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ORIGIN OF ORBITAL DEBRIS IMPACTS ON LDEF'S TRAILING SURFACES

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SUMMARY

A model was developed to determine the origin of orbital debris impacts measured on the trailing surfaces of LDEF. The model calculates the expected debris impact crater distribution around LDEF as a function of debris orbital parameters. The results show that only highly elliptical, low inclination orbits could be responsible for these impacts. The most common objects left in this type of orbit are orbital transfer stages used by the U.S. and ESA to place payloads into geosynchronous orbit. Objects in this type of orbit are difficult to catalogue by the US Space Command; consequently there are independent reasons to believe that the catalogue does not adequately represent this population. This analysis concludes that the relative number of catalogued objects with highly elliptical, low inclination orbits must be increased by a factor of 20 to be consistent with the LDEF data.

INTRODUCTION

Most of the man-made objects in low Earth orbit that are tracked and catalogued by the US Space Command are in near circular orbits. The number of objects in elliptical orbits are so few that models which describe the directional properties of orbital debris generally assume that all orbits are circular. Such an assumption leads to the conclusion that orbital debris will not impact the trailing surfaces of other spacecraft in circular orbits (ref. 1).

However, objects in elliptical orbits, especially those with low inclinations, are more difficult to detect and catalogue than objects in circular orbit. This is because elliptical orbits spend a smaller fraction of their time at low altitudes where ground based sensors can detect them, and there are fewer ground based sensors located to detect low inclination orbits. Consequently, the US Space Command catalogue is not likely to be representative of the various orbit classes of large objects. This lack of representation of elliptical orbits by the catalogue is likely to increase with decreasing orbital debris size. The orbital lifetime of small debris in circular orbits at low altitudes is much shorter than elliptical orbits. Calculations of collision probabilities integrated over these lifetimes lead to a prediction that orbital debris in elliptical orbits could be important to impacts on spacecraft at low altitudes (ref. 2).

The "Chemistry of Micrometeoroids Experiment" located on LDEF bay A03 has found a significant fraction of the impacts on a trailing surface to be of orbital debris origin (ref. 3). The purpose of this paper is to determine in more detail the types and relative contributions of orbits responsible for these impacts, and the implications to impacts on other LDEF surfaces. This will be accomplished by using collision probability theory to calculate the expected impact crater distribution around LDEF for various types of orbital debris orbits. This expected impact crater distribution is then compared with that observed on LDEF.

FUNDAMENTAL LDEF DATA AND ASSUMPTIONS

Parts of two sets of LDEF data will be used here: The results of chemical analysis of the Chemistry of Micrometeoroids Experiment (CME) given in references 3 and 4, and the flux as a function of direction around LDEF as measured by the Space Debris Impact Experiment and reported in reference 5. The following is a brief summary of that data and the assumptions used in this paper concerning that data.

In analysis completed on the CME, 15% of the impacts on the experiment's rear located gold surface (location A03) was determined to be man-made, 29% was determined to be meteoroid, and 56% had no residue, so their source is unknown. The planned rear locations were actually facing 172 degrees from the spacecraft orbital velocity vector. For the purpose of this paper, all of the impacts into gold which had no residue will be assumed to be the results of meteoroid impacts. This would seem to be a valid assumption because all debris impacts on the rear surface would be at a much lower velocity than most meteoroid impacts. High velocity impacts into a dense material like gold are more likely to cause vaporization, leaving no residue in the surface. About 80% of the man-made impacts contained only aluminum. The remaining 20% of non-aluminum impacts represents a small sample of 5, and although it may not be statistically significant, only one of those 5 was paint.

Analysis of the CME aluminum surface (location A11) has concluded that 17% of the impacts are non-aluminum man-made, 39% was determined to be meteoroids, and 44% had no residue or the residue was aluminum. The lower density of the aluminum surface would suggest that vaporization is less likely to occur on these surfaces than the gold surface. Consequently, meteoroid impacts are more likely to be identified than impacts on the gold surface. This would suggest that the residue was aluminum in some fraction of the pits where no residue could be identified. As will be shown, any orbiting source which impacts the gold surface has an even greater chance of impacting the aluminum surface. So, some of the unidentified impacts into aluminum should be expected to be aluminum. If one assumes the same ratio of aluminum to non-aluminum impacts on the aluminum surfaces as was measured on the gold surfaces, one would expect more than the 44% of the unidentified pits to be man-made aluminum impacts.

However, the orbital debris impacts on the aluminum surface appear to have a different character than on the impacts on the gold surface: 57% of the orbital debris impacts on the aluminum surface are paint. This could suggest different types of orbits for orbiting paint flecks. In addition, the limiting threshold size on the gold surfaces is smaller than on the aluminum surfaces, and a larger fraction of the smaller pits are aluminum. This may also represent a different source of small aluminum pits, aluminum oxide dust from solid rocket motors. If only pits that are 30 microns and larger are counted, the orbital debris flux is reduced to 11% of the total number of impacts on the gold surface. In addition, if paint is subtracted out from both the gold and aluminum surfaces, and only pits that are 30 microns and larger are used, then the ratio of aluminum to non-aluminum, non-paint on the gold surfaces is about 4. If this same ratio is expected on the aluminum surfaces, then 29% of the impacts on the aluminum surface could be expected to be aluminum. This would mean that about 66% of the pits where no residue could be found were aluminum impacts into aluminum, and that the number of orbital debris impacts on this surface was 46% of the total number of impacts. An orbital debris flux which is 46% of the total flux on the CME aluminum surface will be adopted in this paper.

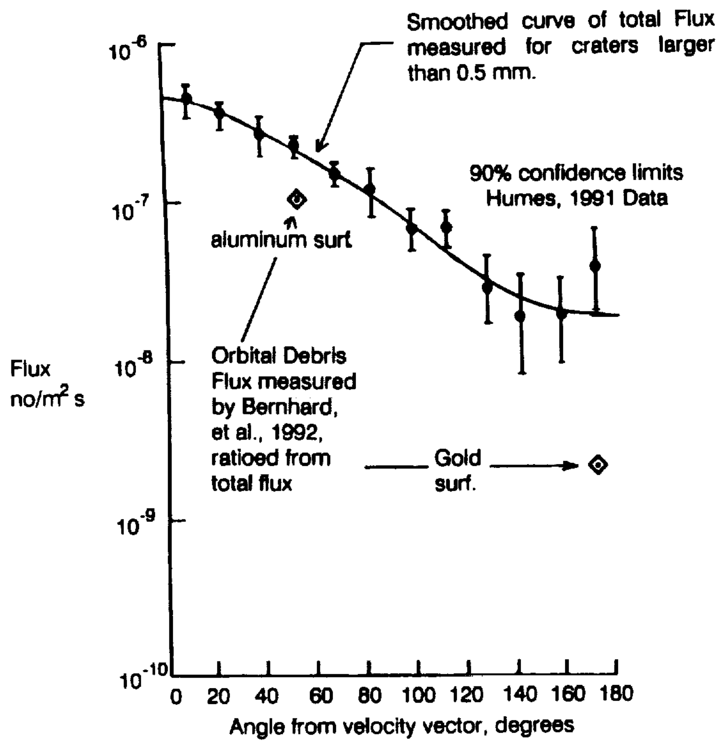

Figure 1. LDEF data used.

The total measured flux on LDEF of impacts craters larger than 0.5 mm as a function of the surface direction (i.e., the angle between the surface normal vector and the orbital velocity vector) is shown in figure 1 (ref. 5). The assumption is made that the smoothed curve also shown is representative of the actual distribution, and that departures from the curve are statistical fluctuations in the data. This assumption seems justified given the error bars, the smoothing effect of similar data in reference 6, and the fact that there is no theoretical reason for a large change in flux on both adjacent surfaces.

Also shown in figure 1 are the CME data points obtained by taking 11% of the total measured flux on the LDEF row 03 (surface direction of 172 degrees), and 46% of the total measured flux on row 11 (surface direction of 52 degrees). By taking these percentages, the assumption is made that the chemistry and frequency of orbital debris in the smaller size range of 0.03 mm craters and larger into gold is also characteristic of 0.5 mm craters and larger into aluminum. A sufficiently large data base containing the chemistry of impact craters larger than 0.5 mm does not yet exist to test this assumption. However, it is apparent that for craters smaller than 0.03 mm, both the chemistry and frequency of orbital debris do change. Although the statistics are still poor, the CME shows increased aluminum impacts for these smaller sizes. In addition, both the Microabrasion Foil Experiment (ref. 7) and the Interplanetary Dust Experiment (ref. 8) have shown an Earth orbiting population which dominates the meteoroid flux for particle sizes of the order of 1 micron and smaller. Ground observations by the Goldstone (ref. 9) and Haystack (ref. 10) radar measure an orbital debris environment larger than 2 mm which exceeds the meteoroid environment; consequently, there is sufficient data to know that the assumption is not valid over larger size ranges. How inappropriate the assumption is for figure 1 will have to await further data.

The problem is then to determine the distribution of orbital debris orbits that will produce an orbital debris flux that passes through the CME points on figure 1. Collision probability theory is used to determine this distribution.

COLLISION PROBABILITY

Theory and Assumptions

The probability that an orbital debris object will collide with LDEF (or any other spacecraft) at a particular point in orbit is a function of the orbital debris' perigee, apogee, and inclination, as well as the relative velocity between the two objects and their collision cross-sectional area. Equations expressing this probability are given in reference 11, as well as equations for the relative velocity (both magnitude and direction). These equations are used to calculate the relative number of impacts, or flux, on each LDEF surface for various orbital debris orbits.

However, the observed data are in terms of a limiting impact crater diameter. Crater diameter is a function of impact speed and direction, as well as debris size; consequently, impact speed and direction are also calculated for each LDEF surface. The assumption is made that crater diameter is proportional to debris diameter raised to the first power and the normal component of velocity raised to the 2/3 power. The assumption is also made that the flux of orbital debris varies as the orbital debris diameter raised to the -2.5 power. This later assumption is consistent with previous orbital debris models (ref. 1) and recent measurements (refs. 9 and 10). These two assumptions are required to convert flux to a limiting particle diameter to flux as a function of limiting impact crater diameter. This conversion is then accomplished by weighting the flux to a limiting size by the normal component of velocity raised to the 2.5 times 2/3 divided by 1.0 power, or 1.67 power (ref. 12).

Results

The orbit sets contained in the US Space Command catalogue for December, 1989 were used to provide a set of orbits to predict the distribution of craters around LDEF. The resulting calculations were normalized to pass through the aluminum surface CME data point. The results are shown in figure 2, assuming an LDEF altitude of 400 km. As can be seen, based on the US Space Command catalogue, a very small fraction of the craters would be predicted to be on LDEF's rear surface. Past approximations obtained this same result, and lead to the conclusion that orbital debris directionality can be approximated by assuming circular orbits. The CME gold surface data point would suggest that the past assumptions are not valid, and that elliptical orbits are important to orbital debris directionality. Figure 2 suggests that the relative number of catalogued objects in certain types of elliptical orbits must be increased by at least an order of magnitude. The amount of increase is a function of the assumed LDEF altitude. An assumed altitude of 500 km for LDEF would have underpredicted rear impacts on LDEF even more than shown in figure 2, while an assumed altitude of 300 km would have underpredicted less than shown in figure 2. This implies that the relative number of orbital debris impacts on LDEF's rear surfaces should increase with decreasing altitude of LDEF. This introduces some uncertainty in the correct "average" altitude; however, the consequences of this uncertainty is small compared to the greater than an order of magnitude underprediction shown in figure 2 for an LDEF altitude of 400 km.

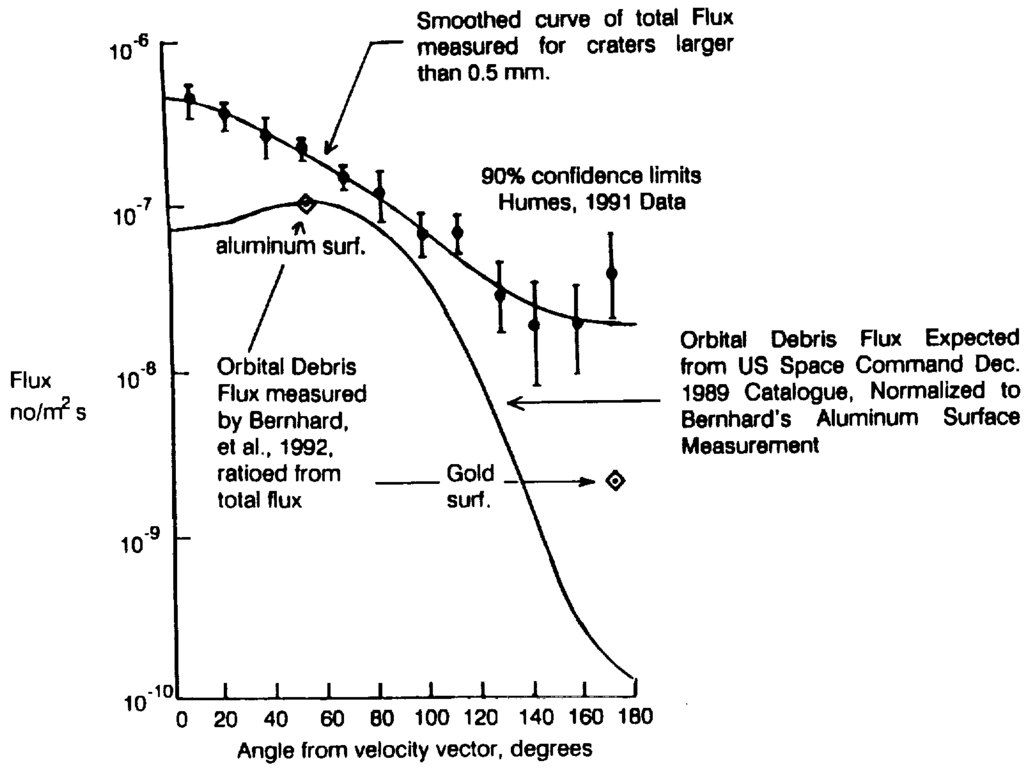

Figure 2. LDEF crater distribution expected form orbits in US Space Command catalogue.

In order to determine which types of elliptical orbits are contributing to impacts on the rear surface, the contribution from individual orbits was also calculated. The results of this calculation are shown in figure 3 for selected orbital debris orbits. The selected orbits fall into three groups: 1. Near circular orbits. 2. Highly elliptical orbits. 3. Moderately elliptical orbits. The results show that for a given number of objects in Earth orbit at LDEF's altitude, circular orbits can be expected to produce about 100 times more craters on LDEF than highly elliptical orbits. Most of the craters from circular orbits would be on LDEF's leading and side surfaces. Lower inclinations would produce fewer craters on the leading surfaces; no craters would be expected on the trailing surfaces from circular orbits.

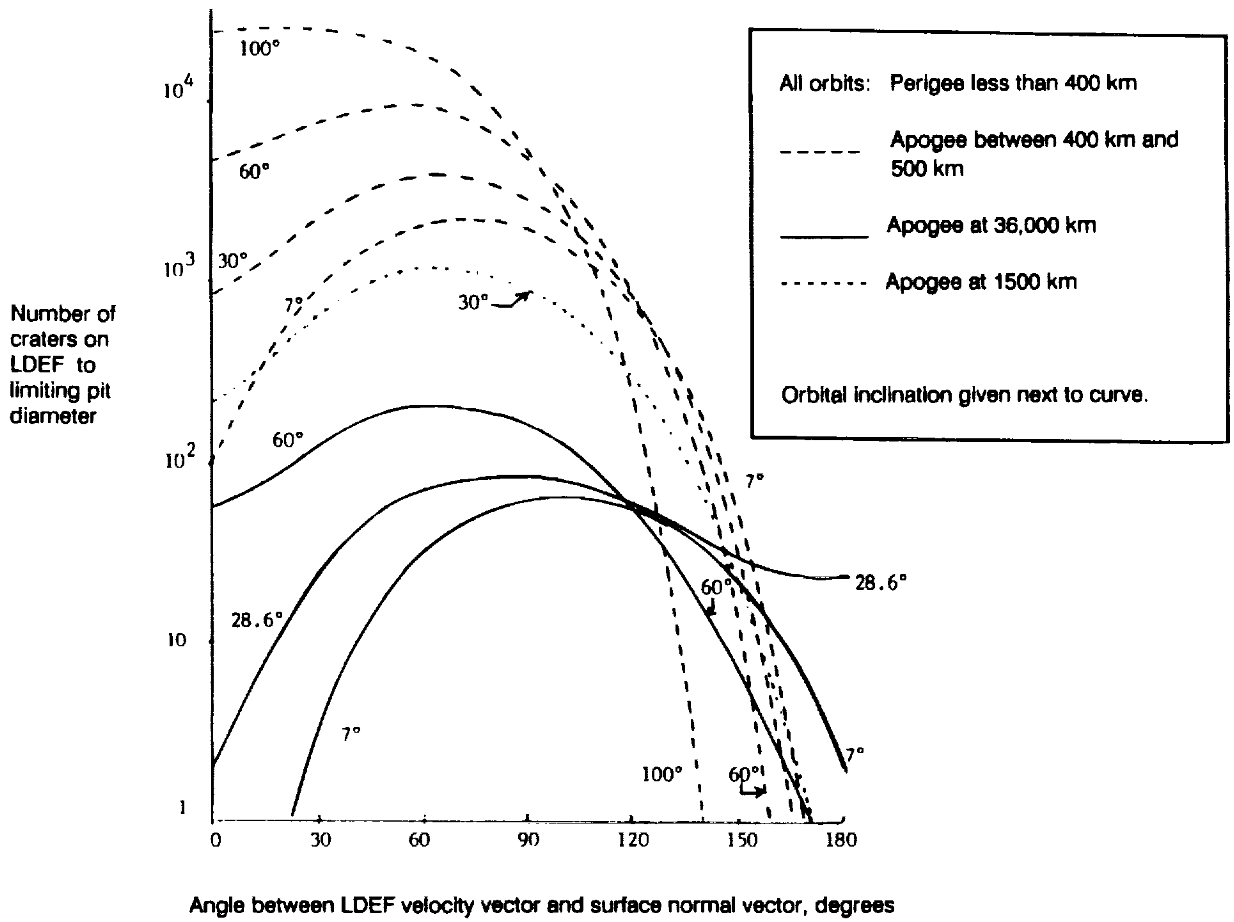

Figure 3. Predicted distribution of craters around LDEF due to various types of orbits.

The highly elliptical orbits have perigees below LDEF's altitude and apogees near geosynchronous orbit. This group of orbits is characteristic of orbital transfer stages from low Earth orbit to geosynchronous orbit. When an object is placed into geosynchronous orbit, an upper stage rocket is usually left in this type of orbit. The results show that these types of orbits are expected to produce craters on LDEF's rear surface only if the inclination is low. Highly elliptical orbits with inclinations larger than about 50 degrees are not capable of producing a significant number of impact craters on LDEF's rear surface without also producing a larger number of craters on the CME aluminum surface than was measured. The orbits most capable of producing a large number of pits on LDEF's rear surfaces are highly elliptical orbits with inclinations close to the inclination of LDEF, or 28.5 degrees. Orbital debris impacts on the CME gold surface from this type of orbit will also produce about 3 times as many orbital debris impacts on the CME aluminum surface. However, figure 1 gives a measured orbital debris flux on the CME aluminum surfaces which is 40 times larger than the flux on the gold surface. Therefore, other inclinations must be responsible for most of the orbital debris impacts on the aluminum surface.

Inclinations as low as 7 degrees can also produce a significant orbital debris flux on the rear surfaces. From figure 3, orbital debris impacts on the CME gold surface from highly elliptical 7 degree inclination orbits will also produce about 10 times as many orbital debris impacts on the CME aluminum surface. This ratio is also less than was determined by the CME, so other sources of orbital debris are required.

Moderately elliptical orbits to circular orbits are required to account for the total number of orbital debris impacts on the CME aluminum surface. A moderately elliptical orbit is one with its apogee near 1500 km and perigee below LDEF altitude. This type of orbit might be expected as a result of explosions at altitudes between 1000 and 2000 km, where nearly all explosions have occurred which produced long orbital lifetime orbits. As can be seen from figure 3, a moderately elliptical orbit with an inclination as close as 30 degrees to the LDEF inclination is not capable of producing a significant crater population on LDEF's rear surface without also producing a much larger crater population on the side surfaces. Consequently, while this type of orbit, along with near circular orbits, may be responsible for impacts on the leading and side surfaces of LDEF, moderately elliptical orbits are not responsible for a significant number of impacts on LDEF's rear surface.

Therefore, the only types of orbits capable of providing the necessary number of impacts on LDEF's rear surface are highly elliptical, low inclination orbits. This is the type of orbit which is most difficult to catalogue and maintain by the US Space Command. The US is mostly responsible for leaving orbital transfer stages in highly elliptical orbits with inclinations near 28.5 degrees, and the European Space Agency (ESA) is responsible for leaving orbital transfer stages with highly elliptical orbits with inclinations usually near 7 degrees. At least 2 of ESA's upper stages in this type of orbit are believed to have exploded (ref. 13); a total of 3 fragments were catalogued from these 2 events. When the same upper stage exploded in a circular low Earth orbit with a high inclination, 488 fragments were catalogued. Consequently, it is not unreasonable to expect that the catalogue does not adequately represent this low inclination population.

The December, 1989 US Space Command catalogue was again used to predict the distribution of craters around LDEF; however, this time all orbits with both apogee greater than 10,000 km and inclination less than 50 degrees were weighted by a factor of 20. All other orbits were unweighted. Again the resulting calculations were normalized to pass through the aluminum surface CME data point. The results are shown in figure 4. As can be seen, the results go through both CME data points.

There have been 17 satellite breakups (mostly upper stage explosions) in highly elliptical orbits with inclinations over 50 degrees; an average of less than 4 fragments per breakup were catalogued (ref. 13). A valid assumption might be that this population is equally not represented by the catalogue. Such as assumption would require a weighting factor larger than 20 because the higher inclination orbits do not contribute to impacts on the trailing surface...only to impacts on the leading and side surfaces. If all orbits with an apogee greater than 10,000 (regardless of their inclination) are weighted by a factor of 30, the results are almost identical to that shown in figure 4 for the lower inclination orbits. Because the directional properties of highly elliptical, high inclination orbits are so close to the directional properties of circular orbits, there is no way to discriminate between weighting factors of 20 or 30 for these two respective possibilities.

Consequently, the ratio in the amount of small debris in these highly elliptical, low inclination orbits to the amount of small debris in other types of orbits must be at least 20 times the same ratio for larger, catalogued objects in order to be consistent with the CME LDEF data. If all elliptical orbits are equally not represented by the catalogue, then the ratio for small debris must be 30 times the ratio for catalogued objects.

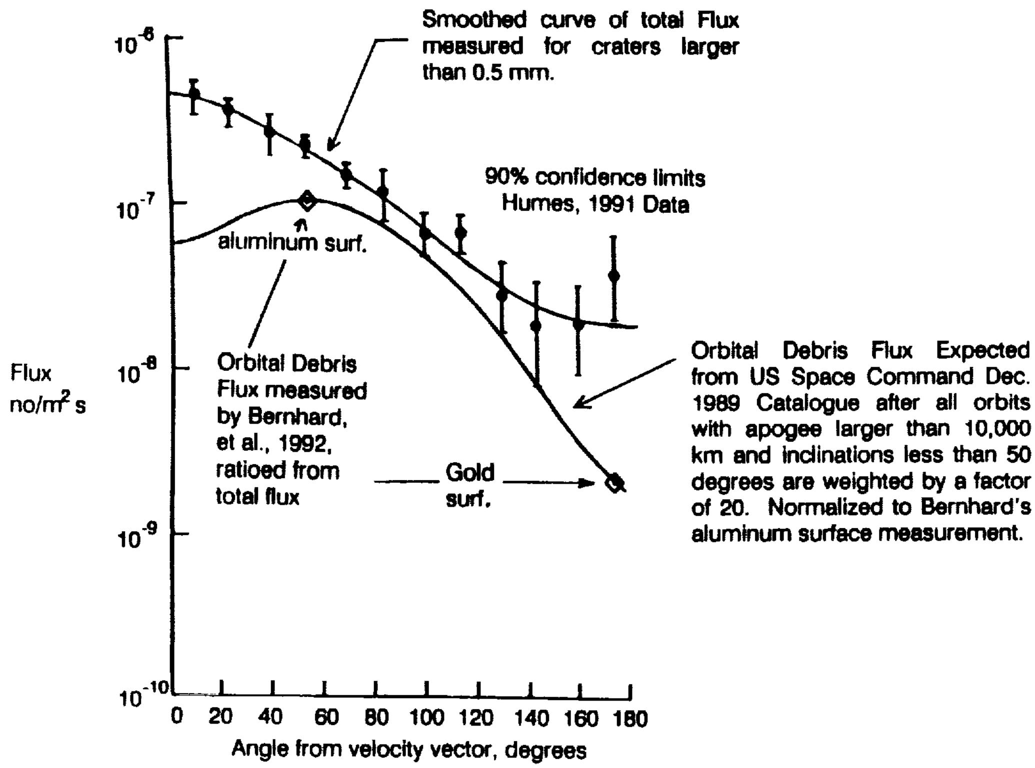

Figure 4. LDEF crater distribution expected from weighted highly elliptical, low inclination orbits in US Space Command catalogue.

CONCLUSIONS

Orbital debris impacts on LDEF's rear surface can only be caused by debris in highly elliptical, low inclination orbits. The US Space Command catalogue underpredicts the relative contribution of orbital debris impacts on LDEF from this type of orbit by at least a factor of 20. The reasons for this underprediction are the result of a combination of difficulty in cataloguing objects in these orbits, and that small debris in highly elliptical orbits is a larger fraction of the flux at low altitudes than is larger, catalogued debris.

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