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MICROMETEOROIDS AND DEBRIS ON LDEF

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SUMMARY

Two experiments within the French Cooperative Payload (FRECOPA) and devoted to the detection of cosmic dust have been flown on the Long Duration Exposure Facility (LDEF). A variety of sensors and collecting devices have made possible the study of impact processes on dedicated sensors and on materials of technological interest. Examination of hypervelocity impact features on these experiments gives valuable information on size distribution and nature of interplanetary dust particles in low-Earth orbit (LEO), within the 0.5-300 micrometer size range. However no crater smaller than 1.5 microns has been observed, thus suggesting a cut-off in the near Earth particle distribution. Chemical investigation of craters by EDX clearly shows evidence of elements (Na, Mg, Si, S, Ca and Fe) consistent with cosmic origin. However remnants of orbital debris have been found in a few craters; this can be the result of particles in excentric orbits about the Earth and of the 8° offset in the orientation of LDEF. Crater size distribution is compared with results from other dust experiments flown on LDEF and with current models. Possible origin and orbital evolution of micrometeoroids is discussed. Use of thin foils detectors for the chemical study of particle remnants looks promising for future experiments.

INTRODUCTION

Interplanetary space contains solid objects whose size distribution continuously covers the interval from submicron sized particles to km sized asteroids or comets. Some meteoroids originate from comets, some originate from collisions within the asteroid belt /1/. In addition to natural particles, a significant and growing number of particles has been added by human activity in near-Earth space. In the vicinity of Earth, gravitational perturbations and the influence of the atmosphere greatly affect the distribution of the particles. In-situ detection and collection of dust by experiments flown on LDEF have already improved our current understanding of this important aspect of the space environment, but many issues are still a matter of debate, namely the relative contribution of natural particles and orbital debris /2/.

Two entirely passive experiments have been flown for the detection of microparticles, as part of the FRECOPA experiment. The first one, Study of Meteoroid Impacts on Various Materials (AO138-1), was composed of a set of thick glass and metallic samples; the second one, Dust Debris Collection with Stacked Detectors (AO138-2), was composed of multilayer thin-foil detectors. The experiment was located inside tray B03, on the trailing side of LDEF. Detailed description of the hardware and preliminary results after retrieval have been given elsewhere /3,4,5 /.

ANALYSIS OF IMPACT CRATERS

The results concerning the largest impact features found in association with the FRECOPA payload were given in a previous paper (ref.5); here we address the size distribution of small-sized (< 100 microns) craters. The initial surveys were conducted with an optical microscope utilizing magnifications of 20X and 100X, while more detailed scanning and examination of peculiar features was carried out with a dedicated Scanning Electron Microscope (SEM). Energy dispersive X-ray analyses (EDX) were performed on the melt residues associated with some craters in order to garner information on the chemical composition of the projectiles.

Crater-Size Distribution

In addition to two large impact features (one full penetration 1.25 mm in diameter and one marginal penetration 1.07 mm in diameter of a 1 mm aluminium shield) about 90 craters larger than 50 microns have been found on a total area of one square meter. Four craters are larger than 500 microns. Most of the large craters are circular in outline, though a few small craters do indicate oblique incidences.

Most of the data about the size distribution of small craters come from two 10 x 10 cm aluminium samples exposed during the entire mission and from samples located inside a canister, exposed only during the first nine months. Four cm² of aluminium (sample A54 from AO138-1 experiment) have been thoroughly analyzed in search of microcraters, less than 20 microns in size. A first scanning of the samples at a magnification of 750X allows a selection of events showing typical crater features (circular feature, prominent rim). A typical flux density of $2.1 \cdot 10^{-4}$ /m²/s of craters larger than 1.5 microns has been derived; a similar flux ($2.2 \cdot 10^{-4}$ /m²/s) has been found on the surface of other aluminium samples (A21, A22 from AO138-1). Flux mass distributions found for larger craters can thus be extended with very good agreement to small sizes.

Scanning of a few samples (from AO138-2) exposed only during the first nine months of the mission has been made. Preliminary data seem to indicate an impact flux higher than for samples that were exposed during the entire 69 month period - with a flux of $6.1 \cdot 10^{-4}$ /m²/s for craters larger than 2 microns, as compared to $2.1 \cdot 10^{-4}$ /m²/s. This flux value must be confirmed by further investigation, currently in progress, but it seems to be consistent with data from the Interplanetary Dust Experiment (IDE) experiment as given by J.D. Mulholland /6/.

We observed no craters smaller than 1.5 microns in size, thus implying a cut off in the natural particle size distribution. Considering simulation experiments giving a factor of 5 between the crater size and the particle diameter suggest the smallest impacting particles had a mass in the 10^{-13} g range.

The cumulative flux size distribution of craters (in aluminium) larger than 1.5 microns is shown on Figure 1. The upper part of the figure shows the crater size distribution of craters between 1 micron and 10 microns as derived from high magnification SEM scanning of small craters on aluminium samples (A54). For comparison we have plotted the size distribution of small craters on a sample (E7.tb), located on the leading side, from the Multiple foil Abrasion Package (MAP) experiment given to us for analysis by J.A.M. McDonnell. The search for craters smaller than 2 microns is not yet finished, but there is some evidence of a cut-off in this size-range.

The figure 2 shows a comparison between the number of craters observed on the MAP experiment and the number of small craters from samples exposed on the MIR space station in 1989 /7/. The flux of small particles is higher on MIR samples than on the leading side of LDEF, and there is evidence of particles smaller than those detected so

far on LDEF. Furthermore the samples on MIR were not always facing the leading side. The 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 could generate more small debris than an unmanned spacecraft such as LDEF.

Comparison With Models

It is interesting to compare LDEF data with values given by existing models describing the earth particulate environment. Such a comparison has been done for some data available to us (MSDIE, MAP, tray clamps) for three different crater diameters (5, 50 and 500 microns). The modeling has been conducted with the Esabase software developed by ESA /8/. Flux models used in the program are Grün's (1985) polynomial model for meteoroids /9/ and Kessler's 1990 model for orbital debris /10/; depth of penetration formula used for conversion of crater diameter to particle diameter is the one used by D. Humes /11/ and originally proposed by B. Court-Palais /12/ (crater is assumed to be near-hemispherical in shape with a depth/diameter ratio of $P/D = 0.55$) :

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

P is given in cm, m in g, ρ in g/cm^3 and V in km/s.

According to the models, average impact velocity for meteoroids and for debris is computed with Esabase for each face of LDEF. Results are shown on Figure 3. The flux of particles responsible for the formation of the craters is then computed for each face of LDEF 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 (see Table 1). Preliminary results given in Figure 4 show good agreement between the observed and computed values. Because of the 8° offset in the orientation of LDEF with respect to the velocity vector, 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 can explain the occurrence, on row 3, of impact craters produced by orbital debris in circular orbits. This is shown by the model and confirmed by the chemical identification of man-made debris remnants inside craters (see ref.13 and lower in this paper). Conversely, only debris in highly elliptical orbits could impact samples located on row 4.

Comparison of the flux of particles on the leading and on the trailing sides is shown on Figure 5. The ratio of maximum (row 10) to minimum flux (row 4) is not constant and depends on the size of the crater: the ratio is lowest at 50 microns crater diameter thus indicating a similar spatial density for meteoroids and orbital debris; for small craters the ratio is increasing and implies that the contribution of orbital debris is dominant for particles in the micron-size range.

Marginal Perforation and Cratering Processes

The impact survey yields a crater-size distribution which should be converted to a particle mass distribution by using the relevant relationship between crater sizes and particle mass and velocity. The final results are based upon processes involved during the crater formation. A variety of experimental and theoretical approaches are used and an important goal of the Meteoroid and Debris Special Investigation Group is to provide a common ground for the conversion of penetration and impact features into particle size. However, on experiments such as those flown on LDEF, several assumptions must be made on the nature of the particles and on their impact velocity in order to derive their mass from the size of the craters formed on the exposed targets. As shown by current models for the velocity distribution in the vicinity of the Earth of meteoroids and orbital debris, average impact velocity is different on the various sides of LDEF (consequently a

crater of a given size has been formed by a larger particle on the trailing side than on the leading side).

The characteristic ratio for impacts on thin targets, at marginal perforation, crater diameter/target thickness, (D/f), was measured for aluminium samples exposed on MIR (foil thickness 0.8, 2 and 5 microns) and on LDEF (5 and 25 microns and 1 mm foils). The D/f ratio appears to be sensibly constant at approximately 1.4 (or $f/D = 0.71$) for the 36 marginal perforation features observed. The impact velocity is unknown, but as shown earlier it should be higher than 10 km/s. Similar results have been obtained by McDonnell /14/ and Hörz /15/ from laboratory experiments (impact velocity: 6 km/s, aluminium target and silica projectile). Under such conditions the value of the foil thickness to particle diameter ratio (f/d) is close to 3.5 and the crater diameter ratio to projectile diameter ratio (D/d) is close to 5.

Chemical Analysis of Particle Remants

A critical problem is the determination of the chemical composition of the impacting particles. In general they are physically destroyed and mixed with target material in the process of crater formation and identification of impactor, even qualitatively, is difficult. The first EDX analysis of 45 small craters has shown the occurrence of elements such as Ca, Na, K, Si, Ti, Fe and S.

Table 2 summarizes our results for the craters investigated so far: light elements C and O are present, with a ratio C/O varying from 0.1 to 3. Significant variations appear inside the distribution of individual craters. The other main elements identified in the various craters are usually referred to as "chondritic" elements, as they exist in various proportions and are signatures of extraterrestrial particles: Na, Mg, Si, S, Ca and Fe (samples 8 and 11). For these elements also, important variations are found from point to point inside the crater reinforcing the idea that the particles are truly aggregates bursting apart during the impact. The systematic presence of C and O components in the various residues analyzed is an important result: the occurrence of CHON particles detected in P-Halley nucleus would not be a particularity of this comet but could be a constant for extraterrestrial particles of cometary origin, as seems to be the case for such particles /5,16/.

Evidence of elements characteristic of orbital debris (Ti, Zn) has been found only inside two craters. Thus we are highly confident that the majority (95 %) of the craters analysed are of extraterrestrial origin, as expected due to the fixed orientation of LDEF during its flight and to the exposition side of the FRECOPA payload on board LDEF. However, there is still a possibility to record impacts from orbital debris in highly eccentric orbits /13/. Sample 9 (Table 2) located on the leading edge shows conversely the occurrence of a large number of craters caused by orbital debris.

Of peculiar interest was the study of impact features on the thin-foil detectors. One of the 5 microns thick aluminium foil (sample AD11) from the AO138-2 detector shows a perforation measuring 55 by 40 microns (oblique impact or elongated projectile). It is a typical "supramarginal perforation" with a crater diameter to foil thickness ratio of $D/f=10$, diameter of the particle is estimated to be 40 microns. The bottom plate beneath the perforation shows a star-shaped distribution of small secondary craters (sample AD12). The top foil acted as a shield, fragmenting the projectile and spreading the fragments over the surface of the thick plate. The craters range in size from 0.6 to 15 microns and are mostly distributed along two perpendicular axes. An angular particle, 18 mm by 15 microns is visible at the intersection of the axes. EDX analysis has provided evidence of impactor fragments. The elements identified in the central part of impact feature (Si, Fe, Na, Mg) are characteristic of interplanetary dust particles from the mafic silicate family, probably olivine. The variation in chemical composition between and within craters confirms the idea of an aggregate particle which burst apart on impact. None of the above elements was found in the craters far from the center of the impact feature which implies that these were caused by the aluminium fragments from the top foil. Detectors consisting of a thin shield and thick bottom plate appear to offer a

significantly higher return of information concerning chemical analysis of impactor residues than do single plate detectors.

CONCLUSION

LDEF gives us a unique opportunity for the study of the many processes involved in high-velocity impact phenomena and for the comprehensive description of the LEO microparticle population. Crater size distribution has already given us a good description of the actual in situ particulate hazard for spacecrafts. There are still some uncertainties on the mass distribution of the particles mainly due to the different hypervelocity impacts equations; however, comparison with current models shows no large discrepancies. A difficult task remains: the assessment of the contribution of the two populations (natural and man-made particles) through chemical identification of impact residues.

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Table 1: Comparison impacts parameters for LDEF and for the Model

Crater size, μm		Mass, gm		Diameter, μm		Impact velocity, km/s		D_c / d_p	
row 3	row 9	row 3	row 9	row 3	row 9	row 3	row 9	row 3	row 9
400	400	1.2×10^{-6}	4.5×10^{-7}	133	95	15	25	3	4.2
50	50	3.2×10^{-9}	1.3×10^{-9}	18	13	15	25	2.7	3.7
5	5	2.8×10^{-12}	1.1×10^{-12}	1.4	1	15	25	3.7	5

Table 2: CHEMICAL ANALYSIS ON LDEF SAMPLES

SAMPLE	MATERIAL	THICKNESS (μm)	CRATER SIZE (μm)	ELEMENTS FOUND ON MATRIX	ELEMENTS FOUND ON CRATER
1. B26	Al	2000	325	Al, Cu, (Mg, Mn)	Cu, Fe, Mg, Mn, C
2. B25	Al	2000	338	Al, Cu, Mg, (Mn, Si)	Fe, Cu, Mn, C, Mg
3. VC-D3-V	glass	1000	940x700 spall	Si, O, Au (coating), Ni	2 part.: Zn, O, Si, C 1 part. : Au
4. B16	glass	1000	180x130 spall	Si, O	Si, O..
5. A2-5	Al	250	190 12.5 (low vel.) 6.5x5 (low vel.)	Al, O, Fe " "	nothing Al, Si, Fe, Ca, C Al, O
6. A2-6	Al	250	4.8	Al, O, (Fe)	nothing
7. A2-1	Al	250	57	n.a.	
8. A2-2	Al	250	14 120 15	Al, O, Fe, Ni " "	Fe, Ca, Cl, K, Si, Na, Mg, O nothing
9. e7tb (MAP)	Al	25	12 craters < 5 μm 3 craters > 5 μm	Al, Fe, Cu, Zn	Si on crater lip, Mg (Fe, Ca, Zn, Mg, C)
10. AD11 (AO138-2)	Al	5 + 150	40 μm perf + ejecta		O, Mg, Si, Al
11. A54-2,4	Al	250	15 craters 1.5>Dc>15 μm		C, O, Na, Mg, Si, S, Ca, Fe
12. A54-3	Al	250			
13. E13 (AO138-2)	Au	150	3 craters < 4 μm		

Figure 1: Crater distribution on LDEF
Comparison of data from FRECOPA and MAP.

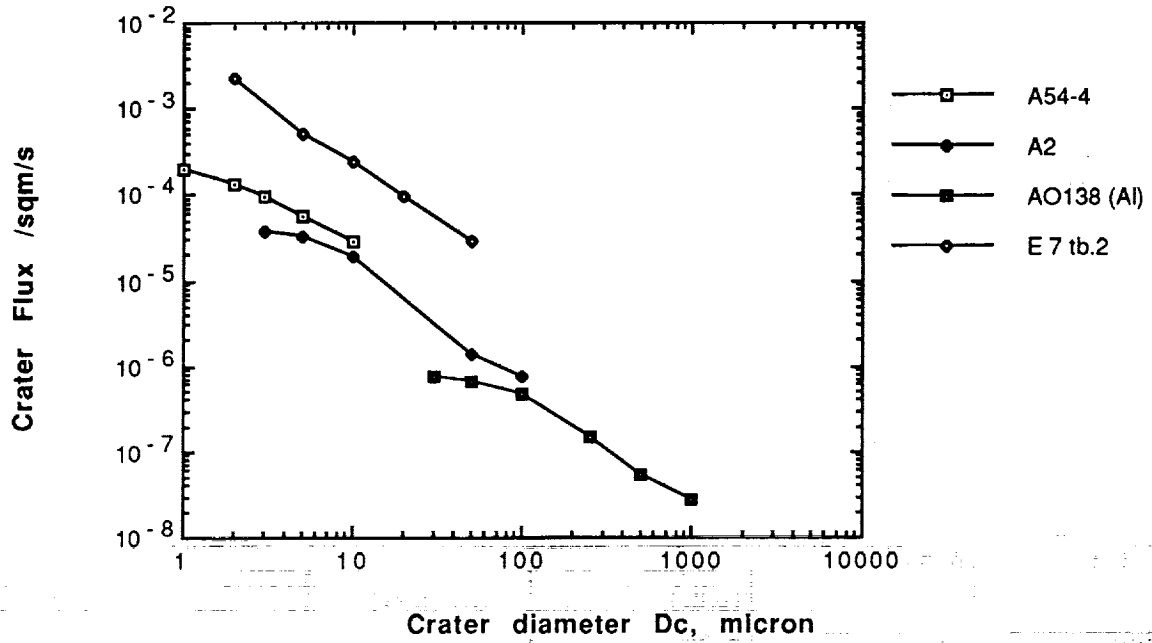


Figure 2: Comparison of crater flux on LDEF
(leading edge) and on MIR.

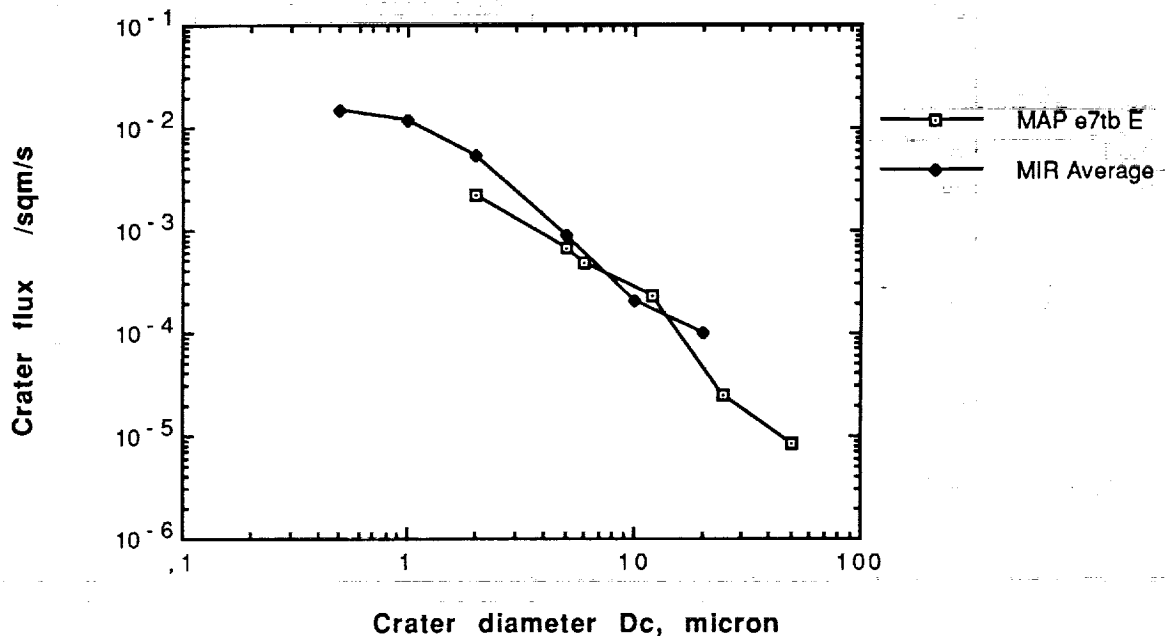


Figure 3: Impact velocity on different faces of LDEF.

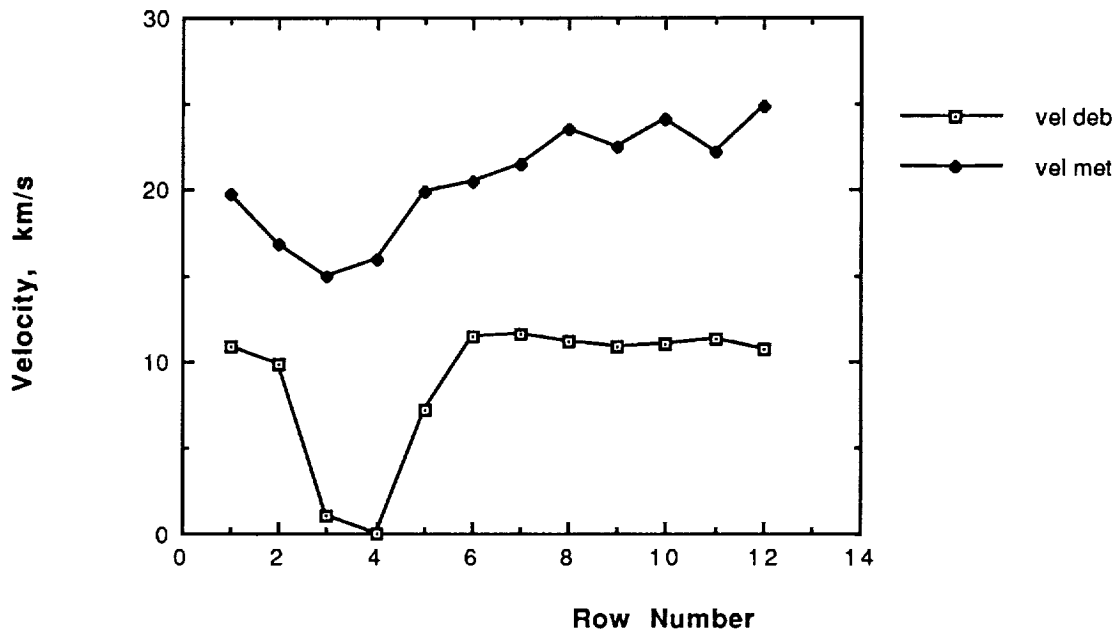


Figure 4: Comparison of crater flux on LDEF with model (Esabase) (crater diameter 5, 50, 500 microns).

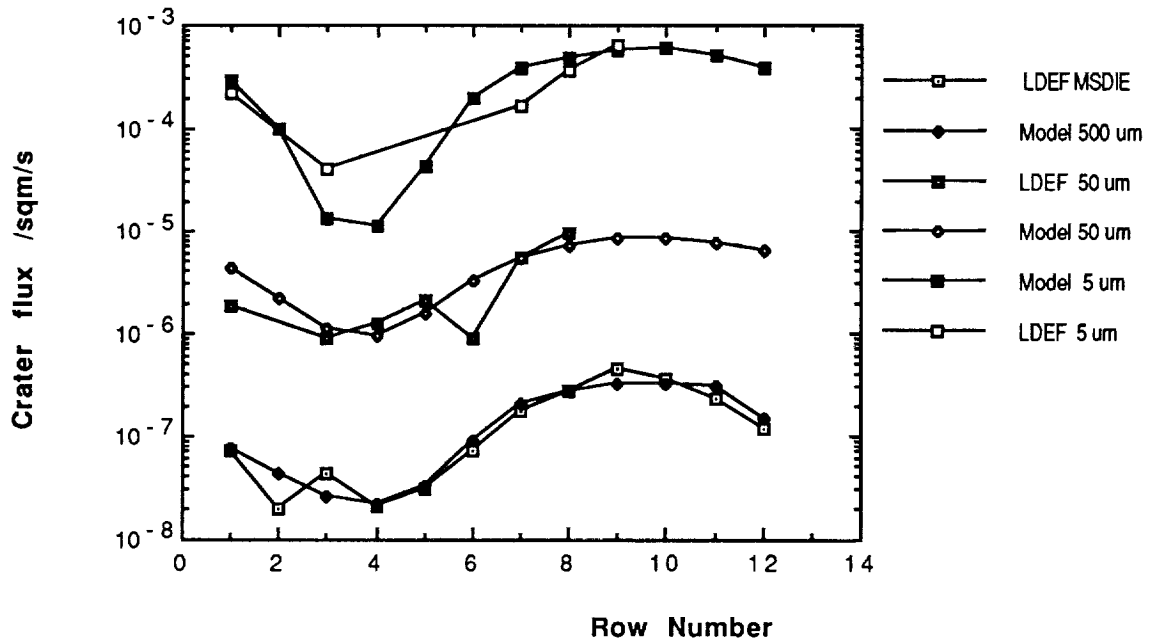


Figure 5: Comparison of flux on leading edge and on trailing edge of LDEF.

