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INTERPLANETARY DUST :
SPACE AND EARTH ENVIRONMENT STUDIES

PARTICULATE DETECTION IN THE NEAR EARTH SPACE ENVIRONMENT ABOARD THE LONG DURATION EXPOSURE FACILITY LDEF: COSMIC OR TERRESTRIAL?

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ABSTRACT. Examination of surfaces exposed for more than five and a half years, from detectors with unique attitude stabilisation relative to the orbital velocity vector, offers scope for examining definitively the sources of hypervelocity space particulates. Surfaces reveal discrete crater morphologies, crater size distributions and incident flux distributions. Discrete crater studies will later also reveal the chemistry of residues which can, especially via the capture cell principle, lead to elemental analysis of micron dimensioned particles.

First analyses of the flux data from the thin foil perforation experiments (MAP) involve a study of the statistics of the forward (ram) direction, the rear (trailing) direction and the space pointing direction. Modelling of the dynamics of geocentrically bound and unbound orbits yields evidence that the characteristics of the particles, and hence probably their source, change over the particle size range measured by the experiment. Smaller particles (< 1 μm diameter) have lower velocities which could include geocentrically bound particulates, whereas the larger particles (5-10 μm diameter) can be identified with "cosmic" particles of interplanetary or interstellar origin.

1. The LDEF Opportunity

LDEF's launch delay and its subsequent perilous approach towards uncontrolled re-entry and total loss in January 1990 can now be seen to have provided a highly significant exposure record and at a unique epoch for current space developments.

The exposure of 5.778 years (from launch on 7th April 1984 to recovery on 12th January 1990) at a 28.5° inclination offers excellent application to LEO satellites and to Space Station Freedom designs, and at a period when the presence of space debris has caused a high level of interest and, indeed, concern. The attitude stabilisation provides very adequate compensation for what could otherwise be a convoluted and confused record of differing exposure geometries (Figure 1). In section 3 we will see also that three faces on LDEF also promise to offer almost exclusive exposure to extraterrestrial particles whereas other surfaces will show high efficiency for the collection of orbital particulates. They may, or may not, prove to be orbital debris.

1.1 ORBITAL PARAMETERS

The temporal mean altitude (H) of LDEF (Figure 1) over its entire exposure duration was 458km and the total exposure time was 5.778 years (1.822×10^8 seconds). The orbital velocity at this altitude, assuming a circular orbit (LDEF's initial eccentricity was approximately 0.00015), is 7.64 km s^{-1} using 6371km for the mean radius of the Earth

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(R_E); the escape velocity at this mean altitude is 10.81 km s^{-1}. A value of 185km for the effective atmospheric height (h_a) is used, based on atmospheric drag calculations on a particle of 10^{-11}g, corresponding to the capture of a typical interplanetary particle within one Earth revolution.

1.2 EXPOSURE FACTORS

TABLE 1. LDEF altitude and Earth obscuration angle history .

Year	Altitude H [km]	$H+R_E$ [km]	Fraction of year	Horizon angle [deg]	Effective flat plate solid angle [ster]
1984	478	6849	0.745	106.82	2.141
1985	473	6844	1.000	106.68	2.137
1986	470	6841	1.000	106.60	2.136
1987	468	6839	1.000	106.54	2.134
1988	459	6830	1.000	106.28	2.124
1989	410	6781	1.000	104.80	2.077
1990	340	6711	0.033	102.34	1.995

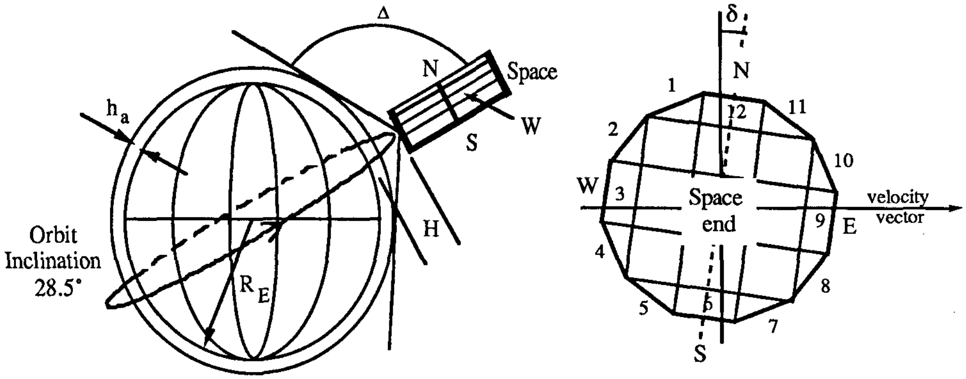

Figure 1. The orbit and the relationship of the actual attitude of LDEF to nominal.The actual attitude departed from the nominal by an angle δ ≈ 8°.

1.3 SOLID ANGLES

The effective solid angle of a flat plate parallel to the Earth's radius vector is given by [$\Delta-0.5\sin(2\Delta)$] steradians, where Δ (radians) is the angle from the horizon to the zenith (Figure 1). This corresponds to $\pi/2$ steradians effective solid angle for $\Delta=\pi/2$ radians, namely a very low orbit, and π steradians for a space facing plate. The effective solid angle for a cone of θ radians half angle from the normal to the surface is $\pi(1-\cos^2\theta)$ steradians. Δ is given by $\sin^{-1}(A/R)$, where $A=R_E+h_a$ and $R=R_E+H$ (Figure 1). The mean LDEF effective peripheral tray exposure solid angle is 2.125 steradians.

1.4 PENETRATION RELATIONSHIPS

The crater depth to crater diameter ratio (d_c/D_c) for a semi-infinite aluminium target was established for the Solar Maximum craters in aluminium as 0.62 (Laurance and Brownlee 1986). The ratio of marginal thin foil perforation thickness to the crater depth of a semi-infinite target (f/d_c) was given as 1.15 (McDonnell 1970). Therefore, for marginal perforation, the ratio of the foil thickness limit to the semi-infinite crater diameter is given as $f=0.71D_c$. Relevant penetration relationships are published in McDonnell et al (1990). We use these relationships currently to compare thick target data and thin foil perforation data for the same type of material (aluminium). More detailed comparisons will at a later stage be established from the actual data. Such detailed comparisons will also incorporate specific material properties but currently these differences should not preclude general conclusions from data which cover a very wide range of magnitudes.

2. Data Available from LDEF's Exposure

Data on LDEF's impact environment are available from spacecraft recovery and de-integration procedures and also from Principal Investigator experiments.

Principal Investigator impact data exist in published form from the A0023 MicroAbrasion Package (MAP) experiment (McDonnell et al, 1990) and from the A0201 Interplanetary Dust Experiment (IDE) (Singer et al, 1990). The plots shown in Figure 2 for the MAP experiment result from a large number of independent measurements on aluminium surfaces of different thicknesses. This is to be contrasted with the cumulative distribution from *one* surface where the flux at one thickness is partially correlated with an adjacent flux measurement and a negative cumulative slope is excluded. It is to be noted that the Space end face has currently only one data point referring to one foil thickness. The form of the marginal penetration distribution on this most valuable pointing direction is not all lost, however, because 5 micron thick brass foil was also flown on this face. Once a calibration of the brass foil has been undertaken from laboratory hypervelocity impact simulations, the Space face will then have two marginal data points, thus yielding valuable information on the interplanetary flux; in the future, supra-marginal data will also be offered.

A co-ordinated and comprehensive approach to the spacecraft operations and de-integration was made by the formation of the Special Investigator Groups (SIGs). The Meteoroid and Debris SIG operations documented impact sites above a diameter of some 300 μm on most surfaces of the entire spacecraft. Although the publication of impact data from dedicated impact experiments remains the prerogative of the Principal Investigator, summary M-D SIG data which incorporate some of these data from the initial operations are now published (See et al, 1990); some of these are included (courtesy of the Principal Investigators) in Figure 2. For example, the first results from the larger craters on the S0001 Space Debris Impact Experiment (SDIE) (Humes, 1984) scanned by the M-D SIG team at Kennedy Space Center are shown by courtesy of D. Humes, but do not represent his analysis of the experiment, which must await his more comprehensive analysis programme. A major potential source of impact data (some 18 square metres) is also offered by the covers of the A0178 Ultra-heavy Cosmic-Ray Experiment (UHCRE) (O'Sullivan, 1984), comprising silvered Teflon sheet 120 μm thick backed by some 80 μm of paint; these showed the first spectacular evidence of sustained impact erosion damage in space, clearly visible to the STS 43 astronauts. Preliminary data relating to the marginal perforation of these covers are included in Figure 2 (courtesy F. Levadou). Figure 2 also includes data from the A0138 Frecopa experiment (Mandeville, 1984).

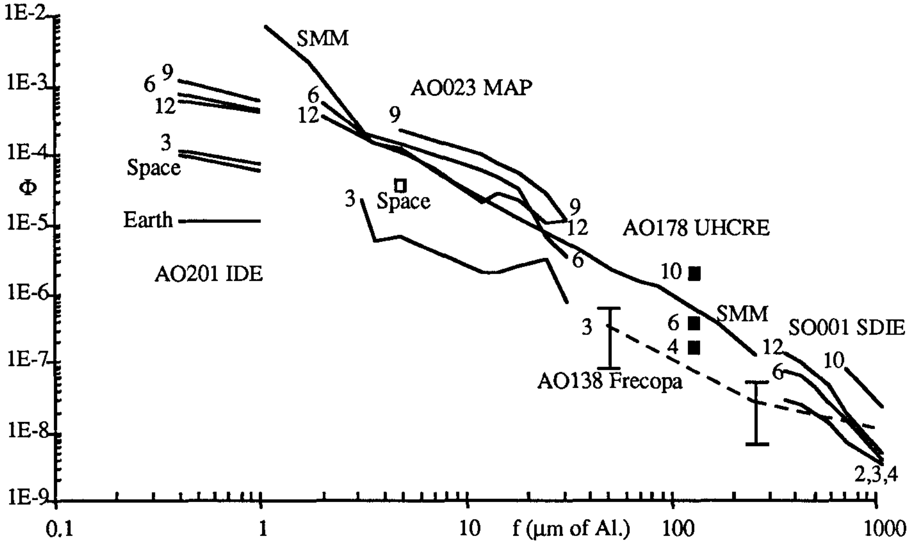

Figure 2. Flux Φ (in $m^{-2}s^{-1}$) versus aluminium foil penetration thickness from the Interplanetary Dust Experiment (IDE), the Micro-Abrasion Package (MAP), the Ultra-Heavy Cosmic Ray Experiment (UHCRE), the Space Debris Impact Experiment (SDIE) and the FRECOPA experiment, compared to the Laurance and Brownlee data from the Solar Maximum Mission (SMM). Numbers represent the nominal LDEF bay angle for each detector.

3. Features of the LDEF Impact Data

Differences between the North and South MAP detectors (Figure 2), representing directions approximately at right angles to LDEF's trajectory, can be examined very closely in the context of the absence of experimental bias, namely in view of the accurately known exposure areas and geometry and calibrated foil thicknesses. Clearly seen is that the South flux exceeds the North flux for small particulates but that the trend reverses for the thicker foils. We must also take note of the *actual* pointing direction of LDEF which does not correspond to the nominal (Figure 1). All LDEF impact experiment data shows a high East flux corresponding to the RAM direction, and a decrease towards the West. We might perhaps expect the North and South fluxes to be somewhat "equal" in LDEF's swathe through various uncorrelated orbits; in this situation the effect of this spacecraft pointing offset would be an increase in the *North* flux relative to the South. This is seen to be true only for larger foil thicknesses, but clearly this trend reverses for smaller particulates. The true bias to the South for small particulates is considerably greater therefore, because of the offset, than that shown in Figure 2 and is clearly of great significance; as yet the cause of this is undetermined!

What should we expect regarding the question of isotropy from existing knowledge of either orbital or hyperbolic (interplanetary) particles? Concerning *orbital particulates,* recent papers by Olsson-Steel and McDonnell (1990), Kessler (1990) and Zook (1990) and supported by simple, but firm, concepts show that intercepting of any two bound circular orbits lead to an exact equality on the (true) North and South faces for any inclination of the two orbits. It extends also to eccentric orbits if the arguments of perigee of the particles are randomly distributed. If the orbital inclination is equal to 63.4° there is no advance of the line of apsides for an elliptical orbit as is the case for the significant number of Molniya-type spacecraft which utilise this property to remain above the horizon of the Soviet Union for as long as possible. If this type of spacecraft produced a debris cloud it could in turn produce a North-South anisotropy in LDEF impact rates. Thus, North-South asymmetry is not explained by inclination distributions unless firstly, orbital eccentricities are significant and, secondly, some quite special non-randomised orbital parameters pertain to the overall distribution.

Concerning *unbound (hyperbolic)* particulates, the distribution of impact rates also reflects the initial (heliocentric) orbital parameters. Although the distribution of larger particles is highly non-isotropic (meteor streams) due to their source in comets, smaller interplanetary grains of the type detected by MAP are unlikely to have retained all the information of their parent bodies' orbits due to non-gravitational forces such as Poynting-Robertson and radiation pressure. Anisotropy for large grains could result from the non-random interception of meteor streams by the Earth; this is less likely for the smaller grains whose orbits are likely to be more evenly distributed in the ecliptic. Arguments on the dynamics of unbound particulates and interception with LDEF (Olsson-Steel, 1990, Zook 1990) show two features of relevance. The first point is that the radius vector of LDEF's 28.5° geocentrically inclined orbit is swept through a wide range of ecliptic latitudes, and can perhaps in the first instance be considered "random". LDEF's orbital plane will have an average ecliptic referenced inclination of +23.5° with a swing of ± 28.5°. The Space end will then point to ecliptic particulates over a very wide range of ecliptic latitudes throughout its orbit, namely over ± 52° which is further convolved with the acceptance angle of a flat plate detector. We should view therefore the extraterrestrial flux on the Space end as an "average" of all ecliptic latitudes and longitudes. The second point is that the Space and West faces have a very low probability of interception with Earth-orbital particulates. Despite LDEF's directional excursions relative to the ecliptic reference plane, the North and South faces *do* have a bias towards ecliptic North and South; always pointing to within 52° of their respective poles. Only if the number of interplanetary particulates in interplanetary space at 1 A.U. is symmetrical with regard to ascending and descending node would there be symmetry (Olsson-Steel, personal communication). The LDEF MAP data would suggest there are more particulates in the ascending node for small masses *if* these North and South fluxes on LDEF were interplanetary in origin. The question of resolving North South (and East) fluxes into a two component model (interplanetary and terrestrial) has not yet been resolved on LDEF, however, and must await the inputs from chemical microanalysis of the residues, in addition to the dynamical arguments presented here.

4. Application of Dynamical Modelling Techniques to Data Interpretation

In all modelling, examination and interpretation of impact/flux data from differing spacecraft attitudes or pointing directions, care must be exercised in distinguishing between flux variations either at *constant mass* or alternatively at *constant crater size*. Crater size is, of course, directly related to the marginal perforation foil thickness (Section 1.4).

Flux enhancement at constant mass is the "sweeping-up" effect of the satellite into the particulate cloud and leads to an enhancement of numbers intercepted compared to the trailing face. A consequential effect of this, but quite separate physically, is that those particles will also have a different relative velocity for the two faces, and hence, will upon impact lead to different crater dimensions; because most impact observations (and observed crater flux distributions) refer to a particular crater dimension, the experiment detector surfaces receiving greater numbers of particles will yield a flux value which is relevant to smaller and invariably more numerous particles. The latter sensitivity enhancement depends on the size distribution of particulates which, fortunately, can be deduced from the data.

Relationships in this sensitivity enhancement have been established (McDonnell et al, 1991). Since the West face flux distribution can be assumed to be the result of non-Earth bound particles, a prediction of the interplanetary flux as encountered by any other LDEF face can be achieved by dynamical modelling. Two transformations must be carried out: one to account for the effective equivalent foil thickness because of the differing relative impact velocities and another to account for both the exposure geometry and also the sweeping effect due to the spacecraft velocity vector.

The West and Space face flux plots can be compared and also can be transposed to give an expected value for any other LDEF face, because of the implicit assumption that these fluxes are due to interplanetary particulates only. By varying the geocentric particle velocity (V_{PE}) in the model input, the West and Space face distributions can be transposed to coincide: this yields a value of $V_{PE} = 16 \pm 2$ km s^{-1}. Incorporating the gravitational attraction, we can then derive a value for the interplanetary approach velocity to the Earth (V_∞) to be $V_\infty = (V_{PE}{}^2 - 10.81^2)^{1/2} = 12 \pm 3$ km s^{-1}. If then the interplanetary flux derived from the West and Space faces is transformed to calculate the expected East interplanetary component, a measure of the excess East flux due to orbital particulates can be derived. Such an excess is found for the smaller masses only. If the transformation is performed for the thicker foils, the predicted interplanetary flux appears to *exceed* the observed East flux. This argues against orbital particulates in this range ($\approx 10^{-9}$g) and indeed at higher masses. It could call for higher particle velocities at these masses, which would be closer to interplanetary approach velocities deduced from meteor studies. Further aspects are developed in an accompanying paper (McDonnell et al, 1991).

5. Conclusions

Impact and penetration data from the LDEF spacecraft shows already the high value of the concept of the return to Earth of the largest area-time product of space age detector. Even the preliminary data shows a high level of definition regarding the size distribution and anisotropy of the flux. The completion of this morphological analysis and its extension into the dimension of particulate chemistry and isotopic abundances will lead to a "gold standard" in the definition of the near Earth space particulate environment.

At this stage we are able to see that data from several key experiments, and from the spacecraft as a whole, is leading to a coherent size distribution for craters ranging from sub-micron to millimetre dimensions. Detectors on the East (ram) face universally demonstrate "high" fluxes, but the maximum appears shifted towards the South for small particulates, indicating a departure from the North-South symmetry which would be expected *a priori* . Surprisingly, the asymmetry is reversed for particles capable of penetrating some 20 to 30 μm of aluminium or greater, which show an excess on the North, and this feature is shared by the penetration of the UHCRE cover and craters observed from the M-D SIG data from the spacecraft.

It can be shown that the Space and West faces are accessible to extraterrestrial particles rather than to orbital particles and, by invoking modelling, a geocentric velocity can be deduced for this extraterrestrial component of about 16 km s^{-1} corresponding to an approach velocity of 12 km s^{-1} to the Earth for particulates of mass 10^{-10}g. This velocity is slightly lower than that anticipated from extrapolations based on data from the interplanetary meteoroid flux; the small difference could, however, be very significant and point to lower eccentricities and inclinations of the orbits of these smaller particles.

Within the measurement range of LDEF, therefore, dynamical modelling applied to the data shows that Earth orbital particulates are significant only at the small (sub-micron) dimensions and that these are detected dominantly on forward faces. At larger dimensions than the 50 micron range, interplanetary extraterrestrial particulates are found to dominate the impact scenario on all LDEF's surfaces, and are hence the major penetration and erosion risk for millimetre dimension spacecraft surfaces. The space pointing, trailing and very probably the Earth facing directions appear to be accessible only to these extraterrestrial components at all dimensions.

The identification of an Earth orbital component with space debris can thus be demonstrated as a possible hypothesis only at small dimensions (sub-micron). This hypothesis has been strongly indicated by crater residues on the Solar Max mission by Laurance and Brownlee (1986). However, it is shown that the choice of penetration formula referring those data to particulate mass (Pailer and Grün 1980) is at variance with other calibration data. The raw data of Laurance and Brownlee compare excellently with LDEF data; it is argued therefore that their data do not indicate a dominance of space debris below 10^{-9} g. It *could yet* be found to be significant, and correspond to the excess flux seen on the East penetrations below approximately 25 μm.

Arguing against this source being space debris, the temporal behaviour of the near Earth satellite flux is seen to be remarkably stable over the development of a growing space population (McDonnell et al, 1991). If this micron dimensioned particulate flux is supposed to be debris related, as concluded by Laurance and Brownlee's association of residual elemental comparisons with typical spacecraft material, then we could be forced to conclude that there was as much space debris in the early 1960s as in 1984, despite the linear growth of space launches and the orbital satellite population.

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