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INTERPRETATION OF THE DISTRIBUTION OF LARGE CRATERS ON THE LONG DURATION EXPOSURE FACILITY (LDEF)

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ABSTRACT

The expected crater distributions around LDEF resulting from debris particles on near-circular orbits as well as on highly elliptical orbits with different inclinations are calculated. Based on these distributions, the distribution of large craters found on LDEF surfaces is analysed, and the orbits of debris particles producing these craters are estimated. A very large fraction (maybe more than 98%) of the small debris particles has been found to be on highly elliptical orbits with low inclinations. We have also verified the existence of small debris particles on sun-synchronous orbits. Finally, the recorded increased flux on LDEF's trailing side is analysed. If this increase is real, the only explanation is to assume impacts of debris particles with not randomly distributed ascending nodes.

1 INTRODUCTION

Today, there are many efforts in the world to develop mathematical models describing the number of debris particles, as well as their orbital parameter distributions. Since the large objects > 10 cm in diameter are repeatedly tracked by the US Space Command, their orbital elements are well known. There is evidence of the existence of a large number of small debris particles in the submillimeter range from examination of materials returned from space, but it has been so far very difficult (or impossible) to determine their orbital parameter distributions.

The first information of interest is the inclination distribution. The NASA model (Ref. 6) assumes that the small particles have the same inclination distribution as the catalogued objects. However, experimental support for this assumption has not been found. According to the model presented in Ref. 9, based on the simulation of 31 fragmentations in space, small particles are concentrated from 60° to 80° inclinations. This has not been confirmed experimentally, either.

Another information of interest is the eccentricity distribution. The NASA model assumes that the small particles are orbiting on circular orbits as most of the catalogued objects. However, analyses of the orbital dynamics of small particles lead to the conclusion that a large fraction of small particles should be on highly elliptical orbits (Refs. 5 and 7). Otherwise, they do not have enough life time to produce a fairly large flux in LEO.

Is it possible to provide any evidence to prove (or disprove) these assumptions?

The Long Duration Exposure Facility (LDEF) is a significant new source of data. Since it was three-axis gravity-gradient stabilized, it shows a significant variation of the impact flux over the different parts of its surface. As there is a dependence of fluxes on different surfaces of LDEF on the debris particle orbits, it is theoretically possible to estimate the particle orbits (inclination and eccentricity) from the LDEF data. In this paper it is attempted to gain some understanding along these lines.

2 EVALUATION DATA FROM LDEF

Humes (Ref. 2) documented 606 craters with lip diamters ≥ 0.5 mm from the examination of 29.37 m^2 of thick aluminum plates. Zolensky et al. (Ref. 10) have recorded 433 craters ≥ 0.5 mm in lip diameter on the LDEF frame. Combination of these data results in a total number of 1039 craters ≥ 0.5 mm in lip diamter which are statistically large enough to warrant serious consideration here. The diameters of meteoroid and debris particles producing these craters are over a wide range dependent on impact velocity and impact angle. For a first estimation, the average diameter can be assumed to be around 0.1 mm (Ref. 9). In Figure 1, the circle symbols illustrate the measured flux on the 12 sides around LDEF where the yaw angle (ordinate) is the angle between the surface normal vector and the orbital velocity vector of LDEF. The solid line is obtained from smoothing of the LDEF data.

For a first analysis, the smoothed curve is considered as representative of the actual distribution, and departures from the curve are considered as statistical fluctuations. It should be noted that the difference between the smoothed curve and the measurement on the trailing edge (172° yaw) is fairly large. The flux at 172° yaw is a remarkable point anyway because it is larger than the fluxes at the adjacent surfaces (158° and 142° yaw). There is not so much theoretical reason for an increased flux towards the trailing edge so that in Refs. 2 and 3 this point is explained as a statistical variation in the measured flux. However, we will also attempt to give a theoretical explanation in Section 4.2.

The 1039 craters considered here contain meteoroid impacts as well as debris impacts. For estimation of the percentage resulting from debris versus meteoroids, we use the results of the Chemistry of Micrometeoroids Experiment (CME) (Ref. 1). CME consists of a gold plate on the trailing edge (172° yaw) and an aluminum plate at 52° yaw. On the gold plate, 198 craters ≥ 10 µm in lip diameter have been found of which 15% were determined to be man-made, and 29% to be natural origin. 56% of the craters had no residue, so their origin is unknown. On the aluminum plate, 102 craters ≥ 70 µm in lip diameter have been recorded. The chemical analysis has concluded that 17% of the impacts are man-made, but non-aluminum, 39% are of natural origin, while the origin of the remaining 44% is unknown.

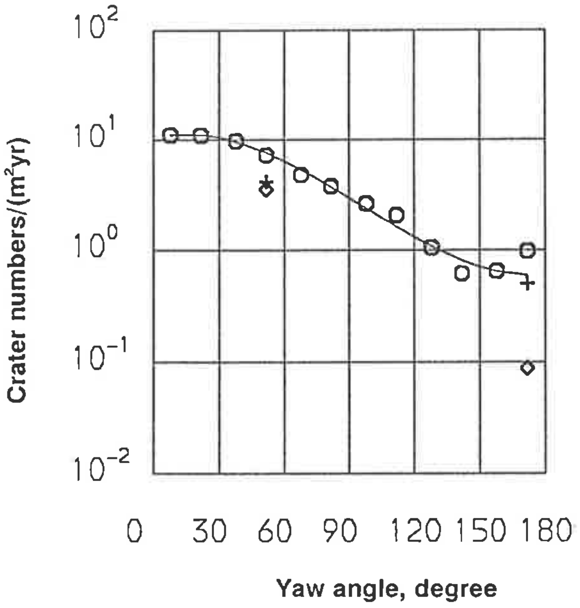

Figure 1. Evaluation data from LDEF.

The fraction of the two sources for the unknown craters was thoughtfully analysed in Ref. 3. On the gold plate (172° yaw), all craters without residue were assumed to be meteoroid impacts which results in 15% of the total craters due to debris impacts and 85% due to meteoroid impacts. Under the assumption that the same ratio of aluminum impacts to non-aluminum and non-paint impacts ≥ 30 µm found on the gold plate should also apply to the aluminum plate (52° yaw), 46% of the total craters at 52° yaw were determined to be debris impacts, and 54% to be meteoroid impacts. This result will also be used in the following analysis. It should be noted that the 46% debris impacts on the aluminum plate can be considered as a nominal fraction, while the 15% debris impacts on the gold plate is the lower limit.

In Figure 1, the cross symbols indicate the meteoroid flux by taking 54% of the total flux at 52° yaw and 85% at 172° yaw, while the quadrangle symbols show the debris flux by taking 46% of the total flux at 52° yaw and 15% at 172° yaw.

3 SURFACE DISTRIBUTION OF CRATER FREQUENCY

Since LDEF was three-axis gravity-gradient stabilized, its orientation was fixed with respect to the orbital velocity vector. Calculation of crater distributions over such a spacecraft is a complex task. In general, theories about collision probability between the spacecraft and a debris particle are to be utilized. For a given spacecraft orbit, distributions of impact probability, impact angle and impact velocity resulting from a considered debris particle can be obtained as a function of the particle's perigee, apogee and inclination. These distributions can be used to calculate the impact flux on each surface of the spacecraft to a limiting particle diameter; this is the so-called "surface distribution of impact flux". Since the observed data are given to a limiting crater diameter, the impact flux must be converted into relative crater numbers on each surface; this is the so-called "surface distribution of crater frequency". Because the same particle does not produce the same crater on different spacecraft surfaces, there is not a linear connection between the distributions of impact flux and crater frequency.

There is an analytical method consisting of a set of equations (Ref. 4) for the calculation of the surface distribution of impact flux. Kessler (Ref. 3) used this method and derived crater distributions around LDEF resulting from selected debris objects. The conversion of impact flux into crater frequency was accomplished by the normal component of velocity raised to the power of 1.67 which assumes that the debris flux varies as the debris diameter raised to the power of -2.5.

Independently, Zhang and Rex (Ref. 9) derived the same distributions by means of a numerical technique. In the first step of this technique, debris particles on a given orbit with different masses are generated. An impact of a particle on the spacecraft is then simulated for a series of constellations of ascending nodes. The ascending node constellations are generated using a Monte-Carlo simulation. The simulated impacts are retained in a file which can numerically be processed to obtain all of the flux distributions (angular distribution, velocity distribution, surface distribution of impact flux, surface distribution of crater frequency, etc.). For conversion of a particle diameter into a crater diameter, eq. 3 in Ref. 2 is used.

Figure 2 shows the result of a principal analysis of selected particle orbits. The crater frequencies around LDEF resulting from these orbits are given as a function of the yaw angle. The LDEF orbit is assumed at 470 km altitude with 28.5° inclination. The thicker lines represent near-circular orbits with a perigee at 400 km and an apogee at 500 km, while the thinner lines represent highly elliptical orbits with a perigee at 400 km and an apogee at 36000 km. It can be observed from Figure 2 that particles on near-circular orbits produce about 100 times more craters than the same particles on highly elliptical orbits (due to their low residence probabilities at low altitudes). Furthermore, the following general relationships can be concluded from Figure 2:

1) Debris particles with high inclinations (100°) make a

large contribution to impacts on LDEF's leading surfaces (yaw < 60°), independent of orbital eccentricities.

2) Particles with medium inclinations (60°) can partly contribute to impacts on the leading surfaces, but mainly to impacts on the left and right sides (yaw around 90°).

3) Debris particles with high eccentricity and low inclinations are the only types of orbits capable of producing craters on LDEF's rear surfaces. These orbits will also contribute to impacts on the left and right. The largest contribution to impacts on the trailing side results from highly elliptical orbits with the same inclination of LDEF (28.5°).

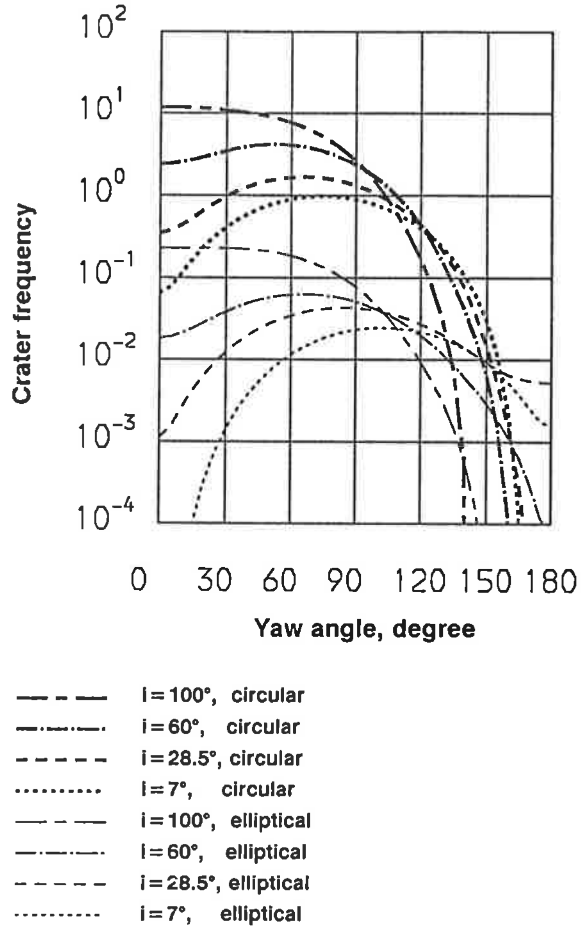

Figure 2. Predicted crater distributions resulting from debris particles on near-circular and highly elliptical orbits with 4 different inclinations.

4 ESTIMATION OF APPROPRIATE DEBRIS ORBITS

4.1 Consideration of the smoothed LDEF data

It is now attempted to find appropriate debris orbits to satisfactorily explain the observational data as shown in Figure 1. First, the modelled debris flux should pass through the two CME points of the debris flux (quadrangle symbols in Figure 1). Secondly, the smoothed curve should be rendered after superposition of the modelled debris flux and the meteoroid flux.

Kessler (Ref. 3) has found that the predicted crater numbers on LDEF's trailing side are far too low if the orbits contained in the US Space Command catalogue for December 1989 are assumed to be representative for the small debris particles. To predict a higher contribution of craters on the trailing edge, he weighted all orbits with apogee larger than 10000 km and inclinations less than 50° by a factor of 20, and obtained a favorable agreement with the measurement. His result is given in Figure 3 as the dash-dotted line which goes through the two quadrangle symbols (the measured debris flux).

However, the crater distribution resulting from meteoroid impacts was not calculated in Ref. 3. Such a calculation was performed in Ref. 2, however, only under the assumption that the orbital debris flux is given in Ref. 6. Therefore a comparison of the total flux with this new insight into the orbital debris environment has not been carried out.

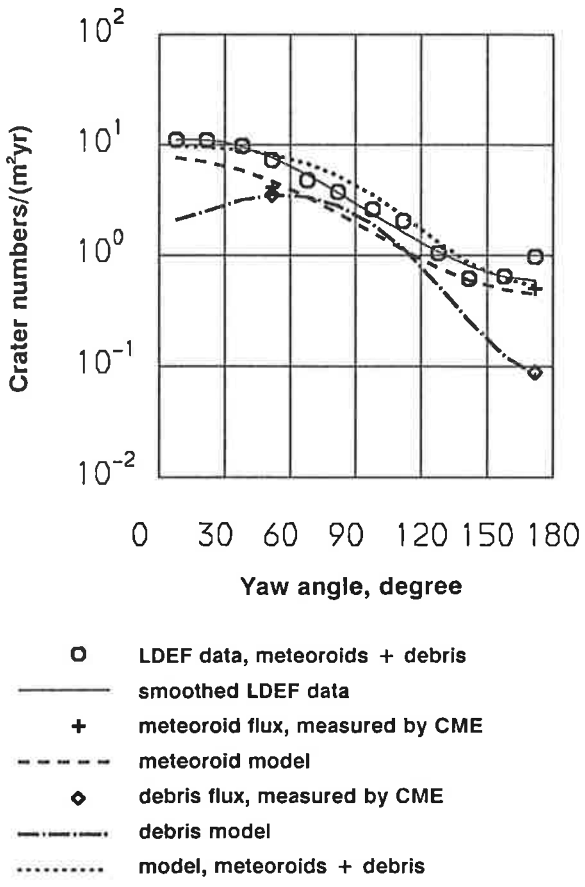

Figure 3. Comparison of measurement with modelled flux. The modelled debris curve results from weighted highly elliptical, low inclination orbits in US Space Command catalogue (from Kessler, 1992).

In Ref. 9, a numerical meteoroid model was also presented which can be used to predict the meteoroid craters around an orbiting spacecraft. The predicted crater distribution from this model is also shown in Figure 3 as the dashed curve. The curve is normalized to pass through the two measured meteoroid points (cross symbols) as close as possible. As discussed in Ref. 9, the absolute crater numbers predicted from the meteoroid model contain large uncertainties; however, there are not so many parameters which can change the relative crater numbers around LDEF. Therefore, the shape of the meteoroid curve can be considered as correct. This is again confirmed in Figure 3, as the two CME points are very close to the modelled meteoroid curve.

The modelled meteoroid craters and the modelled debris craters are superimposed which results in the dotted curve in Figure 3. A fairly good agreement with the smoothed curve can be found. However, the agreement is by no means excellent, because the shape of the modelled flux is different from the smoothed curve. While the modelled flux is slightly lower on the leading surfaces (yaw < 30°), it is higher in the yaw range from 60° to 140°. It is also questionable that the modelled debris flux around 90° yaw is higher than the meteoroid flux.

More attempts must be taken to obtain a better agreement. Ignoring the US Space Command catalogue, we have considered idealized debris orbits based on the crater distributions shown in Figure 2. Since highly elliptical orbits with low inclinations account for the measured debris flux on LDEF's trailing edge, we assume debris particles on the orbit with a perigee of 400 km, an apogee of 36000 km and with an inclination of 28.5°. To simulate the measured debris flux on the aluminum plate (yaw = 52°), the best way seems to assume debris orbits with high inclination, for example i = 100°, since only such orbits (independent of orbital eccentricity) produce monotonously increasing crater numbers towards the leading side of LDEF (see Figure 2) which is required to explain the difference between the observed total flux and the modelled meteoroid flux. Since there are not actual highly elliptical orbits with 100° inclination, near-circular orbits are considered in the following analysis.

The right percentage of particles on the two orbits have been determined in an iterative procedure. If we assume 1.8% of the small debris particles orbiting at near-circular orbits with 100° inclination and 98.2% orbiting at highly elliptical orbits with 28.5° inclination, the dash-dotted line in Figure 4 is obtained. The modelled debris flux increases monotonously from the trailing surface towards the leading surface and goes through the two measured debris points. The superposition with the modelled meteoroid flux results in the dotted line which agrees excellently with the smoothed curve.

The extremly small percentage of particles on near-circular orbits with 100° inclination is attributed to the fact that circular orbits produce about 100 times more craters on LDEF than highly elliptical orbits (see Figure 2). Reversely, only few particles on such an orbit are sufficient to produce the observed crater numbers on the leading surfaces, while much more (54.5 times) particles on the highly elliptical orbit with 28.5° inclination are required to produce the observed crater numbers on the rear surfaces.

Still, it is a surprising result that more than 98% of the small particles have to orbit on highly elliptical orbits. However, in retrospect this is not so much surprising because this is consistent with the conclusions in Refs. 5 and 7 that most of the small particles should be on highly elliptical orbits. The assumption made in Ref. 3 that highly elliptical orbits with low inclinations must be weighted by a factor of 20 means a similar high fraction (about 96%) of particles on highly elliptical orbits. It should be noted that this percentage is only valid for particles encountering the LDEF orbit. Taking also orbits with a perigee higher than 500 km into account, totally different percentage is imaginable.

The assumptions made above are by all means realistic. Highly elliptical orbits with 28.5° inclination are characteristic of orbital transfer stages from low Earth orbit to geosynchronous orbit, while near-circular orbits with an inclination of around 100° are intensely used as sun-synchronous orbits. We did not consider other orbits which can be assumed to be negligible compared to the two orbits mentioned before.

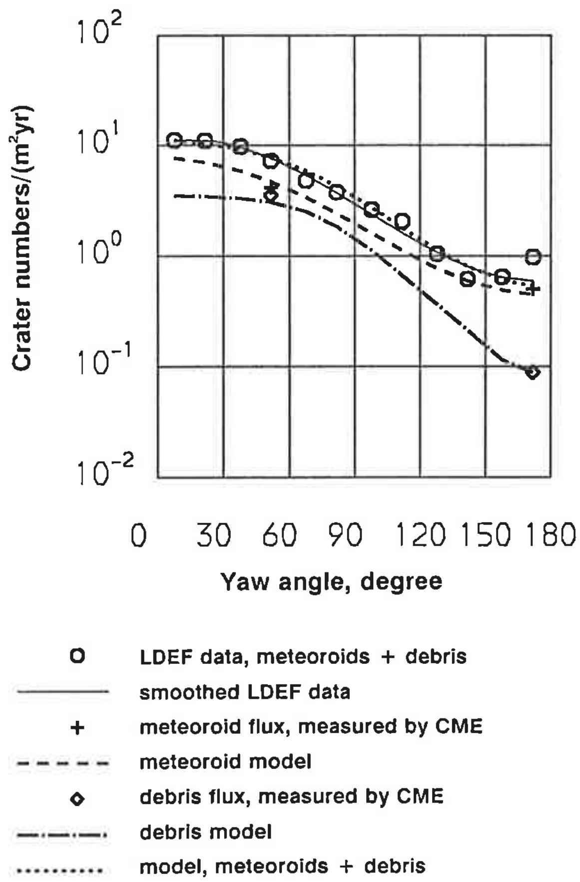

Figure 4. Comparison of measurement with modelled flux. The modelled debris curve is obtained from 1.8% of particles on near-circular orbits with 100° inclination and 98.2% on highly elliptical orbits with 28.5° inclination.

4.2 Explanation of the increased flux on LDEF's trailing surface

In the above analyses, the smoothed curve was considered as representative of the actual crater distribution, and departures from the curve were assumed to be statistical fluctuations in the measurement. The largest departure from the smoothed curve occurs on the trailing edge (172° yaw). This point is remarkable because it is higher than the points at 158° and 142° yaw. It is absolutely acceptable to explain this point as a statitical fluctuation. Still, it would be helpful to find a theoretical explanation.

Meteoroid models do not give an increased flux towards the trailing side, neither do the selected debris orbits in Figure 2. Debris particles on highly elliptical orbits with 28.5° inclination make the largest contribution to LDEF's trailing surface. They even produce less craters on the trailing surface than on the adjacent surfaces. We did not find any debris orbit capable of producing an increased flux towards the trailing side until we changed one of the basic assumptions, e.g. the ascending nodes of debris particles to be randomly distributed. If we assume the ascending nodes of debris particles on highly elliptical orbits with 28.5° inclination are, instead of a random distribution, very close to the ascending node of LDEF (for example within 10°, 30° or 60°), the expected crater numbers increase continuously towards the trailing side, as shown in Figure 5.

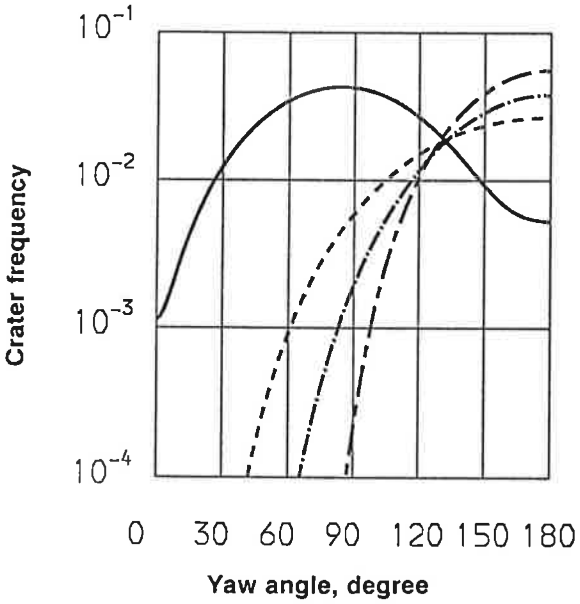

Figure 5. Crater distributions resulting from debris particles on highly elliptical orbits with 28.5° inclination. The solid line is obtained from randomly distributed particle nodes, while for other lines the particle nodes are close to the LDEF node.

The ascending nodes of debris particles, as well as the ascending node of a spacecraft changes progressively due to natural perturbations. Consequently, the relative position between the spacecraft's node and the node of a debris particle changes with the time, so in which relative node position the particle hits the spacecraft is random. If a debris cloud is just generated, the ascending nodes of all particles are close to each other at the beginning. Some time later, they will be distributed over a wide angular range. As a result, the nodes of the particles relative to the spacecraft's node can also be considered as randomly distributed. That is why a random distribution of the ascending nodes is generally assumed.

But in some special cases the ascending nodes may not be randomly distributed. One possibility could be that the debris particles of a freshly generated debris cloud decayed, or LDEF was returned to the ground, before there was enough time for the nodes to become distributed. Another possibility would be that the perigees of the particles increased and moved above the LDEF altitude due to solar pressure or solar-lunar perturbation, so they were not able to encounter the LDEF orbit after a short period.

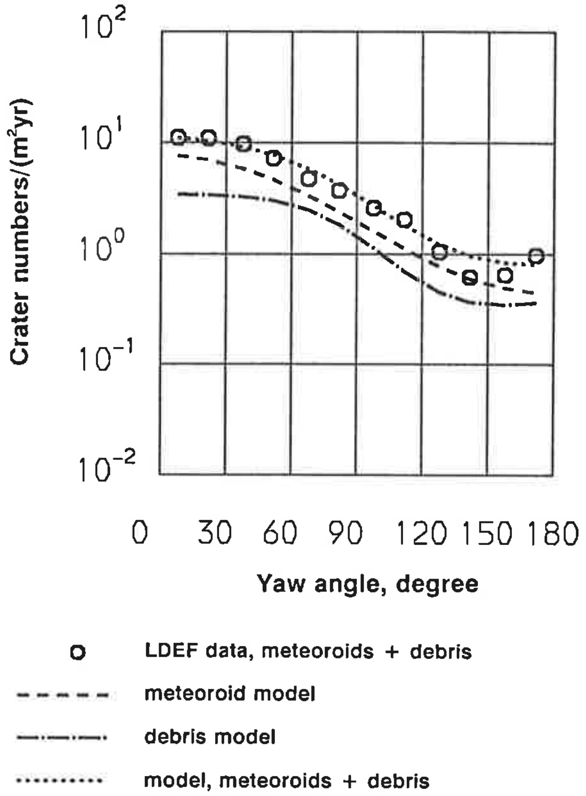

Figure 6. Comparison of measurement with modelled flux. The modelled debris curve is obtained from 1.35% of particles on near-circular orbits with 100° inclination, 75.51% on highly elliptical orbits with 28.5° inclination (with random nodes) and 23.14% on the same orbit with nodes within 10° to the LDEF node.

The results of the Interplanetary Dust Experiment (IDE) show a strong time dependency of debris impacts (Ref. 8) which was possibly due to not randomly distributed nodes. Although the detected particles are below the size range responsible for craters ≥ 0.5 mm, they provide experimentally an indication along this line.

The next attempt taken is to assume 1.35% of debris particles orbiting on near-circular orbits with 100° inclination (with randomly distributed nodes), 75.51% orbiting on highly elliptical orbits with 28.5° inclination (with randomly distributed nodes) and 23.14% orbiting on highly elliptical orbits with 28.5° inclination, too (but their nodes were within 10° to LDEF's node). Figure 6 illustrates the result. Although there is not a visible increase in the total flux towards the trailing surface, the modelled flux on the trailing surface has moved very close to the measurement, without the agreement on other surfaces becoming worse.

Now, there are even 98.65% of the small debris particles orbiting on highly elliptical orbits with low inclinations.

5 CONCLUSIONS

The analyses carried out in this paper underline the existence of a large number of small debris particles orbiting on highly elliptical orbits with low inclinations (maybe more than 98% of all small particles being able to encounter the LDEF orbit). In addition, the existence of small particles on sun-synchronous orbits (near-circular with high inclinations) must also be assumed to explain the observational data on LDEF's leading surfaces, while particles on other orbits could be neglected.

So the present models describing the orbital parameter distributions (inclination and eccentricity distribution) are not valid, as could be proved.

If the observed increased flux on the trailing edge is real, we must change a basic assumption made so far, namely the ascending nodes of debris particles to be randomly distributed. Only by assuming the nodes of debris particle streams were close to LDEF's node, more crater numbers on the trailing surface than on adjacent surfaces can be achieved. This situation needs not have prevailed over the whole LDEF mission time, but only lasted for a few weeks (or days).

6 ACKNOWLEDGEMENTS

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