MICRO-METEOROID AND DEBRIS IMPACT RISK ASSESSMENT FOR *LOFT* USING ESABASE2 AND ACCELERATOR TESTS

E. Perinati[1], S. Bugiel[2], E. Del Monte[3], S. Diebold[1], M. Feroci[3], E. Kendziorra[1], A. Rachevski[4], A. Rubini[3], A. Santangelo[1], R. Srama[2], S. Suchy[1], C. Tenzer[1], A. Vacchi[4], G. Zampa[4], N. Zampa[4]

[1]IAAT – Institut für Astronomie und Astrophysik, Universität Tübingen, 72076 Tübingen, Germany
Email:Emanuele.Perinati@uni-tuebingen.de
[2]MPIK – Max Planck Institut für Kernphysik, 69117 Heidelberg, Germany
[3]INAF – Istituto di Astrofisica e Planetologia Spaziali, 00133 Roma, Italy
[4]INFN – Istituto Nazionale di Fisica Nucleare/Sez. di Trieste, 34127 Trieste, Italy

ABSTRACT

The ESA M-3 candidate *LOFT* (*Large Observatory For X-ray Timing*) mission will be equipped with two instruments based on Silicon Drift Detectors (SDDs). Both the Large Area Detector (LAD) and the Wide Field Monitor (WFM) may suffer hyper-velocity impacts by orbital dust particles which might alter the surface properties of the SDDs. In order to assess the risk posed by these events, we perform simulations and laboratory tests. ESABASE2 is a powerful tool to model the dust environment in space and its interaction with the instrumentation, and we use it to estimate the expected fluence of micro-meteoroids and debris in the LOFT LEO orbit and simulate the structural damage resulting from impacts. In parallel, we conduct experimental tests on SDD prototypes at the dust accelerators at the MPIK in Heidelberg and TUM in Munich, aimed at verifying to what extent the impact structural damages affect the SDD functionality.

1. INTRODUCTION

The space environment contains dust. Dust refers to both micro-meteoroids and debris. Micro-meteoroids are natural interplanetary fragments with mostly cometary and asteroidal origin, while debris are fragments originating from manmade objects placed in orbit. These particles, whose size ranges from less than 1 µm to above 1 cm, are accelerated to hyper-velocities of the order of 10-20 km/sec by the Earth's gravitational field. Therefore, the impacts by orbital dust grains are a potential threat for space-born instruments due to the structural damages they can produce, which in turn may imply degradation of the performance or even, in the worst case, the failure of the instruments. As an example, the Charge Coupled Devices (CCDs) aboard *XMM-Newton* [1] as well as the one aboard *Swift* were damaged by a number of impacts. The assessment of the impact risk is crucial to estimate the probability of damages, quantify the degradation of the instrument performance, and possibly identify and implement suitable shielding solutions. We are performing such investigation in the framework of the *LOFT* space mission [2], which is based on the usage of innovative Silicon Drift Detectors (SDDs) [3]. We use ESABASE2 to model the dust environment in the *LOFT* orbit and the structural damage resulting from the impacts between hyper-velocity projectiles and the SDDs, and experimental tests at accelerator facilies to reproduce the dust space environment in laboratory, validate the predictions of the models and simulations, and quantify the degradation of the SDD performance caused by impacts. In this paper we provide an overview of these activities, which are currently in progress.

2. CRATERS

When a hyper-velocity projectile impacts against a target,the resulting structural damage is the formation of a crater on its surface (or of a clear hole in case the projectile has enough energy to fully penetrate through the target).

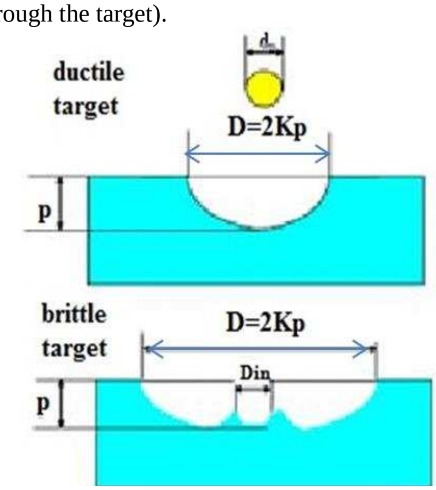

Figure 1. Crater morphology: in the case of ductile targets the crater is nearly spherical,while in the case of brittle targets an inner smaller crater forms within the larger outer crater. The characteristic constant K is different in the two cases, K~1 for ductile materials, K~10 for brittle materials.

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The morphology of the crater is somewhat different for ductile and brittle materials: in the first case the crater is nearly spherical, while in the other case typically an inner crater with smaller diameter forms within the larger outer crater. The *crater equation* allows to predict the crater size and depth as a function of a number of parameters. For single-wall targets the general equation for the crater depth (p) is:

$$p = c \cdot d_p^{\alpha} \cdot v_p^{\beta} \cdot \rho_p^{\gamma} \cdot \rho_t^{\delta} \cdot \cos^{\varepsilon} \Theta \quad (1)$$

where d_p, v_p and ρ_p are diameter, velocity and density of the impacting particle, Θ is the angle of incidence, ρ_t is the density of the target, and c is a characteristic constant. This empirical formula has a general validity, however the values of the parameters α, β, γ, δ, ε are somewhat different for ductile and brittle materials and also vary depending on the range of the variables. Equation (1) and commonly used values of the parameters are reported in ESABASE2 [4].

3. OUR CASE STUDY: *LOFT*

LOFT [2] is a medium-class space project proposed as part of the ESA Cosmic Vision program, and is currently one of the space missions candidate for a M-3 launch in 2022-2024. It will be placed in a low-Earth near-equatorial orbit (inclination < 5º) at ~600 km altitude. The scientific goal of *LOFT* is the investigation of the strong-field gravity and the equation of state of the ultradense matter through the observation at high count-rate of compact objects in the band 2-30 keV, with an unprecedented effective area of ~10 m^2. The innovative adopted technology relies on the usage of SDD tiles [3] derived from those developed by INFN for the ALICE experiment at LHC/CERN. Each tile is a 450 μm thick fully depleted Silicon wafer with a quite large size (about 15x7 cm) and capable of achieving very good performance in terms of time resolution (~7 μsec) and energy resolution (~260 eV FWHM @ 6 keV). A system of cathodes implanted at the surface, on both sides, provides a strong electric field variable from the center of the surface towards the edges, allowing for a fast drift of the charges generated by the absorbed photons towards a set of miniaturized collecting anodes (see Fig. 2).

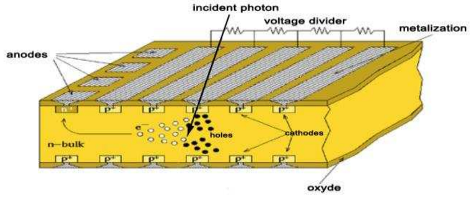

Figure 2. Schematic of the SDD used aboard *LOFT* (courtesy of ISDC).

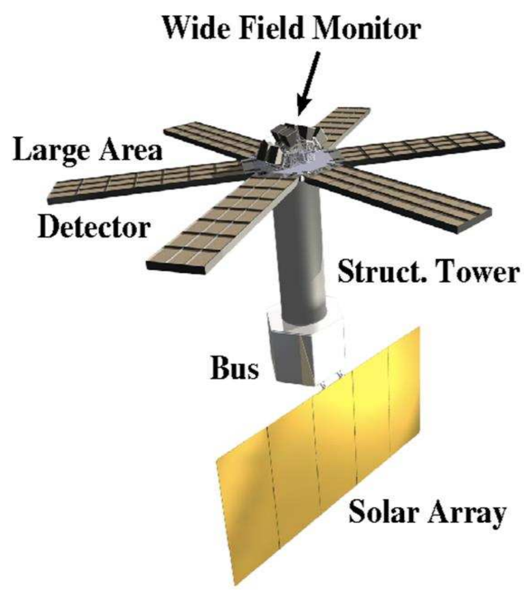

Figure 3. *LOFT* geometry showing the LAD and WFM instruments (courtesy of ISDC)

There are two instruments aboard LOFT (see Fig. 3): the Large Area Detector (LAD) [5] and the Wide Field Monitor (WFM) [6]. The LAD features a geometric area of ~18 m^2 achieved by assembling 2016 SDD tiles in 126 modules (4x4 tiles each), and the modules in 6 panels (3x7 modules each). It is a collimated experiment and the micro-pored glass collimator on top the SDD assembly has a FoV~1°. The WFM consists of 10 cameras divided in 5 pairs, each camera is a coded-mask instrument with 4 SDD tiles in the detector plane. The WFM features a very large FoV~180°x90° useful to detect variable sources, with a total geometric area of ~0.18 m^2.

The expected effect of hyper-velocity impacts on the SDD tiles aboard *LOFT* is some permanent increase of the anode leakage current, and a possible alteration of the electric field at the surface caused by craters. The SDD surface has ~1 μm Silicon Oxide passivation on top, that works as a protection of the underlying active region, only hyper-velocity particles with energy enough to penetrate through and reach the field oxide and the bulk below are expected to produce real damages. Therefore, in applying Eq. 1 for the crater depth estimate we refer to a set of parameters suited to describe brittle materials, such as Silicon Oxide. In particular, the Cour-Palais set of parameters is commonly adopted:

$c=0.53 \quad \alpha=1.06 \quad \beta=0.667 \quad \gamma=0.5 \quad \delta=0 \quad \varepsilon=0.667$

4. MODELING WITH ESABASE2

ESABASE2 [4] is a newly developed toolkit that allows to model the dust space environment and simulate the structural damage resulting by the impacts of hyper-velocity particles onto target materials. We use it to derive the expected fluence of micro-meteoroids and debris in the *LOFT* orbit. The differential curves based on the MASTER-2005 model are reported in Figure 4.

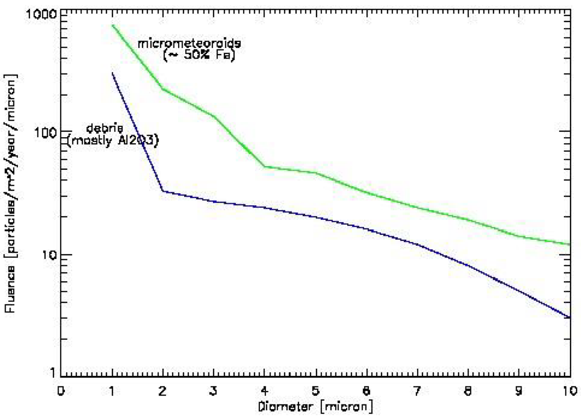

Figure 4. Differential fluence of micro-meteoroids and debris expected in the *LOFT* orbit from the MASTER-2005 model in ESABASE2.

In the 1-10 μm diameter range, where ~80-90% of all micro-meteoroids and debris in space are found, the expected mass composition of micro-meteoroids is ~46% Iron, ~17% Silicate and ~37% of some lower density material [7], while orbital debris is likely composed mostly by Alumina particles ejected from solid motor boosters [8]. The average velocity expected in orbit is ~20 km/sec for micro-meteoroids (see Fig. 5) and ~10 km/sec for debris. The curves of Fig. 1 are the input to estimate the impact probability and evaluate the related structural damage.

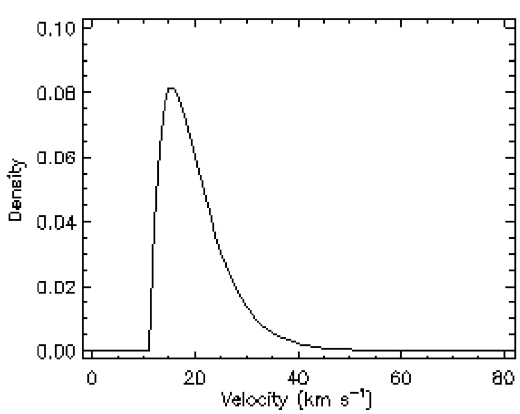

Figure 5. The expected velocity distribution for micro-meteoroids.

5. ASSESSMENT FOR LAD

As it is shown in Fig. 3, the LAD design envisages 6 panels, each one composed of 21 modules arranged in a 3x7 array (see Fig. 6). Each module consists of 16 SDD tiles. The total geometrical area is ~18 m^2, covered by a micro-pored glass collimator (open fraction = 0.7) with FoV ~ 1°

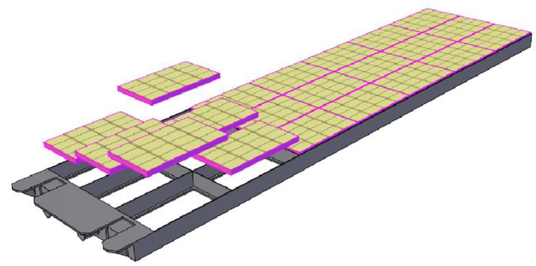

Figure 6. LAD panel: array of 3x7 modules (courtesy of ISDC)

From the curves of Figure 4 we calculate the average number of impacts by micro-meteoroids and orbital debris expected for the LAD in 5 years, which is the nominal duration of the mission. They are listed in Table 1.

Table 1. Average number of impacts by micro-meteoroids (MM) and orbital debris (OD) expected on the total exposed surface of the LAD (~10 m^2) in 5 years.

particle size (μm)	#impacts (MM)	#impacts (OD)
≥1 , ≤ 2	2.34	0.925
≥2 , ≤ 3	0.69	0.100
≥3 , ≤ 4	0.41	0.082
≥4 , ≤ 5	0.16	0.073
≥5 , ≤ 6	0.14	0.061
≥6 , ≤ 7	0.097	0.048
≥7 , ≤ 8	0.073	0.036
≥8 , ≤ 9	0.058	0.024
≥9 , ≤ 10	0.043	0.015
≥1 , ≤ 10	**3.68**	**1.36**

Therefore, considering both micro-meteoroids and debris, we expect a total average rate of ~1 impact per year, most probably from particles with size between 1 μm and 2 μm, which according to Eq. 1 with the Cour-Palais parameters would produce craters with depths ranging from ~3 μm to ~15 μm. Assuming a Poisson distribution, we have that with an average rate of 1 impact per year the probability that 1 tile per year is affected is ~37%, the probability that 5 tiles per year are affected is ~0.3% (since the number of expected impacts is low compared to the number of tiles we do not take into account the probability that a tile is hit more than once).

Considering that LAD is composed by 2016 electrically independent tiles and that the damage produced from micron-sized particles would likely be localized and would affect mainly the anodes closest to the region of the tile where a crater is produced, the risk of a significant degradation of the LAD performance due to hyper-velocity impacts seems low enough. In the worst case, i.e. assuming that each impact implies a complete failure of the hit tile and that 5 tiles per year are actually hit, the LAD would suffer only ~0.25% loss of effective area per year.

Despite the low probability of having a significant degradation of the LAD performance in orbit, it is mandatory to perform a qualification of the SDDs against hyper-velocity impacts. We tested a prototype SDD (see Fig. 7) at the dust accelerator of the Max Planck Institut für Kernphysik in Heidelberg to verify its robustness and characterize the electronic response to the structural damages produced on its surface. We shot 23 grains made of Olivine onto the SDD active area. Among the materials available at MPIK Olivine has a density (~3.3 g/cm^3) intermediate between Silicon and Alumina, so that it can simulate reasonably well both the orbital debris and light micro-meteoroids.

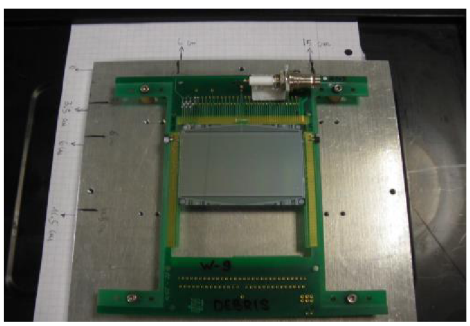

Figure 7. The SDD prototype tested at MPIK

The SDD was mounted in a vacuum chamber and biased at -1300 V using the feed-throughs on the interface flange of the chamber. We monitored in real-time the leakage current of all anodes bonded together during the bombardment. Even though it was not possible to reproduce in laboratory the most probable events expected in orbit due to the trade-off size-speed of the particle distribution available at the accelerator (see Fig. 8), from Eq. 1 we expect from the shot particles crater depths in a range ~0.5 μm to ~3 μm, so that at least a few particles should have reached the bulk region below the passivation. However, we could not appreciate any clear variation of the leakage current level. We observed a jump only when particles were shot onto the voltage divider area, a particularly critical area which in the final design of the instrument might not be directly exposed to the space environment thanks to the presence of the collimator. It is worth to be stressed that besides Cour-Palais there are other empirical sets of parameters to predict the characteristics of the craters, which can differ at least within a factor of 2. That means that we cannot exclude the possibility that all the shots onto the active area have been stopped within the passivation layer without reaching the substrate. On the other hand, if the Cour-Palais prediction for Silicon Oxide overestimates the crater depth by a factor of 2 or more, we likely should assume that the 1-2 μm particles expected in orbit will be fully stopped within the passivation, at least in the case of low density particles. To obtain some direct information on the actual depths of the formed craters we use an *Atomic Force Microscope* (AFM) [9], Fig. 9 shows a scanning of the profile of one of the craters produced on the triangular region above the voltage divider area (outside of the active region).

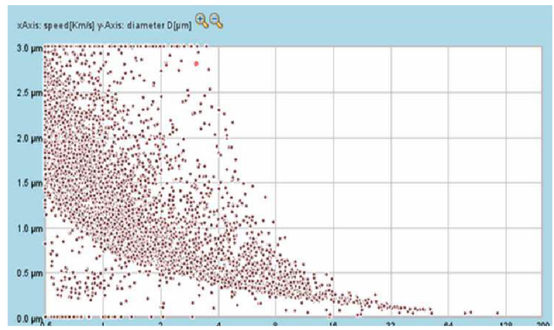

Figure 8. Size-velocity distribution of the Olivine particles available at MPIK

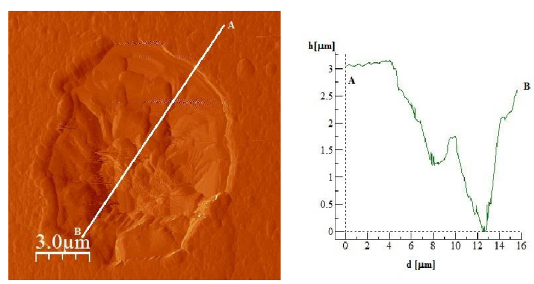

Figure 9. *Left*: 3D view of a crater on the triangular region above the voltage divider; *Right*: the crater profile along the track from A to B obtained with an AFM microscope. The max depth of the crater measures 3-3.5 μm.

We have scheduled a new test at MPIK with Iron particles which are expected to simulate more realistically the actual population of micro-meteoroids in orbit. To optimize the strategy and get a clearer understanding of the impact process, we will select preliminarly the parameters of the particles capable to produce an electronic response of the device by bombarding a number of small diodes having a surface structure equal to that of the SDD (see Figure 10). This will also allow to create a dataset related to the crater characteristics useful for a systematic comparison of the measured values with the predictions by the empirical formulas.

Figure 10. A 3x3 cm PCB with 4 small diodes prepared at INFN as a test structure for hyper-velocity particle selection. The diodes have a surface structure equal to that of the SDD. Particles that will produce electronic response from the diodes will be shot onto the SDD as well.

6. ASSESSMENT FOR WFM

The WFM design envisages 10 coded-mask cameras containing each 4 SDD tiles in one detector plane (see Fig. 11)

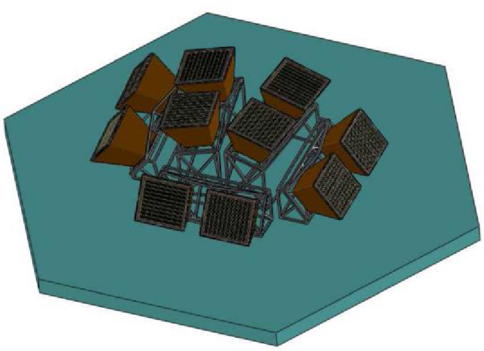

Figure 11. The 10 WFM cameras (courtesy of ISDC)

In the case of the WFM the approach to the question of the risk posed by hyper-velocity impacts is different with respect to the LAD. Being the FoV of the WFM much larger, the average number of impacts is expected a factor of ~50 higher than for the LAD, so that even bigger particles (with diameter between 2 μm and 20 μm) are an issue. Even tough the SDDs have never been tested up to now with such energetic particles, it is reasonable to expect that the impacts may compromise their functionality, which for WFM would be critical as the number of tiles here is much less. For this reason, the baseline design of the WFM foresees the usage of a Whipple shield (see Fig. 12) in front of the SDDs to stop hyper-velocity particles up to about 100 μm in size. The Whipple shield for the WFM consists of a layer of Kapton (acting as a bumper), which is already envisaged in the WFM configuration as an optical filter, coupled to an additional layer (acting as a rear-wall) made of a material having a good strength yield against hyper-velocity grains. The distance between the two layers is approximately 20 cm, corresponding to the distance between the coded-mask and the detector plane. The bumper layer is expected to convert part of the kinetic energy of the impacting particles into heat, producing some fragmentation into smaller grains. The cloud of secondary less energetic fragments and ejecta from the bumper is then stopped in the rear-wall layer.

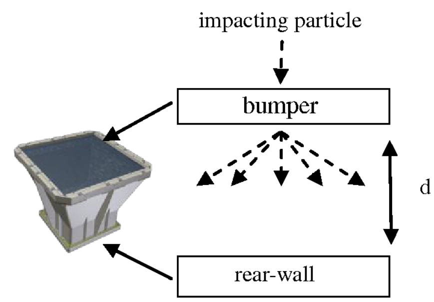

Figure 12. A Whipple shield is composed by an outer bumper layer placed at a certain distance off a rear-wall. The bumper produces some fragmentation of the primary impacting particle, the cloud of less energetic secondary ejected fragments should be stopped by the rear-wall layer. Arrows indicate where the bumper and rear-wall layers would be placed in the WFM.

The investigation of the properties of such a shield is currently in progress. ESABASE2 permits to simulate the shielding performance and the *penetration limit* (d_p^{lim}) as a function of the variables of the configuration, i.e. materials, thicknesses and geometry, and of the parameters of the impacting particles. For a double-wall Whipple shield the general formula for d_p^{lim} is:

$$d_p^{\lim} = \left[\frac{t_{rw} + c1 \cdot t_b^a \cdot \rho_b^b}{c2 \cdot v_p^c \cdot \rho_p^d \cdot \rho_{rw}^e \cdot s^f \cdot \cos^g(\Theta)} \right]^{1/\lambda} \quad (2)$$

where t_b,ρ_b and t_{rw},ρ_{rw} are thickness and density of the bumper and rear-wall respectively, s is the spacing between bumper and rear-wall, v_p , ρ_p and Θ are diameter, velocity and angle of incidence of the impacting particle, and c1 and c2 are characteristic constants. This analysis is useful to optimize the trade-off between the stopping power of the shield and the quantum efficiency of the instrument. In fact, any layer interposed between the WFM and the sky implies to some extent a degradation of the quantum efficiency at lower energies. Therefore, ideally the shield should be capable to stop all the potentially risky particles with the lowest degradation of the quantum efficiency. Beryllium is considered as a baseline material for the rear-wall, thanks to its high transparency in the soft X-ray range, but we are investigating other solutions as well. One of this consider the usage of 10-15 μm Polypropylene, which, according to our preliminary simulations, shows promising shielding properties. The analysis with ESABASE2 is preparatory to laboratory tests on shielding prototypes that we are planning to perform at the plasma accelerator of the Technische Universität in Munich, where it is possible to shoot silicate particles up to 80-100 μm in size at 5-10 km/sec. The experimental validation of the shield strength and effectiveness is important as the set of parameters a,b,c,d,e,f,g,λ in Eq. (2) has been derived for some common materials, such as Aluminum, but the applicability and validity in other cases is not obvious and has to be confirmed by laboratory tests.

7. CONCLUSIONS

We presented the current status of our activities to assess the impact risk for the *LOFT* mission. Through simulations in ESABASE2 we model the space environment and calculate from the expected populations of micro-meteoroids and debris the impact probability for the LAD and WFM instruments. We also model the structural damage that impacts might produce on the surface of the SDDs, and investigate different possible shielding configurations for the WFM instrument, in order to optimize the trade-off between the penetration limit of the shield and the quantum efficiency of the detector. In parallel, we conduct experimental tests on both SDD prototypes and shielding materials at the accelerator facilities at MPIK and TUM, to determine to what extent the expected structural damages may affect the SDD functionality and validate in laboratory the predictions of simulations on the shield effectiveness.

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