Orbital Dust Impact Experiment (ODIE) – A Passive Dust Collector Designed to Address the Dust Flux Data Gap

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ABSTRACT

Monitoring dust particle populations in the vicinity of the Earth is vital to understand and mitigate against the hazards they pose to spacecraft, driving design of effective spacecraft shielding and optimum operational protocols. The flux of particles > few mm orbiting Earth has been investigated remotely using radar and optical telescopes [e.g. 1, 2], revealing that objects in this size range have increased in abundance rapidly since the dawn of the space age. Despite their diminutive size, objects smaller than the radar detection limit are still capable of significant damage to spacecraft. Such particles are expected to be far more numerous, with estimates in the trillions for the total number of particles >100 µm in size [3]. The degree of damage caused by these dust particles is heavily dependent on characteristics such as their relative velocity, impact angle, shape and composition, which vary as a function of origin (e.g. orbital debris originating from human activities in space have relative velocities that are typically slower than for natural micrometeoroids originating from comets and asteroids). It is therefore important to be able to distinguish between these two dust populations, to fully understand the threat posed by these particles.

Previous flux measurements for smaller dust populations have largely been based on passive collection surfaces retrieved from dedicated missions, such as the long duration exposure facility (LDEF) [e.g. 4, 5], and opportunistic analyses of returned surfaces, such as solar cells and radiator panel from the Hubble Space Telescope [e.g. 6-9]. For many impact features it has been very time consuming, difficult or even impossible to give unambiguous attribution of particle origin due to the nature of the collection surface. Consequently, we lack significant and important information for both populations, but especially orbital debris. Whilst there is general agreement as to particle origins between studies of smaller grain sizes impacted on different surfaces [e.g. 7, 9], despite efforts [e.g. 9, 10], the origins for those impact features between 200 µm and 2 mm in size remains ambiguous – hence there remains uncertainty as to how to fill an important gap in our knowledge of the particle population.

The Orbital Dust Impact Experiment (ODIE) is a dedicated, passive dust collector that we have designed to verify and understand the flux and origins of these particles. By exposing in low Earth orbit for a period of at least 1 year and returning to Earth for analysis, it will enable the unambiguous identification of both micrometeoroid and orbital debris particles over size ranges including 200 µm to 2 mm. This paper introduces our design and potential deployment options, as well as details of the analyses that would need to be performed upon its return.

1 INTRODUCTION

Over the past six decades, the near Earth environment of space has changed dramatically, from one traversed only by naturally occurring meteoroids and micrometeoroids (MMs), to one that is populated by thousands of artificial satellites dedicated to communications, navigation and the collection of Earth observation and astronomical data. Although around 1,200 operational satellites currently orbit Earth, the planet is also currently surrounded by a much larger number of other objects produced by human activities in space - orbital debris (OD) (e.g. https://www.esa.int/Our_Activities/Operations/Space_Debris/About_space_debris). Many of the largest objects are defunct satellites and spent upper stages of rockets and fairings, but much is in the form of smaller (<10 cm) particles from material erosion in the harsh environment of space. Extreme temperature variations, oxidising effects of atomic oxygen and direct exposure to solar radiation erode and break down surfaces to produce dusty particles. Catastrophic events, whether by intentional destruction or accidental collision, as well as deployment, activation and
use of space hardware also generate debris (e.g. aluminium oxide particles produced by firing of solid rocket motors). Due to their high relative velocities, these OD particles, along with their naturally occurring MM counterparts, pose a significant threat to spacecraft, with impacts having the potential to cause payload degradation, failure of spacecraft operation, or even total loss of missions [3]. Monitoring OD and MM populations is therefore vital to understand and mitigate against the hazards to spacecraft, driving design of effective spacecraft shielding and optimum operational protocols (e.g. see [11] for a recent discussion).

To enable predictions of particle flux with time for the OD and MM populations, and hence the hazard they pose to spacecraft, environmental computer models such as NASA’s Orbital Debris Engineering Model (ORDEM) and ESA’s Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) have been developed. Agreement between the fluxes predicted by these two models is not always good [12] and it is therefore vital to validate and improve their predictive power with real data. Objects larger than ~few mm can be detected using ground and space-based radar and optical telescopes [e.g. 1, 2]. Such data suggests that on the order of 500,000 objects with a size greater than approximately 1 cm currently orbit the Earth (https://orbitaldebris.jsc.nasa.gov/measurements/radar.htm). Despite their diminutive size, objects smaller than this detection limit are still capable of significant damage to spacecraft. Such particles are expected to be far more numerous, with estimates in the trillions for the total number of particles >100 μm in size [3]. To verify these estimates, and determine whether the near Earth environment is becoming increasingly hazardous, with critical altitudes approaching cascade levels [13], it is necessary to directly measure their abundances. The degree of damage caused by these dust particles is heavily dependent on characteristics such as their relative velocity, impact angle, shape and composition (e.g. OD relative velocities are typically slower than for MM, but OD particles are likely to be less porous). It is also therefore important to distinguish between the OD and MM populations, to fully understand the threat posed by these particles.

2 PREVIOUS STUDIES OF DUST PARTICLES IN LEO

A number of active dust sensors designed to measure dust impacts in real-time have been flown to investigate the dust populations in the near Earth environment, such as the Debris In-Orbit Evaluato (DEBIE) [14] and the Geostationary Orbit Impact Detector (GORID) [15]. These are able to measure numbers, velocities and trajectories of particles, but have rarely incorporated compositional analysis and therefore cannot distinguish between OD and MM origins. They are also usually of small size, and can therefore only sample a small number of impacts in a typical deployment interval, probably missing the rare, but very significant larger particles (more recently, NASA flew the Space Debris System SDS [16] on the ISS, although it was only operational for a short time). In contrast, passive collectors can incorporate large surfaces, onto which particles can impact, leaving behind residues that line the craters, or penetration holes that they create in these surfaces [e.g.17, 18 and Fig. 1]. Laboratory experiments using light gas gun (LGG) and electrostatic accelerator facilities to replicate impacts have revealed that these residues retain chemical compositions indicative of their pre-impact compositions [e.g. 19-27]. The application of high sensitivity analytical instruments to studies of returned passive collections can thus permit rapid identification of MMs versus OD, based on their distinctive chemical signatures. For example, OD particles are commonly composed of metallic elements in major element combinations not typically found in natural MMs (e.g. Al, Fe, Ti, Ni, Cu, Cr, Mn in OD alloys). By performing complementary simulations in the laboratory, additional information such as dust grain dimensions may also be estimated from measurement of the resulting impact features. Opportunistic studies of space-exposed materials date back to the early days of human space-flight, e.g. Apollo spacecraft surfaces [28]. While the NASA Shuttle orbiter program was active, it was possible for large sections of spacecraft to be returned to Earth. Consequently, several were examined in detail, including thermal blanket and aluminium thermal control covers from the Solar Max Satellite [e.g. 29], metal foils and clamps on the Long Duration Exposure Facility (LDEF) [e.g. 30], solar cells and a radiator panel from the Hubble Space Telescope (HST) [e.g. 6, 7, 9], and multi-layer insulation foils (MLI) from the Space Flyer Unit (SFU) [e.g. 31]. However, the composition of these passive, non-dedicated collection surfaces had to reflect their primary structural and experimental function, and therefore unambiguous recognition of dust residue often proved difficult to impossible (depending on the nature of the serendipitous collection surface), and very time-consuming, ultimately limiting the number of impact features that could be analysed. For example, the identification of Al-oxide OD residues on the aluminised Kapton foils of MLI would be extremely problematic as there would be no way to discriminate between the aluminium originating from the particles and that of the coating of the film. A range of passive dedicated collectors have also been flown in LEO. One of the earliest was the microabrasion foil experiment (MFE) flown on the space shuttle and composed of Al foil overlying a Kapton sheet [32]. Additional collections have since been performed by experiments including the Timeband Capture Cell Experiment (TiCCE) on ESA’s European
Retrievable Carrier (EURECA) [33], and the Various Materials Experiment (A0138-1), Chemistry of Micrometeoroids Experiment (A0187-1) and Space Debris Impact Experiment (S0001) on LDEF [34-36]. Whilst these detectors were all impacted during their flight, demonstrating the capabilities of such dedicated collectors, none have yet been designed to incorporate compositions that facilitate impactor recognition.

Fig. 1: Chemical map highlighting residue A: in a crater on LDEF Al clamp and B: around a penetration hole on MULPEX#1 foil.

3 CURRENT UNDERSTANDING OF THE DUST FLUX IN LEO

Whilst many studies have made some measurement of total flux, the lack of compositional analyses by active collectors, and the difficulties interpreting residue origins associated with passive collectors has meant data for the individual MM and OD populations cannot always be separated [19, 37]. Despite the deployment of a range of both dedicated passive and active collectors, perhaps the most extensive recent analytical data for the largest sub-mm particles has come from the analysis of the solar cells and a painted metal radiator panel returned from HST (2002 and 2009), each of which had an exposure time and area integral of > 10 m²years. Data from both the solar cells and the radiator present problems in interpretation. Both surfaces experienced extensive brittle spallation on impact by larger particles, ejecting variable quantities of material, introducing potentially large errors on original particle size estimates, and reducing the amount of residue that may be retained, hence making identification of the impactor composition very difficult. Furthermore, both surfaces have complicated chemical compositions, severely limiting interpretation of impactor origins from remaining residues, and there is extensive surface contamination from post-flight handling, particularly on the radiator surface.

We have now revisited all of the original residue data from our studies of both surface types (previously summarised by [7-9]). Our lengthy program of laboratory experimental impacts onto similar substrates and using a wide range of MM and OD analogue projectiles has now established reliable minimum threshold criteria for unambiguous recognition of hypervelocity impact processing and incorporation of projectile remnants (e.g. as applied to the HST radiator, Kearsley et al. 2017). On this basis, to remove uncertainties, we now exclude any attributions made solely upon the evidence of discrete surface grains whose relationship to hypervelocity impact cannot be satisfactorily proven. It is possible that these grains may be either post-flight surface contamination or unrecognised minor components of the complex substrate. When these less reliable data are omitted, there is clearly a size gap in current attribution of impactors to MM and OD populations, as we show on a simplified version of a plot published in the US National Academy of Sciences report of 2011 (Fig. 2). It should be noted that the HST fluxes plotted in Fig. 2 are raw data, not corrected for any model of cumulative facing direction (e.g. Earth-facing, space-facing, ram facing etc., as could be defined on the stabilised LDEF). Nevertheless, it is clear that we lack significant and important information for both populations, but especially OD, and we probably have no positive identification of impacting
OD particles substantially greater than 200 µm in size. There is therefore currently a gap in our knowledge of the OD particle population between approximately 200 µm and 2 mm.

A further complication to our current population datasets lies in the fact that these data are now considerably out of date, with HST data based on impacts made over a decade ago. Data from other passive dedicated experiments such as LDEF and EURECA are more than 20 years old. Given that more recent debris generating events, such as the collision between Iridium 33 and Cosmos 2251 satellites in 2009 and the intentional destruction of the Fengyun-1 satellite by China’s anti-satellite test in 2007, have substantially increased the LEO particle population [38-40] none of the available data can provide a true reflection of the contemporary flux for OD and MM populations. Indeed, recent results from post-flight examination of an Orion capsule after a very short orbital flight (2 eccentric orbits across a wide range of altitudes, in a total of 4 hours from launch to landing [41]) identified at least three orbital debris impacts with particles of 180 µm up to 300 µm, suggesting substantially higher numbers of sizeable orbital debris particles now populate low Earth orbit. Launches of broadband satellite constellations over the coming years (http://www.bbc.co.uk/news/business-43090226 published online 23.02.2018) will only add to levels of traffic in LEO, and will continue to modify the dust inventory in the vicinity of the Earth. It is therefore vital to continue efforts to study the dust population and constantly monitor its changes in order to accurately assess the hazards posed, validate models and develop effective mitigation strategies.

Fig. 2: The current understanding of dust flux in LEO. Radar and optical telescope data enable measurement of populations larger than a ~few mm. Returned surface analyses of HST surfaces enable separation of OD and MM populations for small particles. Modified from NAS 2011 with plotting of the raw data, as reported in summaries by [7-9], and with omission of low reliability data.

4 THE ORBITING DEBRIS IMPACT EXPERIMENT (ODIE)

In order to address the flux gap, a new particle collector is required that must be capable of recording and, importantly, allowing interpretation of, details of both impactor size and composition (and hence whether OD or MM). From our extensive experience studying both dedicated and non-dedicated surfaces exposed to LEO, we propose that the ideal collector be a retrievable dedicated passive collector composed of multiple polymer foil
layers. This Orbiting Dust Impact Experiment (ODIE) is similar in concept to the multi-layer polymer experiment (MULPEX) [37]. Multi-layer foil structures are able to capture impacting particles by replicating the effects of a Whipple shield: the initial foil(s) disrupt the projectile, spreading its energy over a larger surface and capturing multiple lower speed fragments on subsequent foils. Such foils can capture and retain substantial quantities of easily identifiable residue, as demonstrated in studies of LEO exposed MLI (e.g. [42-43] and Fig. 3). The multilayer structure also has the advantage that it protects lower layers from accumulation of surface contamination which might be confused with impactor residue. Laboratory experiments have shown that projectiles ranging in size from a few microns to millimetres leave behind residues on all foils that they contact (e.g. [37, 44] and Fig. 1B). State-of-the-art analytical techniques in the laboratory can then be used to identify the impacting particles chemistry and mineralogy [e.g. 19, 20, 22-26], with modern large area silicon drift energy dispersive X-ray detectors now capable of providing efficient and highly sensitive means to analyse large numbers of impact features, both rapidly and at high spatial resolution. As well as enabling the identification of an OD vs MM origin for residues, such data can provide valuable information regarding the processes occurring on the parent bodies of MMs. Dimensions of the impacting particle may also be estimated from the size of the crater/penetration hole on the surface foil.

The polymer foils will be either Mylar or Kapton. The composition of these foils is such that residues of OD and MMs will easily be recognised against their organic background. However, since polymers degrade in the LEO environment when exposed to atomic oxygen (AO) [e.g. 45], all foil surfaces will require a protective coating. We have chosen a Pd-coating since this composition will not hinder residue SEM-EDX analysis, unlike conventional Al- or Au-coated polyimide: Previous work [e.g. 37] has shown that the presence of Al will complicate identification of OD whilst the presence of Au (and Pt) make SEM-EDX survey analyses difficult to interpret due to their primary X-ray emission lines overlapping with those of S, a diagnostic signature of MMs. When surveying foils in the SEM, the Pd coating also provides a uniform, high contrast medium on which dark penetration holes and craters are easily identifiable and automated feature recognition may be employed to search for impacts. We are in the process of conducting tests to establish the best practice coating method (e.g. sputtering, organic functionalisation of foil prior to sputtering, thermal evaporating) as well as investigating the durability of the Pd-coating under simulated LEO conditions (e.g. exposure to AO as well as thermal-vacuum cycling).

In order to ensure collection of sufficient particles to determine confident flux data for LEO and to provide the highest chances of collecting a large (mm) particle, ODIE must have a minimum collection area of ~1 m² and be exposed for a minimum of 1 year. We propose that this area be divided up into smaller individual collection cell modules, each measuring 10 cm × 10 cm [Fig. 4]. Division of the collector into cells is necessary to facilitate foil manufacture, handling during the build onto the frame, and analysis after retrieval (SEM would be used for much of the survey and analysis work – standard SEM chambers permit the analysis of samples up to ~10 cm × 10 cm in size). It also provides a means of limiting potential damage to the collector by large impactors should any of these result in tearing of the foils. A free rear surface is also important to the safekeeping of our collector: Although a large ~ cm scale particle is extremely unlikely to hit during the deployment interval (see Fig. 2), it would be capable of passing through all collector foils and, upon encountering a solid rear surface, would generate a cloud of secondary ejecta that might re-enter the collector, creating extensive tearing of the foils, thereby making interpretation of primary impact features very difficult. In each cell module, the polymer foils may be chemically bonded or pinned in place onto PEEK supports, whilst the PEEK supports will be secured onto the Al alloy frames using registration dowels to enable identification of features relating to the same impact on multiple foils.
Fig. 3. SEM images superimposed with elemental maps highlighting the results of an impact on MLI from the SFU. The impacting particle generates a hole ~equal in size on foil 1 and deposits residue on all foils it penetrates/comes to rest on. (Images modified from [42]).
Fig. 4. CAD rendering showing A, potential complete collector (1 m diameter) and B, polyimide foil, PEEK support strut and registration dowel configuration in an individual cell module. Each cell is 10 cm long.

The exact configuration of ODIE is still to be determined: Capture of particles by disruption requires careful consideration of the foil thicknesses being used. The initial experiments with MULPEX investigated collectors composed of multiple 7.8 µm foils and a final 80 µm foil, finding that mm projectiles were not stopped by up to 7 foils. ODIE will be composed of at least 4 layers of polyimide substrate foil, with the front foil being 13 µm or 25 µm thick to ensure full penetration (allowing particle size to be determined) by particles down to ~15 or ~30 µm. Subsequent foils will be 75 µm or more in thickness. Given that we aim to capture particles up to a few mm in size, ODIE will incorporate thicker foils at the rear of the collector that are capable of disrupting particles of mid-size range, and capturing particulate residue. Such thicker foils will not be torn severely by a larger grain (mm-scale), but will preserve traces around the penetration feature (e.g. Fig. 1B). The optimal number and thickness of foils in ODIE is now being experimentally investigated using the two stage light gas gun (LGG) at the University of Kent [46]. We are currently investigating how the relation between impacting particle size and crater/penetration hole geometry vary with foil thicknesses, particle shape and velocity.

The delicate detector films must be protected from damage during terrestrial transport and spacecraft loading. It must also be protected from atmospheric degradation (high humidity and salt at a launch site). Should the experiment be deployed by astronauts, it may be at risk during any handling in a confined volume (e.g. space station) and during its eventual integration on the exposure platform by remote manipulator or human EVA. A multi-purpose cover (MPC) is therefore proposed that is a passively sealed rigid construction that facilitates a purged gas environment and incorporates an equalisation valve for launch. The cover would also be used during ODIEs return where it protects the instrument (during handling and from contamination) prior to careful analysis.

The passive nature of ODIE means that it requires no power supply or data connections from the host platform, it simply requires a mechanical interface. Should details of the impactors trajectory be required (to link specific particles to parent bodies/spacecraft/orbits) it would also be possible to modify this design to incorporate PVDF sensors which would record the timing and location of individual impact events on each foil. By identifying impact features related to the same impactor on multiple foils when the collector is returned to Earth, it is possible to estimate the impacting particles trajectory with relation to the facing (ram) direction and then link this information with that obtained from the PVDF sensors and knowledge of the host spacecraft attitude at this time to determine details of the impactors orbit/origin.

5 POTENTIAL DEPLOYMENT OPPORTUNITIES

The ODIE collector has been designed for deployment in LEO on, for example, the International Space Station (ISS). In order for ODIE to address the flux gap and provide data on the hazard posed by dust grains in LEO, it is imperative that the collector have constant facing in the ram direction with no obstructions ahead of it in the direction of flight (obstructions will not only potentially bias the collection by effectively shielding ODIE from incoming particles with certain trajectories, but, if impacted themselves, may also spray unwanted secondary debris over the collection surface). Given these requirements, we would propose that ODIE be deployed on the Airbus Bartolomeo platform, an external payload hosting facility attached to the European Columbus module scheduled to
begin hosting payloads from 2020 [https://www.airbus.com/space/spaceinfrastructures/bartolomeo.html]. The individual payload volumes on this platform are currently defined as \(1 \text{ m} \times 0.8 \text{ m} \times 0.8 \text{ m}\), thus ODIEs \(1 \text{ m}^2\) collection area extends beyond this volume. Several of the payload bays, however, will permit us to mount the collector off center, such that the additional surface area extends into free space or alternatively, the collector may be mounted across two payload bays (pers. Comm. Airbus). Given the requirement for free space ahead of the collector and a ram facing direction, the preferred bays for deployment include 3, 4 or 5B (in order of preference). Alternatively, the necessary LEO data may be obtained via collaborations with other agencies (e.g. China, who have invited UN applications to fly scientific payloads c. 2022 [https://www.space.com/40727-china-space-station-unitednations-experiments.html]). Performing multiple flights of ODIE collectors would permit the study of particle flux evolution with time. Although designed with LEO in mind (e.g. incorporation of protective coating for AO environment of LEO), it can also be deployed anywhere that dust populations need to be investigated/monitored providing that a return phase is planned (e.g. Lunar Gateway).

6 ANALYTICAL PROTOCOL

The investigation of particle flux requires a clean working environment and well-planned analytical procedure be in place at the time of ODIE’s return. Upon its return, the ODIE collector would first be examined for signs of any damage during deployment or retrieval. It would then be subjected to collector-wide surveys and in depth analyses of features of interest, progressing from total coverage, low resolution studies with non-destructive techniques to more in-depth analyses of chosen areas or particular features at higher resolution with non-destructive and subsequently destructive techniques. For example, we envisage our analytical protocol would proceed as follows: 1) Initial optical survey of all top foils for impact features down to 500 µm in diameter; 2) Removal of top foils and remounting for optical scanning in transmission mode to reveal all penetrations (size limit dependent on front foil thickness); 3) Automated scanning electron microscope (SEM) imaging to reveal locations of micron-scale impacts. 4) Repeat 1 and 2 for lower foils layers; 5) Mapping and analysis of residues around large (> 500 µm) impact features on top foil; 6) Mapping of individual impacts on lower foils; 7) Analysis of residue particles by Raman, followed by SEM-EDX, then focused ion beam preparation for transmission electron microscopy study and synchrotron beam line facilities (e.g. FTIR, micro X-ray diffraction, XANES and XRF at \(\approx 50\) nm resolution). Any relict crystalline material will be studied to characterise its mineralogy and compositions. Analogous techniques have successfully been used on micron-scale impact craters and terminal grains in aerogel to determine cometary high temperature and water-rock reaction processes [47-48]. Synchrotron analyses can provide information on both soft and hard X-rays, enabling both organic structural analyses and major element compositional data to be achieved.

7 SUMMARY

We have designed ODIE with the aim of collecting and retrieving dust particles in LEO in order to investigate the populations of OD and MMs. The residues created on ODIE foils by impacting particles provide the means to identify its origin (OD vs. MM) and thus constrain the flux of these two populations and the relative hazard each pose to spacecraft. Further, MM particle residues may provide information about their extraterrestrial parent bodies. The design and choice of materials allows for large surface coverage whilst, critically, keeping the mass of the experiment low. The passive nature of ODIE means that it requires no power supply or data connections from the host platform. ODIE is therefore simple to construct, deploy and maintain during deployment. While deploying and returning samples to Earth is costly, it is necessary to access the suite of highly sensitive analytical techniques needed to analyse residues and address the data gap for OD and MM flux; the instruments invaluable to the investigation of impact residues (e.g. high resolution analytical electron microscopy, secondary ion mass spectroscopy, synchrotron beamline facilities) are too large for deployment in space.

8 REFERENCES


