{-1}, if DDA were also positioned in GEO and assuming an isotropic flux. Note that this rate is by about one magnitude higher than the estimates derived from the MASTER simulations in Sect. 3.

More recent deployment of active dust sensors for debris measurement has been focussed on LEO altitudes, such as the DEBIE and SODAD sensors. DEBIE-1 aboard the sun-synchronous satellite PROBA determined a particle flux about a factor of three over the MASTER predictions [22]. DEBIE-2, mounted on the ISS, measured fluxes one to two orders of magnitude above the MASTER predictions, which was attributed to noise events of an unknown source [19]. SODAD-1 and SODAD-2 on the other hand, mounted on the ISS and on the sun-synchronous satellite SAC-D respectively, measured fluxes consistent with the predictions of the MASTER model [9, 10, 11]. While the DEBIE and SODAD sensors were essentially plate sensors with limited retrieved dynamical information, they all reported the occurrence of non-random or clustered impacts, indicating that particle clouds were encountered.

5. DISCUSSION

We analyzed the debris dust environment encountered by DESTINY$^+$ with MASTER and derived a fluence for DDA of a few detectable human-made grains for the first 6 to 8 months of the mission. This flux is highest at altitudes between 10 000 km and 30 000 km, with the predominant incident direction veering up to 50° off the apex direction. We discussed previous measurements of the Earth's dust environment, which found a significant fraction of the impact events to occur in clusters, meaning that clouds or streams of dust particles were encountered. The average flux of clustered particles determined by GORID would translate to an impact rate of 0.25 d^{-1} for DDA, which is about an order of magnitude higher than the herein derived MASTER flux predictions for the quasi-static debris dust environment encountered by DDA. Notwithstanding the fact that DDA will operate in an orbit different from that of GORID, this discrepancy is noteworthy.

Since these particle clouds are not observed in interplanetary space, they must originate in near-Earth space. A natural origin has been hypothesized, where low-density meteoroids would fragment into small clouds upon entering the Earth's magnetosphere, due to a sudden negative chargeup in the ambient plasma [12]. GORID revealed that some cloud phenomena can be explained by solid rocket apogee motor firings, yet others cannot [6]. Another origin for clouds could be the electrostatic fragmentation of SRM slag particles as suggested by [13]. Considering the consistent findings of various active dust detectors, the existence of clouds and streams in the vicinity of Earth seems fairly certain. Yet without accurate dynamical and compositional information, their origin(s) may not be resolved satisfyingly. With its trajectory sensing and mass analyzing capabilities, DDA is in a unique position to accomplish this task. Complementary to another dynamics-sensing impact ionization detector soon to be deployed in LEO, MOVE-3/DEDRA [23], DDA will supply high-altitude data, striving to provide an overarching picture of the Earth's intricate immediate dust environment.

ACKNOWLEDGMENTS

The DDA project is funded by the German Aerospace Center (DLR) under the grant 50 OO 2101.

REFERENCES

1. Akiba, R., and Inatani, Y. Alumina Particles Exhausted from Soild-Propellant Rocket Motor As a Potential Source of Space Debris. In *ISAS Science Report SP 11 - Proceedings of the Workshop on Space Debris* (Mar. 1990), pp. 51–59.
2. Auer, S. Two high resolution velocity vector analyzers for cosmic dust particles. *Review of Scientific Instruments 46*, 2 (Feb. 1975), 127–135.
3. Bedford, D. K., Adams, N. G., and Smith, D. The flux and spatial distribution of micrometeoroids in the near-Earth environment. *Planetary and Space Science 23*, 10 (Oct. 1975), 1451–1456.
4. Braun, V., Horstmann, A., Lemmens, S., Wiedemann, C., and Böttcher, L. Recent developments in space debris environment modelling, verification and validation with MASTER. In *Proceedings of the 8th European Conference on Space Debris* (2021).
5. Bunte, K. D. The Detectability of Debris Particle Clouds. In *54th IAC of the IAF* (2003), pp. IAA–5.1.07.
6. Bunte, K. D., and Drolshagen, G. Detection and Simulation of Debris Cloud Impacts. In *ESA SP-587* (Aug. 2005), p. 201.
7. Carpenter, J. D., Wells, A., Abbey, A. F., and Ambrosi, R. M. Meteoroid and space debris impacts in grazing-incidence telescopes. *Astronomy & Astrophysics 483*, 3 (June 2008), 941–947.
8. Drolshagen, G. In-situ Observations of Space Debris at ESA. In *Advanced Maui Optical and Space Surveillance Technologies Conference* (Jan. 2006), p. E68.
9. Durin, C., and Mandeville, J. C. SODAD: First results and post-flight analysis. In *Proceedings of ISMSE* (2009), vol. 11.
10. Durin, C., Mandeville, J. C., and Perrin, J. M. System for an Active Detection of Orbital Debris in Space. *Journal of Spacecraft and Rockets 53*, 6 (2016), 1178–1184.
11. Durin, C., Mandeville, J. C., and Perrin, J. M. Active detection of micrometeoroids and space debris SODAD-2 experiment on SAC-D satellite. *Advances in Space Research 69*, 10 (May 2022), 3856–3863.
12. Fechtig, H., Grün, E., and Morfill, G. Micrometeoroids within ten Earth radii. *Planetary and Space Science 27*, 4 (Apr. 1979), 511–531.
13. Graps, A. L., Green, S. F., McBride, N., McDonnell, J. A. M., Bunte, K., Svedhem, H., and Drolshagen, G. GEO Debris and Interplanetary Dust: Fluxes and Charging Behavior. In *ESA SP-643* (Jan. 2007), pp. 97–102.
14. Grün, E., Krüger, H., Srama, R., Kempf, S., Auer, S., Colangeli, L., Horanyi, M., Withnell, P., Kissel, J., Landgraf, M., and Svedhem, H. Dust telescope: A new tool for dust research. In *Proceedings of the IAU Colloquium 181* (Jan. 2002), pp. 181–194.
15. Iglseder, H., Münzenmayer, R., Svedhem, H., and Grün, E. Cosmic dust and space debris measurements with the Munich dust counter on board the satellites hiten and brem-sat. *Advances in Space Research 13*, 8 (Aug. 1993), 129–132.
16. Kearsley, A. T., Drolshagen, G., McDonnell, J. A. M., Mandeville, J.-C., and Moussi, A. Impacts on Hubble Space Telescope solar arrays: Discrimination between natural and manmade particles. *Advances in Space Research 35*, 7 (Jan. 2005), 1254–1262.
17. Kolesnikov, E. K., and Chernov, S. V. Orbit lifetime for microparticles in highly elliptical orbits with low perigee. *Cosmic Research 49*, 4 (Aug. 2011), 360.
18. Li, Y., Simolka, J., Millinger, M., Farahvashi, E., Mocker, A., Sommer, M., Bunte, K. D., and Srama, R. Measurement of fragments generated by hypervelocity impacts of micron-sized iron particles at grazing incidents. *Advances in Space Research 69*, 6 (Mar. 2022), 2629–2635.
19. Menicucci, A., Drolshagen, G., Kuitunen, J., Butenko, Y., and Mooney, C. In-Flight and Post-Flight Impact Data Analysis from DEBIE2 (Debris In-Orbit Evaluator) on Board of ISS. In *Proceedings of the 6th European Conference on Space Debris* (2013).

20. MUELLER, A. C., AND KESSLER, D. J. The effects of particulates from solid rocket motors fired in space. *Advances in Space Research 5*, 2 (Jan. 1985), 77–86.
21. OZAKI, N., YAMAMOTO, T., GONZALEZ-FRANQUESA, F., GUTIERREZ-RAMON, R., PUSHPARAJ, N., CHIKAZAWA, T., TOS, D. A. D., ÇELIK, O., MARMO, N., KAWAKATSU, Y., ARAI, T., NISHIYAMA, K., AND TAKASHIMA, T. Mission design of DESTINY+ : Toward active asteroid (3200) Phaethon and multiple small bodies. *Acta Astronautica 196* (July 2022), 42–56.
22. SCHWANETHAL, J. P., MCBRIDE, N., GREEN, S. F., MCDONNELL, J. A. M., AND DROLSHAGEN, G. Analysis of Impact Data from the Debie (debris In-Orbit Evaluator) Sensor in Polar Low Earth Orbit. In *Proceedings of the 4th European Conference on Space Debris, ESA SP-587* (Aug. 2005), p. 177.
23. SCHWEINFURTH, A. G., FIRBACH, F. S., PUCKNUS, P., AND ZORBACH, N. MOVE-III and DEDRA: In Situ Sub-millimetric Space Debris and Micrometeoroid Detection and Characterisation. This volume.
24. SRAMA, R., SROWIG, A., RACHEV, M., GRÜN, E., KEMPF, S., MORAGAS-KLOSTERMEYER, G., SROWIG, A., CONLON, T., HARRIS, D., GRÜN, E., AUER, S., GLASMACHERS, A., HELFERT, S., LINNEMANN, H., AND TSCHERNJAWSKI, V. Development of an Advanced Dust Telescope. In *Modern Meteor Science An Interdisciplinary View*, vol. 95 of *Earth, Moon, and Planets*. 2005, pp. 211–220.
25. WEGENER, P., KRAG, H., REX, D., BENDISCH, J., AND KLINKRAD, H. The orbital distribution and dynamics of solid rocket motor particle clouds for an implementation into the master debris model. *Advances in Space Research 23*, 1 (Jan. 1999), 161–164.