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THE LEO MICROPARTICULATE ENVIRONMENT: LDEF's 5.75 YEAR PERSPECTIVE ON ORBITAL SPACE DEBRIS AND METEOROIDS

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ABSTRACT

The Long Duration Exposure Facility (LDEF) provides, by virtue of an unprecedented area-time product and gravity gradient stabilisation, a study base particularly well oriented towards identifying orbital flux components. The anisotropy of flux rates for hypervelocity impact perforations and craters demonstrates that meteoroids are dominant for some 5 microns and greater in dimension, but at smaller dimensions a dominantly *orbital* flux is evidenced. A clear link between the microparticle and the Molniya population (with perigees in the southern hemiphere) is indicated. This manifests itself in an impact crater morphology signature, originating from trajectories from the East-South-Earth quadrant relative to LDEF's reference frame.

1. OVERVIEW OF LDEF RESULTS.

For meteoroids of interplanetary origin, exposure on the different faces is largely randomised, although a differential impact velocity on the faces *is* still retained; indeed, this leads to a ready derivation of both the flux and velocity of the meteoroid component. By reason of the difficult access by circular orbits to LDEF's "end" and trailing faces, and by the reduced impact effects of (even highly eccentric) orbital debris there, we look first to the West and Space faces for identification of the meteoroid component. A mean velocity varying from 17km/s to 22km/s has been reported (Ref. 1) compatible with the interplanetary meteoroid population. Furthermore, comparison of the penetration record of thin films with the (thick) cratering record on the LDEF structure for the flux incident on the space pointing face permits us to infer the meteoroid *density*; a value varying from between 0.5 g/cc and 1.5 g/cc is deduced for particulate dimensions in the range 5 microns to 100 microns. Little significance is attached to the *exact* value deduced from the intercepts; very low densities are certainly needed though. The meteoroid flux for larger particles shows a bias towards ecliptic North compared to the South by a factor of 1.7, which may indicate the dominance of a small number of cometary or meteoroid sources. For orbital space debris, interaction with LDEF's orbit provides a significant challenge for orbital dynamics and modelling. Although the intersection of an arbitrary pair of orbits may be readily solved, the *total* orbital population demands not only a wide distribution of orbital elements, but also a size distribution *and* aspects of temporal development. From other faces, such as the North, South and East, bound particulate orbits have greatly improved access. Flux distributions have been shown (Ref. 1) to demand an Earth-orbital origin, especially at smaller dimensions, though not all bound orbits are necessarily all space debris. The possibility of Earth capture and fragmentation of interplanetary particulates remains a possibility yet unquantified. The microparticulate orbital fluxes dominate the leading face of LDEF; at the very smallest dimensions detected (corresponding to diameters of 0.2 microns) impact fluxes are biased towards LDEF's South. New data, derived from the study of the ellipticity of craters (below) provides evidence on their incident direction and orbits. Whereas circular orbits would always intersect in the local horizontal plane of LDEF, observed impact directions show a wide departure of the elevation angle from this plane, and demand a high concentration of (probably yet unaccounted for) elliptic orbits. Interpretation of the source of this population as *debris* calls for a link with objects in such orbits. This bias towards South is then suggested to result from the origin of particulates in orbit which have a perigee in the Southern hemisphere - e.g. the Molniya orbits.

Further study of the sources of particulates in Earth orbit calls for several developments, especially time resolution and chemical studies. Currently however we present a basis for tests of flux modelling, namely a consistent flux distribution for crater dimensions on LDEF for aluminium from some 1μm to 1,000 μm. Such data, now available (Ref. 2) via the NASA Meteoroid and Space Debris group (M-D SIG) is provided in LDEF-reference coordinates and also corrected for

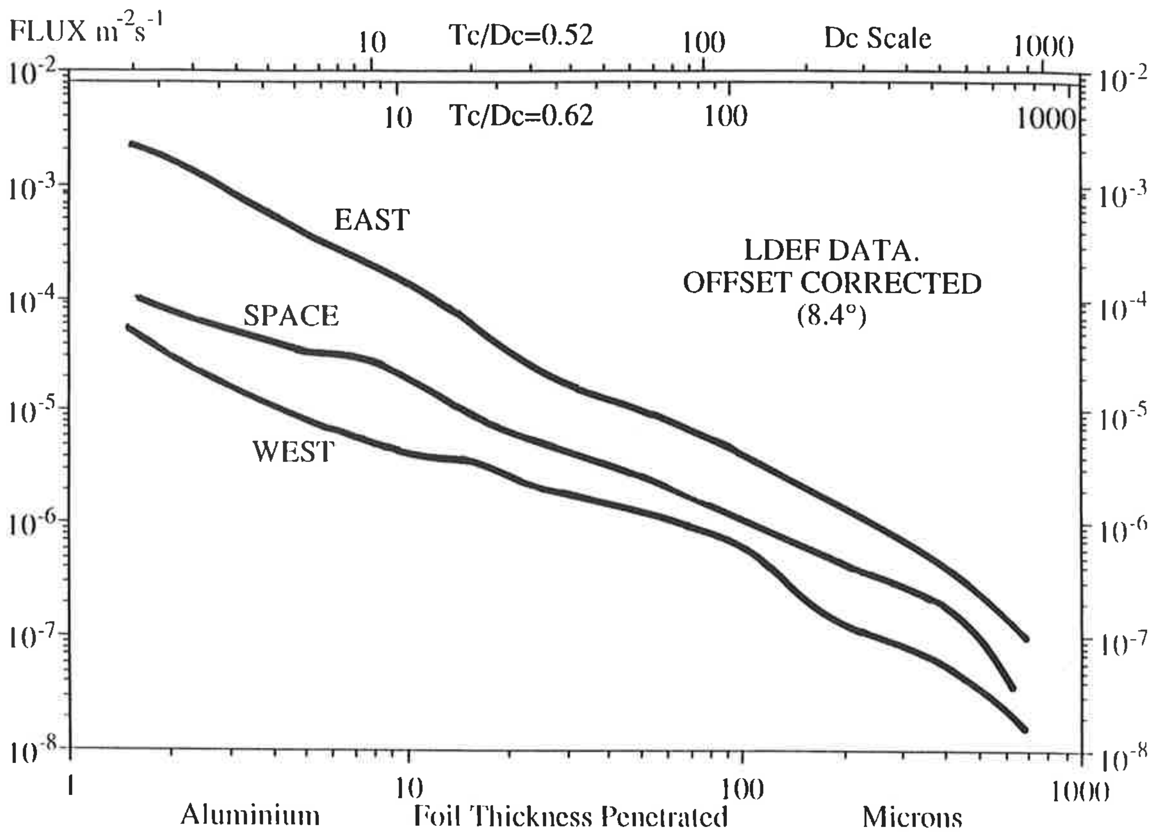
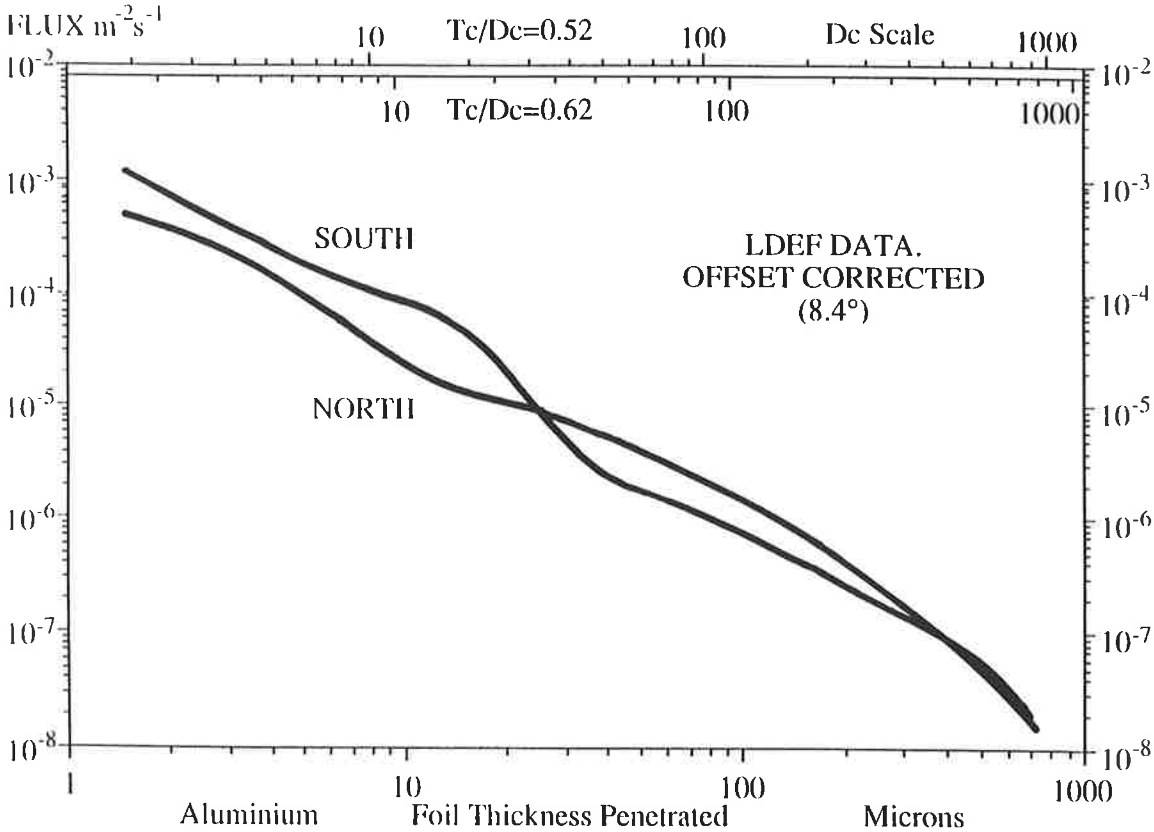


Figure 1. Flux distributions derived from the LDEF data set for aluminium shown for the East (ram) and West (wake) directions of orbital motion after correction for LDEF's offset. The space pointing flux is also shown.

Figure 2. Flux distributions for the North and South vector directions after correction for LDEF's offset. Asymmetries due to an imbalance of natural particulates relative to the ecliptic plane for $D_C > 30\mu m$ gives way to a bias towards South for the orbital component at small dimensions. This is also reflected in the increasing East to West ratio (Fig.1).



LDEF's (8.4 deg.) offset relative to the orbit vector.

2. EVIDENCE FROM FLUX RATES

2.1. Target material

The formulation of a coherent flux distribution curve for the pointing direction of a particular surface on LDEF generally requires a number of assumptions or intercalibration data on the behaviour of differing target materials. LDEF's variety of materials, and combination of thick and thin targets has lent itself to the assessment of a number of these parameters and, indeed, some parameters of the impactors. In the study to date on the collation of data on the flux distribution, we have chosen Aluminium as a target material since this covers the widest range of exposure to meteoroid and space debris projectiles. The ratio of crater depth (Tc) to crater diameter (Dc) is fixed, in this survey, to Tc/Dc = 0.62 for smaller particulates (Dc<30microns) and Tc/Dc=0.52 for larger particulates (Dc>30microns) for all faces. Similarly the ballistic limit of penetration (fmax) is fixed at fmax = 1.5.Tc.

2.2. Data sources

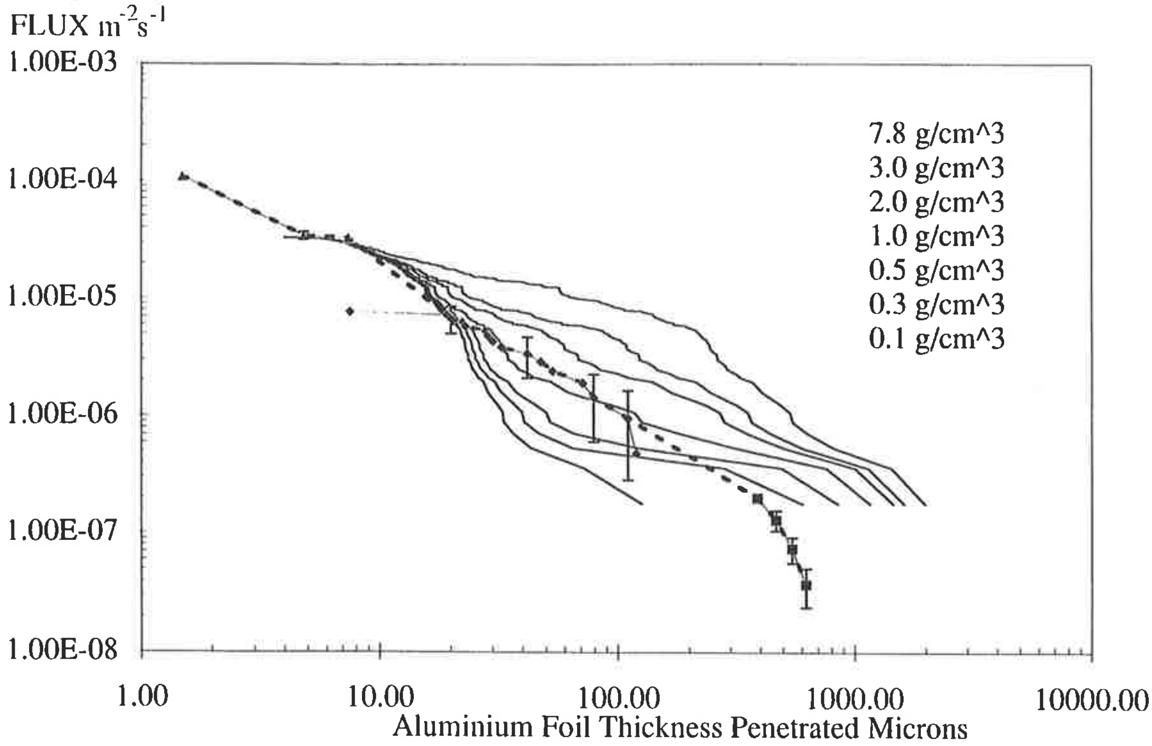
The penetration of thin foils, dominantly aluminium on the microabrasion experiment (MAP) provides the most abundant information on impact crater size distributions in the medium and small range for five of the cardinal directions of LDEF (N,S,E,W,Sp). These demonstrate (ref 1) the transition between natural unbound and Earth orbital particulates at some 30µm diameter (Figure 1). The "shoulder" on the East flux distribution where a sharp increase occurs in the small particle flux illustrates this point and is reflected by analysis of the East-West ratios. Extremely interesting temporal behaviour of the flux, especially in the rear and side directions is demonstrated in the IDE experiment corresponding to a sensitivity of fmax ~ 3µm in our data (Ref. 3,4). The flux is both periodic and episodic, indicating frequent orbit plane intersections.

At larger dimensions the thin foil MAP data are augmented by surface crater counts from NASA's M-D SIG database (Ref. 2) and from the SDIE experiment (Ref. 5). At dimensions smaller than perforation of the 5µm MAP foils, which represent the thinnest of defect foil surfaces, foil penetration data is also augmented by surface crater counts to Dc = 1µm. Such data are carefully selected to avoid the possibility of secondary cratering; such events are found to be surprisingly prolific at generating micron dimensioned craters despite the fairly "open" geometry of the detector surfaces on LDEF. See also Ref. 2.

2.3. Data Reduction

All available impact data on aluminium for the N,S,E,W and SPACE faces are selected and error limits considered; a consistent best fit through

Figures 3. For the very large particles penetrating the space foils, we calculate the ballistic limit perforation flux and compare to the thick target crater data on the same face. The comparison, sensitive to assumed particle density, leads to a *measure* of particle density for the larger natural particulates impacting the Space face.



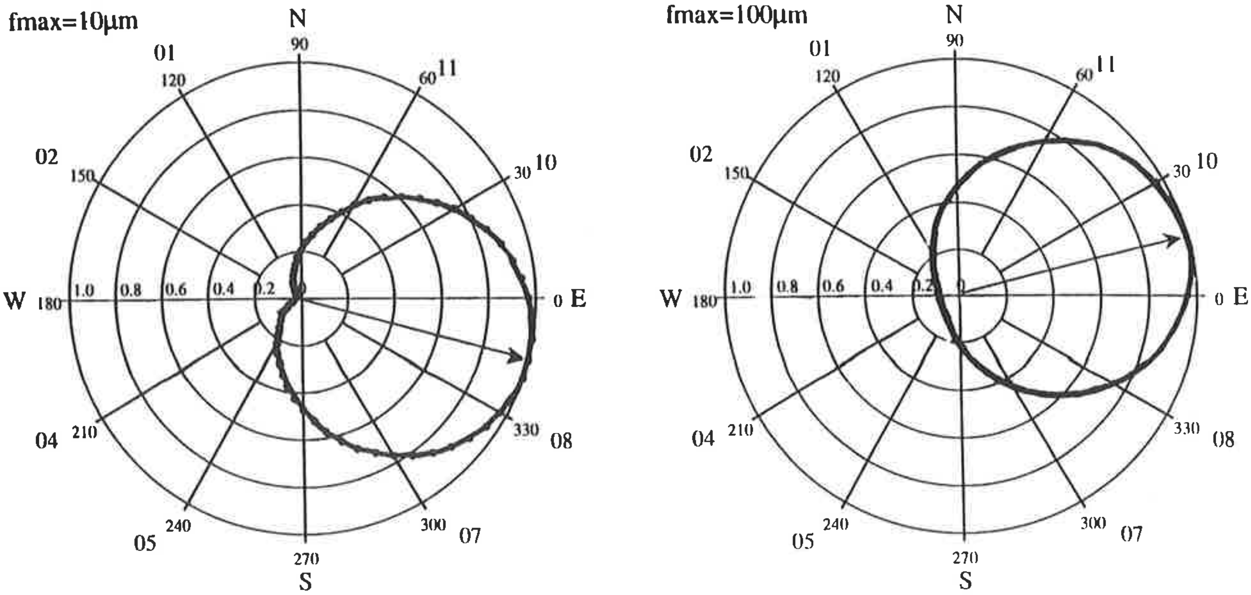


Figure 4 and 5. Angular distribution of the penetration flux for f_{max} = 10 microns (left) and f_{max} = 100 microns (right). The modest East to West ratio of the larger particles is seen, characteristic of a flux dominated by natural particulates, but in contrast to the space debris "signature" seen an the left at 10 microns.

the data is established bv 'consensus' of the Canterbury LDEF MAP team. "Rashes" of secondary craters, identified by either spatial anisotropy or a grouping of crater ellipticity are eliminated; such events are, of course, identified as of special interest for future studies. From this "eye fit" through the data, a computer smoothing routine is then effected, yielding a cumulative distribution which can be differentiated without discontinuities.

The LDEF source flux data thus smoothed are then sampled and tabulated at 30 logarithmic intervals per mass decade; this is then used to derive an angular flux distribution, fitted at each sample point. This takes the form $E = A \cos(\phi + \theta) + B \cos 2(\phi + \theta) + C$ where ϕ is the LDEF position angle and θ LDEF's offset (8.4 degrees). This then permits the derivation of offset - corrected fluxes for the N,S,E and W directions relative to LDEF's orbital vector (Ref.2). No corrections are made for the 1° tilt, which generally has a very minor effect. An exception to this generally would be e.g. the angular distribution of impacts on the space faces and Earth faces and, especially, their exposure to orbital debris.

3. SIGNIFICANCE OF FLUX RATIOS

The smoothed offset-corrected impact data provide opportunity for examination of a number of hypotheses in the separation into meteoroids and space debris sources Of special interest in the data are the following flux data ratios:

3.1. East to West

This provides a ready indicator of the geocentric velocity relative to LDEF's orbital motion of 7.6 kms^{-1}. Circular (bound) orbits have little or no impact effects on the West face; elliptical orbits can, however, gain access and (combined with the reduced impact effect from lower velocities of meteoroids on the West face) do appear to be significant at the level of ≅ 15 to 20% (Ref. 6). Figure 1 shows this varies very significantly over the size range and calls for very dfferent parameters of the particulates.

3.2. West to Space

With both faces dominated (though not exclusively) by unbound natural meteoroids these surfaces provide means for definition of the interplanetary population incident on the Earth and its velocity. From this delineation, after accounting for a small fraction of orbital debris from chemical evidence, we can readily predict the interplanetary component *on all other faces* ; the excess flux then observed on these faces is therefore *either* a limitation of the modelling *or* the orbital component!

3.3. North to South

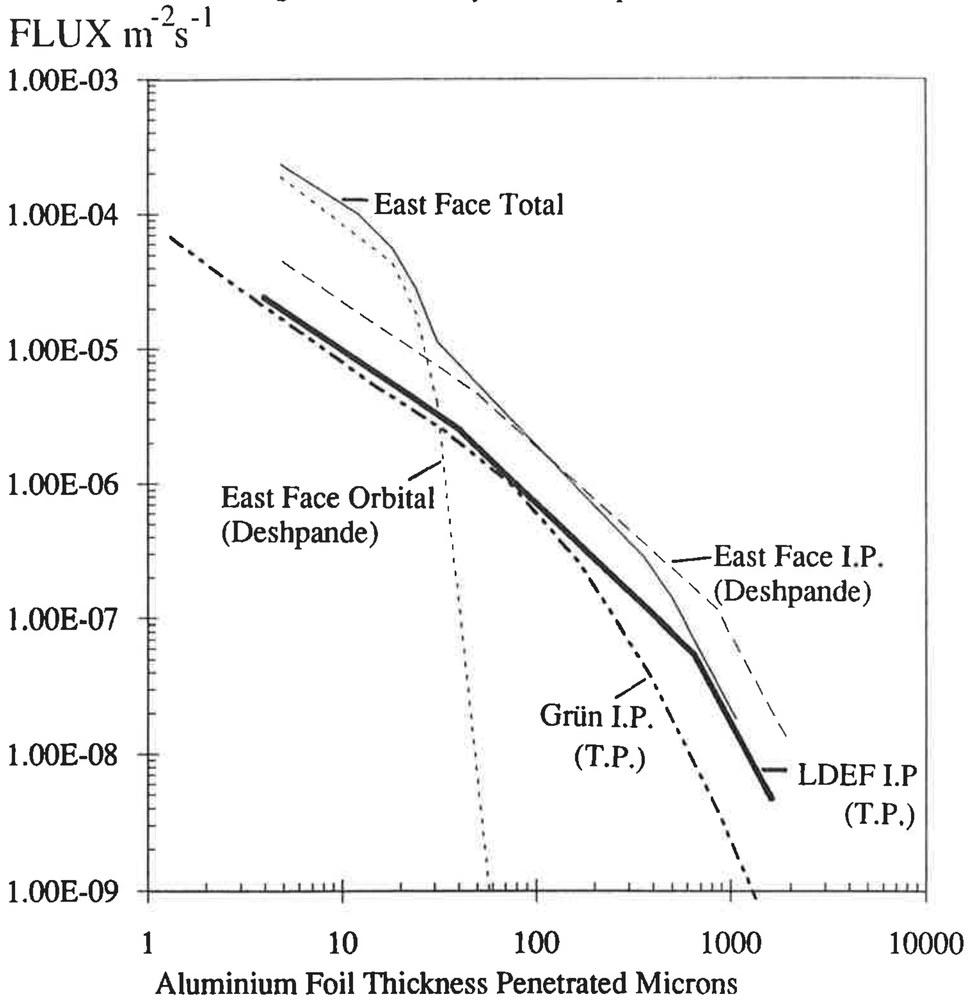
Dependent on the origin of the particulates - either unbound interplanetary meteoroids or bound orbit space debris - we may draw entirely different conclusions. If the source is interplanetary - and these are dominant for fmax between 30μm and 150 μm - then the offset-corrected North to South ratio of 1.7 derived from Figure 2 is interpreted as an interesting imbalance of interplanetary particulates relative to the ecliptic plane because LDEF's fast precession rate provides a balanced exposure of N and S relative to the ecliptic plane. The space face has a mean exposure centred on the ecliptic plane, also with precession but additionally a faster orbital modulation. The origin of this North-South imbalance in flux, given the ecliptic exposure condition, is inferred to lie in the limited number of sources of either comets or meteoroids which can access LDEF's N and S faces. This result may be acconted for by an excess of meteoroids in the descending nodes at 1AU. Calculations are being performed (Ref. 7) to quantify the relative access to known sources of comets and meteoroids to LDEF's surfaces.

If the source is, alternatively, orbital particulates - and further debris - then we look to known or presumed sources. The imbalance at small dimensions (fmax < 25μm) towards South, and especially where we know there is a dominance by orbital particulates, points to imbalances in the number of tracked objects. Calculations for a 500km circular orbit show a clear bias of tracked objects towards South exists (Ref. 8); this is attributed to the bias of perigees towards the southern hemisphere. In terms of a source of "dust", we might have to point to these objects or their launch operations. At the dimension of particle considered (diameter ~ 1μm) we would be recoding a population which decays very rapidly due to atmospheric drag; it would though retain the Southern hemisphere perigee bias until circularised close to entry but, significantly , *after* intercept with LDEF.

3.4. Space Perforations versus Impact Cratering

The distribution of *large* holes in the thin MAP foils (5μm) provides a measure of the size of particles'; the cross section of the perforation hole (D_H) approaches the particle size (Dp) at large dimensions i.e. $D_H \rightarrow D_p$ as $D_p \rightarrow \infty$. This region of perforation has been studied quantitatively (Ref. 9) and is incorporated in the CMD formula (Ref. 10). If we then calculate the crater which that particle would create if it were to have impacted in a thick target, we find that this is dependent on the particle *density* assumed.

Figure 6. Particulate Flux resolved into orbital and natural components for key directions. Also shown is the flux at LDEF derived from the Grün interplanetary flux survey (Ref. 21) using a ballistic penetration limits. The resolution of the interplanetary component, performed at fmax = 5μm target thickness yields a velocity of 22 kms/sec; for larger particles (f_{max} = 375 μ; D_c = 500 μm) a velocity of 17 km/sec is derived. The resolution of the flux shown here is from previous data on aluminium from LDEF, which was not as complete as that now available. Figures 1 & 2 analysis will be presented (Ref 22).



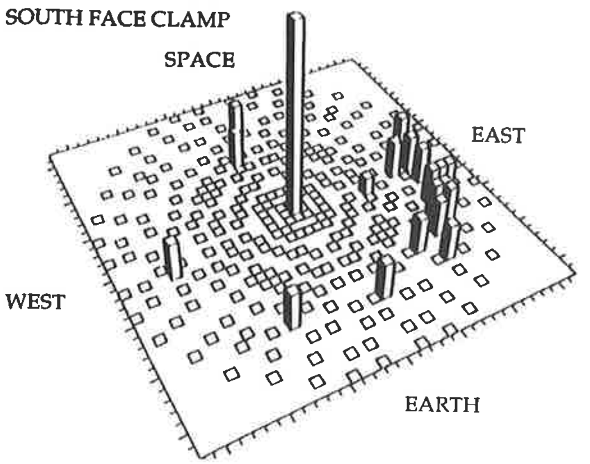


Figure 7. Plot of the elliptical craters on the South pointing clamp on LDEF. The "earth direction" impacts on the from particles in elliptical orbit with a southern perigee bias are seen. At the centre, the unresolved circular impacts are shown.

We already *know* the crater distribution on LDEF for thick targets from other data in the same pointing direction and hence by ensuring convergence of the fluxes the average particle density of the flux is derived. Figure 3 shows this procedure applied for particle density varying from 0.2 $g.cm^{-3}$ up to 8 $g.cm^{-3}$. The intercept of the crater distribution with one of the predictions yields an estimate of the average particle density. This is, perhaps the first direct measurement of particle density, supported by other work showing that at larger dimensions the craters are shallower (Ref 1,5).

At smaller dimensions of hole diameter the method is insensitive to assumed density, but examination of the depth-to-diameter ratio of surface craters does show that the particles are compact and densities ranging up to those of e.g. stainless steel are called for for particulates of a few microns. This would support the origin of the small particle fluxes being debris related.

4. OTHER SUPPORTING DATA

Chemical evidence from crater residue composition analysis on the chemistry of Meteoroids Experiment (CME) is convincing (Ref 6) though the measurements not trivial and are incomplete regarding LDEF's whole surface; there are strong selection effects also in the retention of chemical signatures. Spectra are often not recoverable by EDS and meteoroids, with a higher velocity than debris, are mostly "unresolved". At smaller dimensions, we have very little chemical evidence though the Solar Maximum data (Ref. 11) did demonstrate a strongly increasing component of elements typical of man-made debris at smaller dimensions. Data from germanium surface on LDEF (Ref. 12) using an ion probe shows that some 15% to 20% of the impacts on the trailing (West) surface could be space debris. Combined with the analysis of impact flux ratios on LDEF (Ref. 13,14) this calls for (e.g. Ref. 15) the existence of high numbers of eccentric orbits. Other workers (Ref. 8) have drawn attention to the significance of elliptical e.g. GTO transfer orbit data. The angular distribution of the small particles shows in Figure 4 both the South bias and the hgh East to West ratio characteristic of an orbital population; by contrast at lager dimensions, this ratio has reduced and the peak swung around towards North. Meteoroids are dominant.

The resolution of the flux distribution into Meteoroids and Space Debris is shown in Figure 6, following Sullivan and Deshpande. Arguments presented in this work lead to a separation in good agreement with the interplanetary flux incident on the Earth as measured from deep space probes. This (previously reported) analysis does not yet take advantage of the new data presented here and it is certain that the picture will change quantitatively.

5. CRATER ELLIPTICITY INFORMATION

Analysis of the "ellipticity" of craters has been stressed as an important tool for deducing the impact direction. In many cases this vector is not decodable; the shape may also be influenced by the irregularity of particles, but the latter is randomised and a clear, and substantial, sub-set of data remain where impact direction *can* be determined. This is assisted by recent hydrocode modelling of inclined impacts (Ref. 16). This removes therefore, in many instances, limitations imposed by the smoothing of flux data by flat surface detector geometry. First results of this work (Ref. 17) yielded a directional distribution compatible with meteoroids, dominated by Apex-Space directions, but referring to craters with D_c > 20μm. More recently, data has been extended (Ref. 18) to impact craters for D_c < 20 μm and for the South face of LDEF. This reveals a directional distribution (with impactors approaching LDEF at deviation angles significantly different and often much lower elevation than the ram direction). Figure 7 shows the observations. This distribution can only be explained by highly elliptical orbits. Furthermore, noting the need for a South bias at this dimension, this population must call for elliptic orbits with perigees in the southern hemisphere; the Molniya or sun-synchrous orbits are likely candidates.

6. STUDY AREAS AHEAD

Whilst we now do have a good first measure of the relative importance of meteoroids and orbital particles in two size regimes and ideas for the types of orbits needed for the orbital component we have certainly not quantified the problem.

Further data - or data analysis - is called for especially in the time-resolved IDE data showing the episodic and periodic flux changes. Preliminary analysis (Simon, 1993) of the detector records, searching for multiple orbit events (which could be the crossing of a debris orbit plane) have identified the South-facing detector as highly active in this classification; several orbits have been associated with high ellipticity orbits with perigees in the southern hemisphere, supporting the statistical arguments presented here on flux anisotropy and crater ellipticity.

Special significance for future studies - now that we have identified the location of a significant sub-set of impacts where the impact direction is known - is attached to chemical analysis, and especially by ion probe of residues. This subset would then provide chemical evidence of a much more specific - and probably very much underestimated category of orbital debris. We must also see modelling, including elliptical orbits, *applied* to the new LDEF flux data and the crater ellipticity evidence.

The return of ESA's EuReCa mission in 1993 has been identified as a target for study in the important task now facing space environmental assessment (Ref. 20) namely the determination of role; past, present and future, of the Space Debris

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