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ORBITAL DEBRIS AND METEOROIDS: RESULTS FROM RETRIEVED SPACE EXPERIMENTS.

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ABSTRACT

Near-earth space contains natural and man-made particles, ranging from submicron particles to cm sized objects. This environment causes a grave threat to space missions, mainly for future manned or long duration missions. Experiments devoted to the study of this environment have been recently retrieved from space. Among them several were located on the NASA Long Duration Exposure Facility (LDEF) and on the Russian MIR Space Station. Evaluation of hypervelocity impact features on selected targets gives information on size distribution of small dust particles present in low earth orbit. Chemical identification of projectile remnants, although not easy, allows a discrimination between natural particles and man-made orbital debris. A comparison of flight data with current modeling of meteoroids and space debris shows a fair agreement for LDEF. For MIR, results show differences with current modeling. Occurence of secondary impacts is a common phenomenon which must be seriously taken into account in the design of future spacecraft.

1. INTRODUCTION

Interplanetary space contains a wide variety of solid bodies whose sizes range from the submicron to kilometers. Some meteoroids originate from comets, others from collisions within the asteroid belt (Ref.1). In addition to natural particles, a significant and growing number of artificial particles has been added by human activity in near-Earth space (Ref.2). In the vicinity of Earth, gravitational and no-gravitational perturbations greatly affect the distribution of the particles. Due to the high velocity of impact of the dust particles with exposed surfaces, damage caused to the spacecrafts can be significant (Ref.3). In general the velocity of interplanetary particles lies in the range 10-70 km/s, with an average impact velocity on a vehicle in Earth-orbit of 20 km/s. Similarly, orbital debris impact at velocities up to 15 km/s.

The need for a monitoring program of millimeter and micron sized particles is obvious. In-situ detection and collection of dust by experiments flown on LDEF and on MIR have already improved our current understanding of this important aspect of the space environment, but many issues are still a matter of debate, particularly the relative contribution of natural particles and orbital debris (Ref.4,5).

2. EXPERIMENTAL RESULTS

The NASA Long Duration Exposure Facility (LDEF) has been retrieved after 2105 days in orbit. During its mission LDEF was stabilized with the long axis continually pointed toward the center of the earth, and surfaces perpendicular to this axis pointed at fixed angles with respect to the direction of orbital motion (Ref.7).

The tray allocated to French experiments (FRECOPA) was located on the face of LDEF (B3) directly opposed to the velocity vector. Two passive experiments have been flown for the detection of microparticles. The first was composed of a set of thick metallic samples (Al, Au, Cu, W, Stainless Steel) and quartz surfaces; the second was composed of aluminium multilayer thin foils detectors. The collection area was about 2000 cm^2. Detailed description of the hardware has been given elsewhere (Ref.8,9).

The MIR Russian Space Station has been in a 350 km circular orbit since February 1986. The experiment, "Echantillons", was deployed outside the station during the Aragatz Mission in december 1988; it was retrieved 13 months later. Dust detectors flown on MIR carried basically the same passive sensors, as for LDEF, with two sets of stacked thin foils (DMC) looking in two opposite directions, and an active dust detector (Ref.10). This second type of detector (DIC) was based upon the monitoring of the discharge of a capacitor upon impact of a particle with a mass greater than a given threshold, depending on the thickness of the dielectric.

Due to the normal stabilization mode of the station, sensors were facing the velocity vector direction during approximately half of the orbit. However, during short periods of time the attitude of the station was different from the normal mode, thus introducing an uncertainty in the determination of experiment orientation.

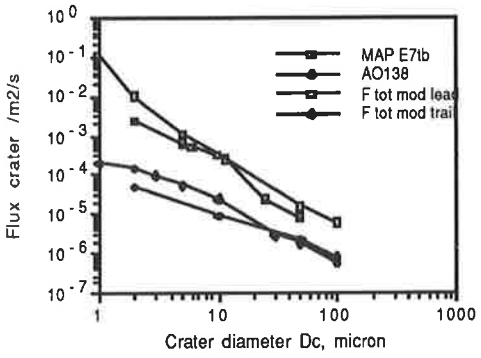
Crater size distribution on the various targets make possible, using laboratory calibration with solid particle accelerators, the evaluation of the incident microparticle flux (see Ref. 11,13 and 22).

A more critical issue is the determination of the origin of the impacting particles. In general they are physically destroyed and mixed with target material in the process of crater formation. The aim of the multiple foil penetration experiment was primarily to investigate the feasability of multilayer thin film detectors acting as energy sorters in order to collect the debris, if not in their original shape, at least as fragments suitable for chemical analysis (Ref.11).

2.1 Crater-size distribution.

Most of impacts in aluminium targets showed similar features: approximately circular symmetry, evidence of melting and fusion and a raised circumferential lip; they agreed with initial NASA findings for LDEF (Ref.12). Information on the velocity, particle density and incident direction can be partially derived from the geometry of impact craters. Results about the flux distribution of large craters have been given elsewhere (Ref.4,19); this paper will present mainly data from impacts produced by small particles.

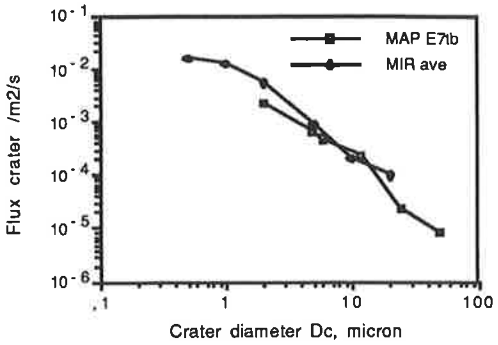
Figure 1 LDEF: Comparison data and model (leading and trailing sides)



The cumulative flux size distribution of small impact craters is shown in *Figure 1*. This figure shows the size distribution of craters between 2 and 100 microns as derived from high magnification SEM scanning of aluminium samples, from FRECOPA (AO138) trailing side, and from a sample (E7tb), located on the leading side, from the Multiple foil Abrasion Package Experiment (MAP). There is clear evidence of a cut-off in the 1-2 microns size-range.

The F*igure 2* shows a comparison between the number of craters observed on the MAP experiment and the number of small craters from detectors exposed on the MIR space station. The flux of small particles is somewhat larger on MIR samples than on the leading side of LDEF, and there is evidence of particles smaller than those detected so far on LDEF.

Figure 2 Comparison data LDEF (leading side) and MIR / Aragatz



However when comparing the MIR and LDEF fluxes it is important to bear the following in mind:

- As previously mentioned the stabilisation modes of the MIR station and LDEF were fundamentally different. The samples on MIR were submitted to meteoroid and debrix flux, but as debris travel at much lower velocities than meteoroids, few debris impacts were expected on the trailing edge of LDEF, where FRECOPA was located.
- MIR was in an orbit inclined at 58°, whereas LDEF was in an orbit inclined at 28°. They would therefore have passed through different volumes of space with different flux distributions. However present modeling of latitude dependence for orbital debris cannot entirely explain such a difference. A possible explanation for this higher flux is that the environment of a manned station generate more small debris than an unmanned spacecraft such as LDEF.

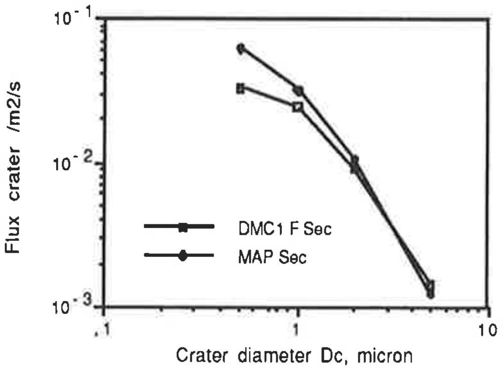
2.2 Secondary craters.

A large density of submicron craters has been found on several aluminium samples from the MIR experiment, located within a zone of about 10 cm in diameter. A significant percentage of these craters appeared to be ellipsoidal in shape. This could be due to an elongated projectile, although this is unlikely, as at high impactor velocities the crater's dependence on the projectile shape is less critical. A more probable supposition is an accentuated angle of projectile incidence (>60° from normal) due to a secondary impact off a nearby spacecraft surface (solar panel generator possibly as shown by analysis of residues).

Secondary impacts also occured on LDEF : ejecta from a nearby identified crater (200 µm in diameter), have been found on the sample from the MAP experiment (Ref.20). Secondary ejecta is characterized by larger number density of micron and sub-micron sized crater, with evidence of oblique incidence and same orientation. Obviously secondary impacts are produced by impact of solid particles (ejecta could be partly in the form of liquid droplets but small droplets cool down very quickly and before impacting the target). The process could be different for larger impact where there is generally a strong evidence of molten ejecta, as shown on many oblique impacts on the Earth and Space sides of LDEF (Ref.21) and on two large perforations on FRECOPA.

The size distribution of the secondary impacts is shown in *Figure 3*, the shape of the distribution is similar for LDEF and MIR samples.

Figure 3 LDEF and MIR : Secondary crater distribution



Secondary impacts are a very common phenomenon as shown by secondaries on lunar samples : results from detectors can be severely biased, and they could increase significantly the degradation of exposed surfaces in the case of complex srtuctures.

2.3 Chemical analysis of particle remnants.

One of the objectives of the FRECOPA and MIR experiments was the identification of the particles responsible for the formation of the craters. In general they are physically destroyed and mixed with target material in the process of crater formation. Laboratory experiments shows that the phenomena depends primarly upon the velocity of impact. For instance, impacts of iron particles on aluminium targets shows that for velocity higher than 12-14 km/s the projectile is almost completely vaporized, for velocities between 5 and 10 km/s the projectile is progressively comminuted and melted but identification of its composition is still easy, for velocities between 2 and 4 km/s the projectile usually remains almost intact. Complexity for actual impacts is increased by the large variety of objects and of impact velocities. However analysis of a few impacts obtained on the multiple foils detectors show that the identification for projectile remnants is easier than inside a single impact crater. According to the conditions of impact the projectile remains partially intact or is scattered into many fragments, producing lower velocity secondary craters where chemical identification is possible.

Energy dispersive spectroscopy (Link Analyser EDS) of several impact features has been carried out in search of projectile remnants.

For FRECOPA : About 50 % of the craters analyzed so far show no residue.

If we consider the craters with residue :

- 15 small craters (1.5 - 15 microns in diameter) shows all evidence for natural origin (see Ref.4).
- 30 craters (diameters between 5 and 100 microns) show that 80 % of particles were from natural origin. Orbital debris with low impact velocity have been found (stainless steel, paint flakes). However identification of aluminium particles was not possible, and as suggested by F. Horz data, at least 50 % of the debris could be made of aluminium (structural material, solid rockets combustion residues).

Results reported by F. Hörz (tray A03 trailing side) for analysis of 187 craters on gold targets (10 - 900 microns in diameter) show that 15 % of the residues are compatible with the composition of orbital debris (among them 65 % apparently contain only aluminium), 30 % with the composition of micrometeoroids and that 55 % show no observable residue (Ref.5).

For MAP the analysis is still in progress, but very few craters show projectile residues. High impact velocity on the leading side leaves few material left for analysis. Morever, impurities scattered within the alloy make analysis difficult.

The analysis of 50 craters from MIR, shows that 60 % contain no residue (some of them could be the result of aluminium particles), that 29 % are consistent with natural particles and that 11 % are consistent with orbital debris (SSM, glass likely from solar panels or paint flakes).

The results are certainly biased toward orbital debris detection because chemical identification is easier than for natural particles, due to the lower impact velocity : there is more orbital debris detected than actually present in the size range investigated. At least 80 % of craters without residue could be the result of natural particle impacts. Orbital debris in GTO as detected on the trailing side of LDEF may account for 20 % of the total. Natural particles detected on the trailing side are larger than 0.3 - 0.4 microns.

3. COMPARISON WITH MODELS.

As expected, for LDEF, the number of impact craters varies significantly with the location around the spacecraft. The highest flux is found on the ram facing direction, the lowest on the earth or the rear facing direction. It is interesting to compare the flight data with values given by existing models describing the earth particulate environment. Such a comparison is shown here for the leading and the trailing sides of LDEF as shown on *Figure 1.* The modeling has been conducted with the Esabase software developed by ESA (Ref.15).The flux models used in the program are Grün's polynomial model for meteoroids (Ref.16) and Kessler's 1990 model for orbital debris (Ref.2); depth of penetration formula used for conversion of crater diameter to particle diameter is the one used by D. Humes (Ref.17) and originally proposed by B. Cour-Palais (Ref.6), (crater is assumed to be near-hemispherical in shape with a depth/diameter ratio of P/D = 0.55) :

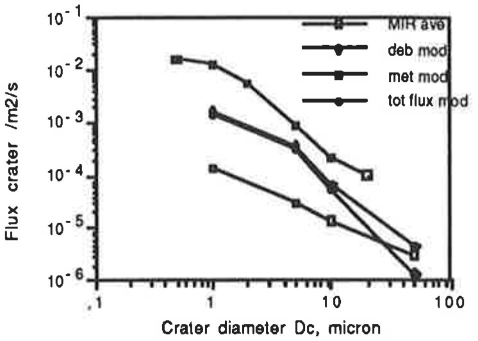
$$P = 0.42m^{.352}\rho^{1/6}V^{2/3} \qquad (1)$$

P (depth) is given in cm, m (mass) in g, ρ in g/cm^3 and V (velocity) in km/s.

Average impact velocity for meteroids and for debris has been computed with Esabase for each face of LDEF. The flux of particles responsible for the formation of the craters is then computed taking into account the fact that craters of a given size are produced by larger particles on the trailing side than on the leading side, due to the differences in impact velocities.The preliminary results show a good agreement between the observed and computed values. Because of the 8° offset in the orientation of LDEF with respect to the velocity vector (Ref.7) the value of the flux is at a maximum on row 10 and minimum on row 4 (instead of row 9 and row 3, respectively). Moreover, this small offset partly explains the occurence on row 3 of impact craters produced by orbital debris in circular orbits. However, some craters are obviously produced by orbital debris in highly elliptical orbits, probably coming from objects in geostationary transfer orbits (GTO). This could explain the difference between observed and computed values for the smallest craters on the trailing edge of LDEF. The contribution of orbital debris is significant for particles in the micron-size range.

A similar computation has been made for MIR. Average orientation of the station has been chosen accornding to available data from Russian Mission Control. The *Figure 4* shows a comparison of the crater distribution as given by experimental data and by the modeling obtained with Esabase. There is an evident discrepancy, mainly for small size craters, between the flight data and the model. The results are however consistent with data shown in *Figure 2* and have been discussed eralier.

Figure 4 MIR / Aragatz : Comparison fligth data and model (esabase)



4. CONCLUSION

LDEF and MIR give us an unique opportunity for the in-situ study of the many processes involved upon high-velocity impacts. Crater size distribution already provides a comprehensive description of the actual particulate LEO population. Orbital debris are dominant on spacecraft surfaces facing the velocity vector. Data from MIR experiments show that the number of small particles (possibly orbital debris) is higher in the vicinity of a permanently manned spacecraft. However more data are still needed for an accurate modeling of the low earth particulate environment.

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