

LONG-TERM MICROPARTICLE FLUX VARIABILITY INDICATED BY COMPARISON OF  
INTERPLANETARY DUST EXPERIMENT (IDE) TIMED IMPACTS FOR LDEF'S FIRST YEAR IN  
ORBIT WITH IMPACT DATA FOR THE ENTIRE 5.77-YEAR ORBITAL LIFETIME

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ABSTRACT

The electronic sensors of the Interplanetary Dust Experiment (IDE) recorded precise impact times and approximate directions for submicron to ~100-micron size particles on all six primary sides of the spacecraft for the first 346 days of the LDEF orbital mission. Previously-reported analyses of the timed impact data have established their spatio-temporal features, including the demonstration that a preponderance of the particles in this regime are orbital debris and that a large fraction of the debris particles are encountered in megameter-size clouds. Short-term fluxes within such clouds can rise several orders of magnitude above the long-term average. These unexpectedly large short-term variations in debris flux raise the question of how representative an indication of the multi-year average flux is given by the nearly one year of timed data. One of the goals of the IDE was to conduct an optical survey of impact sites on detectors that remained active during the entire LDEF mission, to obtain full-mission fluxes.

We present here the comparisons and contrasts among the new IDE optical survey impact data, the IDE first-year timed impact data, and impact data from other LDEF micrometeoroid and debris experiments. The following observations are reported.

- 1) The 5.77 year long-term integrated microparticle impact fluxes recorded by IDE detectors matched the integrated impact fluxes measured by other LDEF investigators for the same period.
- 2) IDE integrated microparticle impact fluxes varied by factors from 0.5 to 8.3 for LDEF days 1-346, 347-2106 and 1-2106 (5.77 years) on rows 3 (trailing edge, or West), 6 (South side), 12 (North side), and the Earth and Space ends.
- 3) IDE integrated microparticle impact fluxes varied less than 3% for LDEF days 1-346, 347-2106 and 1-2106 (5.77 years) on row 9 (leading edge, or East).

These results give further evidence of the accuracy and internal consistency of the recorded IDE impact data. This leads to the further conclusion that the utility of long-term flux ratios for impacts on various sides of a stabilized satellite in low Earth orbit (LEO) is extremely limited. These observations, and their consequences, highlight the need for continuous, real time monitoring of the dynamic microparticle environment in LEO.

## INTRODUCTION AND BACKGROUND

The electronic sensors of the Interplanetary Dust Experiment (IDE) recorded precise impact times and approximate directions for submicron to ~100-micron size particles on all six primary sides of the spacecraft for the first 346 days of the LDEF orbital mission. The resulting data set of over 15,000 impacts represents perhaps the most extensive record ever gathered of the number, locations, and times of small particle impacts on a spacecraft in Earth orbit. The fact that the involuntarily "extended mission" of LDEF assured that the IDE detectors would be exposed to the LEO environment for a much longer time than the duration of their data recording system made it clear from the moment of recovery that it would be desirable to perform impact counts on detectors that remained active during the entire mission in order to compare the IDE 5.77-year integrated fluxes with the 346-day integrated fluxes from the IDE timed data. In this paper we report on that comparison, and on the comparison with full mission integrated microparticle fluxes from other LDEF experiments.

The IDE detectors are constructed from 2 inch diameter, 250  $\mu\text{m}$  thick, boron-doped ultra high-purity silicon wafers covered with either a 0.4 or a 1.0  $\mu\text{m}$  thick layer of thermally grown  $\text{SiO}_2$  insulator, and coated with ~1000 $\text{\AA}$  of high-purity aluminum. The detectors are divided into two sensitivity levels based on the insulator thickness. (The reader is directed to ref. 1, Singer *et al.*, for details of the hardware design.)

Extensive hypervelocity impact testing of the detectors was performed at Langley Research Center by Kassel (ref. 2) prior to LDEF launch. The two different sensitivity detectors were subjected to hundreds of impacts from 0.5 to 5  $\mu\text{m}$  diameter carbonyl iron projectiles (density = 7.86  $\text{g}/\text{cm}^3$ , mass range =  $5 \times 10^{-13}$  to  $5 \times 10^{-10}$  g) at velocities of 4 to 10 km/s and incident angles from 0 to 75° from normal. The applied voltage across the detectors ranged from -60 to -20 volts. These tests indicated that a 0.5  $\mu\text{m}$  particle impacting at 3 km/s (or faster) would trigger the low sensitivity detectors, and a 0.5  $\mu\text{m}$  particle impacting at 2 km/s (or faster) would trigger the high sensitivity detectors. While the tests did not establish an absolute calibration for the detectors, they did demonstrate several important features:

- 1) the detector operation is reliable (stable and reproducible) when the bias voltage is greater than 30V;
- 2) after an impact the detector returns to its original condition with an insignificant loss of active area;
- 3) the sensitivity of the detectors is inversely proportional to the insulator layer thickness;
- 4) the sensitivity of the detectors is strongly dependent on the bias voltage below 40V;
- 5) submicron hypervelocity particles will trigger the detectors.

(A more extensive study of the detectors, which involved an expanded operational parameter set and several thousand hypervelocity microparticle impacts, is the topic of a paper currently under preparation by the IDE team.)

While the IDE detector sensitivities could be related to each other, and they were very stable under stable bias conditions, their absolute sensitivities were not known. When LDEF was retrieved at the end of its 5.77 year mission, nearly all of the low sensitivity IDE detectors were still functional and were operating at a bias voltage of 62V, compared to an initial bias voltage of 71V. Based on observations during impact testing, this difference is not considered significant at this high voltage level. In order to empirically evaluate the extent of this effect, the IDE detector array from the South side of LDEF (tray D-6) was powered up to 71V and monitored for 28 days. Any impact damaged sites that did not cause an active detector to discharge while on orbit under a bias of 62V should have triggered the detector within a few minutes under a bias voltage of 71V. Twenty-two of the 32 low sensitivity IDE detectors on this tray were found to still be active on retrieval. Post flight optical scanning showed an average of ~140 impact induced discharges on each detector. When the 22 detectors were powered up, only one discharge occurred within the first two minutes. A total of 6 discharges occurred within 4 hours, and an additional 3 discharges occurred over the next 28 days. It was apparent that there was not a significant amount of impact damage on the sensors that had not already caused the detectors to discharge while on orbit.

(It should be noted that two similar pre-flight tests of the same detectors showed 1 discharge over 22 days and 0 discharges over 34 days.)

The power-up test of the IDE tray D-6 detectors also provided further evidence that anomalous sensor status readings periodically recorded during the active portion of the mission were unrelated to detector performance. Sensor status readings were designed to give instantaneous checks of the recharge state on the capacitor detectors. The anomalies appear to be the result of the circuit's interaction with the local spacecraft plasma (ref. 3). A detailed report on the IDE system behavior is currently in preparation by the experiment team.

Examination of the impact records on all arrays showed that impact counting rates were not related to the "sensor status" record. There were, in fact, several instances where impacts were recorded immediately prior to, just after, and even *during* a status check that indicated all sensors were uncharged. If the detectors had actually been functioning under a reduced charge state, the impact sensitivity, and thus the counting rates, would be biased negatively. It is also noted that these anomalous status readings were indicated <5% of the time for the low sensitivity IDE detectors on the South panel, and this was the worst case. Overall impact counting rates for tray D-6 (South) and tray B-12 (North), which experienced very few sensor status anomalies during the first year were similar, with the South panel recording ~10% more impacts than the North panel. This was another indication that the anomalous sensor status readings were not related to detector functionality.

Considering this evidence, it appeared practical to count the impact induced discharge sites on the IDE low sensitivity detectors that remained active during the entire orbital mission, and derive impact flux values for all 6 orthogonal sides of LDEF. These values could then be compared to the flux values observed by other LDEF investigators, resulting in an empirical calibration of the IDE detector sensitivity with respect to a standard measure of impact damage, such as equivalent crater size in aluminum. (This is a particularly useful standard, since there was a large amount of aluminum surface area exposed on LDEF.) The long term flux values could also be contrasted to the fluxes recorded electronically by the same detectors during their first year of operation. This permits a determination of microparticle impact flux values for 3 long-term time periods: days 1-346, days 1-2106, and days 347-2106 (by subtraction).

## DESCRIPTION OF IDE DATA SETS

It is important to distinguish among the various impact data sets (IDE and others) and to constantly be aware of which sets are being compared or contrasted. The timed data from the two different sensitivity IDE detectors represent two distinct data sets, labelled "A" and "B" below. The impact-induced discharge record on the low sensitivity detectors that remained active during the entire orbital mission represents a third, distinct data set labelled "C" below. A fourth data set can be derived by subtracting the electronically-recorded impact data on the low sensitivity IDE detectors (data set "B") from the optical record of impact discharges during the entire mission (data set "C"). This data set is labelled "D". To summarize, we have assigned the following labels to the four distinguishable long-term IDE impact data sets:

- A = electronically timed impacts for particles that triggered the high sensitivity IDE detectors during LDEF's first year in orbit (days 1-346),
- B = electronically timed impacts for particles that triggered the low sensitivity IDE detectors during LDEF's first year in orbit (days 1-346),
- C = all impacts that triggered low sensitivity IDE detectors that remained active during the entire LDEF orbital mission (days 1-2106),
- D = all impacts that triggered low sensitivity IDE detectors that remained active during the entire LDEF orbital mission on days 347-2106 (i.e.,  $C-B=D$ ).

The first two data sets, "A" and "B", contain the 15,000 electronically timed impacts recorded by IDE detectors mounted on the six orthogonal sides of LDEF. The impact times are known with a resolution of 13s and an accuracy of 20s (ft. note 1). Even though the recording tape ran out after 346 days, the IDE detectors continued to function. Housekeeping data on the tape indicated that bias voltages on the arrays of both sensitivities of IDE detectors had dropped <1% during the first 346 days. Most of the low sensitivity detectors were active and performing nominally (as described above) on retrieval. Some had suffered catastrophic impact damage. All of the high sensitivity detectors arrays had drained their batteries sometime after the first year (because of higher operational leakage currents) and were inactive upon retrieval.

The third IDE data set, "C", includes over 10,000 impacts and is contained in the optical record of impact discharges on low sensitivity IDE detectors that remained active during the entire LDEF 5.77 year mission. This record has been extracted by optical microscopic examination of these detectors (discussed below) and represents the impact fluxes for the entire mission. Data set "D" contains approximately 6,000 impacts and represents the impact fluxes during the 4.8 years after the IDE recording tape ran out.

It is imperative that readers keep in mind the differences in these three data sets. **Direct comparisons of LDEF flux numbers are valid only when the spatial, temporal and physical impact criteria on which the flux values are based are identical.** For example, it is valid to directly compare long term IDE flux values (data set "C") with other LDEF long term flux values for the equivalent impact feature sizes on surfaces from equivalent LDEF locations. These values should be essentially identical if there are no problems with the associated data sets.

However, it is **not** valid to directly compare IDE first year flux values (data sets "A" and "B") with IDE data sets "C" and "D" or other LDEF 5.77 year long term flux values for equivalent impact feature sizes and locations. These values are not necessarily identical. *Indeed, it is the differences (contrasts) between the 5.77 year long-term fluxes measured by IDE and other LDEF experiments and the one year "long-term" fluxes measured by IDE (and FRECOPA on the West side of LDEF) that constitute a significant discovery and are the bases of the following discussions.*

Comparisons and contrasts of flux values among IDE data sets B, C and D and other LDEF dust experiments will be discussed in this paper. Results from non-temporally-resolved LDEF impact experiments were extracted from the LDEF Meteoroid and Debris Special Investigation Group's Interim Report (ref. 4), which was based on LDEF investigator supplied and reviewed data.

IDE data set A is not included in these discussions since almost no LDEF impact flux data has been generated to date that can be directly compared or contrasted to this data set. Some temporal resolution is available from impacts that occurred on surfaces contained within experiment exposure control canisters (EECC) located on LDEF rows 2, 3, 4, 8 and 9. These canisters were open during the same time period that the IDE experiment was recording impact events. The difficulty is in securing samples from these experiments that have smooth enough surface textures to allow accurate assessment of the 1  $\mu\text{m}$  crater population. This comparison is left to a future study after more information has been reported by other LDEF investigators.

Previously reported analyses of the IDE timed microparticle impact data established their basic spatio-temporal features, including the demonstration that a preponderance of the particles in this size regime are orbital debris (a finding that is consistent with the results of the first catastrophic hypervelocity laboratory impacts on a real satellite, OSCAR-22, recently reported in the press [ref. 5]), and that a large fraction of the debris particles are encountered in megameter-size clouds (refs. 1, 6 and 7; ft. notes 2 and 3). Higher than expected impact fluxes detected by IDE on the West (trailing) edge of LDEF provided the first evidence of a far greater population of debris in highly elliptic orbits (>0.07 eccentricity) than previously known, a conclusion now supported by additional LDEF experiment results (*e.g.* ref. 8). Short-term fluxes within such clouds increased several orders of magnitude above the long-term average. A discussion of the sizes, densities and orbital parameters of several of these orbital debris clouds is presented in footnote 3.

We present here comparisons and contrasts among the IDE optical survey impact data, the IDE first-year timed impact data, and integrated impact data from other LDEF micrometeoroid and debris experiments. There are undoubtedly more observations and conclusions remaining to be discovered from investigation of these impact data. However, in this paper we will limit our discussion to the details of the data collection procedures and the gross conclusions that are immediately apparent from these data.

## OPTICAL SCANNING OF IDE DETECTORS

Flux data from low sensitivity IDE detectors that were active during the entire LDEF mission and were selected for optical counting of impact induced discharges were considered valid when the following criteria were met:

- 1) the detector suffered no significant down time based on interpretation of sensor status check data recorded during the first 346 days on orbit;
- 2) the detector's post-flight capacitance value was within 3% of the pre-flight value;
- 3) no impact craters without associated discharges were noted on the detector in the 125x optical scan.

Hypervelocity impacts that triggered an electrical discharge of the IDE capacitor-type detectors could be readily distinguished from impacts with sub-threshold kinetic energy, and from impacts that occurred on an inactive detector, by the fact that the discharge energy vaporizes the thin aluminum top layer on the detector in an  $\sim 50 \mu\text{m}$  diameter zone around the impact site. The underlying  $\text{SiO}_2$  layer is shockingly pink and is therefore easily identifiable under optical examination. An optical scan at 125x was undertaken to count the on-orbit impact-induced discharges on those sensors that are known to have remained active during the entire 5.77-yr LDEF mission (i.e., met the 3 criteria listed above).

A post-flight photographic catalogue of the entire set of flight detectors has been made with the same optical setup used in 1983 for a pre-flight catalogue. (Both catalogues will eventually be deposited in the LDEF Program data archive.) Comparison of the pre- and post-flight images while conducting optical microscopic examination of detectors permitted segregation of fabrication flaws and pre-flight discharges (caused during ground testing) from orbital impact-induced discharges. Contamination or defect caused discharges, also called "spurious" discharges, that occurred on orbit were identified by the presence of the associated contaminant or defect site in the pre-flight photo. These discharges often have unusual morphologies as well. Thus far, there appears to be an average of  $<1$  of these spurious discharges per detector.

Optical scanning of at least a representative sample of the active IDE detectors from each LDEF location is complete. Each of the detectors has  $\sim 20 \text{ cm}^2$  of active surface area. The results discussed below are based on optical scans of 29 detectors from the West (trailing, row 3) side of LDEF, 18 detectors from the Earth (down) end, 8 detectors from the Space (up) end, and three detectors each from East (leading, row 9), North (row 12), and South (row 6) sides of LDEF. The first three locations (West, Earth and Space) experienced low impact activity, with an average of 10-20 impacts per detector. The latter three locations (East, North and South) experienced high impact activity, with an average of 130-310 impacts per detector.

## DISCUSSION

Calculated impact flux values for IDE surfaces are listed in Table 1 along with flux values reported by two other LDEF experiment teams for indicated impact feature sizes, LDEF locations, and orbital time periods. The additional data are from the Micro Abrasion Package (MAP), experiment AO023 reported by

McDonnell and Stevenson (ref. 9), and from the FRECOPA experiments AO138-1 and AO138-2 reported by Mandeville and Borg (ref. 10, ft.4). Interested readers are referred to ref. 4 for details on the counting statistics and surface areas used to derive the flux values.

Table 1. Selected cumulative microparticle impact fluxes observed on LDEF surfaces. IDE data is for impacts that would produce craters in aluminum  $\geq 3 \mu\text{m}$  in dia. FRECOPA data are for impacts into Al foils or plates with indicated crater sizes counted in SEM scans. MAP data are optical transmission counts of penetrations in thin foils with indicated equivalent crater sizes. Values in [ ] are subject to confirmation. Error estimates,  $s$ , are calculated from Poisson statistics,  $s = (n^{-1/2})(f)$  where  $n$  is the number of impacts in the data set and  $f$  is the flux.

Cumulative LDEF impact flux values for indicated equiv. crater diameters in aluminum ( $\times 10^{-4} \text{ m}^{-2}\text{s}^{-1}$ )									
	time res. IDE ( $\geq 3 \mu\text{m}$ ) days	foil FRECOPA ( $\geq 2 \mu\text{m}$ ) days	inte- grated IDE ( $\geq 3 \mu\text{m}$ ) days	inte- grated IDE ( $\geq 3 \mu\text{m}$ )	plate FRECOPA ( $\geq 3 \mu\text{m}$ )	2.0 $\mu\text{m}$ foil MAP ( $\geq 3 \mu\text{m}$ )	3.1 $\mu\text{m}$ foil MAP ( $\geq 4 \mu\text{m}$ )	3.7 $\mu\text{m}$ foil MAP ( $\geq 5 \mu\text{m}$ )	4.8 $\mu\text{m}$ foil MAP ( $\geq 7 \mu\text{m}$ )
LDEF location	1-346	10-280	347-2106	{-----days 1-2106, (5.77 years)-----}					
North (row 12)	6.1 $\pm 0.18$		3.5 $\pm 0.20$	3.9 $\pm 0.17$		[3.7] [ $\pm 0.19$ ]		[1.5] [ $\pm 0.087$ ]	1.3 $\pm 0.060$
South (row 6)	6.6 $\pm 0.19$		3.2 $\pm 0.19$	3.8 $\pm 0.19$		[6.0] [ $\pm 0.18$ ]	[2.2] [ $\pm 0.15$ ]	[1.9] [ $\pm 0.14$ ]	1.5 $\pm 0.063$
East leading (row 9)	8.5 $\pm 0.22$		8.7 $\pm 0.31$	8.7 $\pm 0.28$					2.3 $\pm 0.22$
West trailing (row 3)	0.99 $\pm 0.073$	0.86 $\pm 0.38$	0.12 $\pm 0.013$	0.26 $\pm 0.016$	0.22 $\pm 0.11$		[0.23] [ $\pm 0.049$ ]	[0.062] [ $\pm 0.025$ ]	0.070 $\pm 0.014$
Space (up)	1.1 $\pm 0.090$		0.48 $\pm 0.039$	0.59 $\pm 0.045$					0.34 $\pm 0.024$
Earth (down)	0.16 $\pm 0.030$		0.30 $\pm 0.023$	0.28 $\pm 0.022$					

The MAP data listed in Table 1 are based on optical transmission scanning of recovered foils. In this technique, the opaque Al foils are back lighted and all points that transmit light are counted. The method is subject to positive bias from secondary impacts and newly formed pinholes (since post flight background counts were made) that are not the result of orbital impacts. At the time of this writing, the MAP impact counts on foils  $< 4.8 \mu\text{m}$  thick (equiv. to craters in Al with diameters  $< 7 \mu\text{m}$ ) are considered preliminary and subject to verification by high magnification microscopic examination of significant areas of the foils. The MAP sensitivities listed in Table 1 in terms of crater diameter in Al were supplied by the experiment team after extensive calibration tests (see ref. 9).

The MAP experiment is particularly useful in supplying the IDE with an on-orbit empirical calibration since the impact fluxes are based on penetration damage to thin Al foils. While the IDE detector substrates are composed of  $\text{SiO}_2$ , the shock-induced impact damage mechanism responsible for triggering the detectors at their minimum threshold is the same mechanism that is responsible for marginal penetration of the MAP Al foils. It should be noted that orbital debris and natural micrometeoroids are expected to

have vastly different encounter velocities on LDEF surfaces. In general, orbital debris particles strike satellite surfaces at much lower velocities than micrometeoroids. This means that for a given mass impactor, more damage will result from natural particles than from manmade debris particles. This results in enhanced detection of natural micrometeoroids versus equal mass manmade debris particles for experiments that depend on impact damage for counting rates, such as IDE and MAP (see ref. 11 for a detailed discussion of this subject). However, both experiments should accurately predict the level and flux of impact-induced damage to spacecraft surfaces by all microparticles in the LEO environment.

FRECOPA data presented in Table 1 were derived from high magnification SEM scans of Al foils and ultrasmooth plates and are not subject to bias at the indicated crater sizes. These values are based on careful counts but are somewhat limited by low counting statistics. As more area is scanned by this research team, the FRECOPA integrated flux numbers may change slightly.

It should also be noted that shielding effects were not considered in this first-order comparison of measured impact fluxes. Shielding can introduce negative bias in perceived impact fluxes due to geometric constraints, but these effects are expected to be minimal for the particular LDEF surfaces under discussion. (The MAP foils are recessed ~10 cm below the tray lips, the IDE detector surfaces were recessed 0.3 cm, and the FRECOPA targets were recessed 0 to ~5 cm.) In general, the more a surface is recessed below the surrounding spacecraft structure, the greater is the degree of shielding from impacts, and the greater is the potential for secondary impacts from material ejected out of impacts in the surrounding structures. Some secondary debris sprays from impacts into IDE Al frames (especially on the space end tray) were noted in optical scanning. While the splatters of melted Al ejected from these frame impacts did not cause the IDE detectors to discharge in any instance, this same material could puncture the thin foils used in the MAP experiment. It is anticipated that the MAP and FRECOPA teams will report on the effects of shielding and secondary impacts on their respective experiments in the future.

### Consistency Among LDEF Experiments

Figure 1 depicts in bar graph format the impact flux data presented in Table 1. The IDE data are segregated into three distinct time periods, one corresponding to the electronically timed impacts recorded on magnetic tape for the first 346 days in orbit, a second corresponding to the visually scanned impact results which refer to the entire 5.77 year orbital mission, and a third time period corresponding to the difference between the first two time periods. These are compared to the Canterbury MAP experiment, which had no time resolution and can only be presented as 5.77-yr averages, and to the French FRECOPA experiment. The latter had two experiment modes, a 5  $\mu\text{m}$  foil mounted in a drawer which was exposed for 0.74 years, starting a few days after LDEF deployment, and a smooth aluminum plate which was exposed for the full 5.77 year mission. These experiments are ideally suited for such a comparison.

Overall, the data show that the low sensitivity IDE detectors responded to impacts that would produce ~3  $\mu\text{m}$  diameter craters in aluminum. Scaling from this result indicates that the high sensitivity detectors were sensitive to impacts that would produce ~1.2  $\mu\text{m}$  diameter craters in Al. These results are consistent with the pre-flight calibration tests by Kassel (ref. 2). The major conclusion from this is that the IDE detectors did, in fact, work as expected, and an on-orbit empirical calibration can be derived from impact damage assessment on adjacent LDEF surfaces.

The most important aspect of Figure 1 is that the IDE 5.77-yr average flux data are consistent with flux data from both of the other experiments on all locations (with one exception). It is particularly gratifying that the results of the *only* other dust experiment which gave data specifically for the first year on LDEF's West panel (FRECOPA) are also consistent with IDE. These are important points since they indicate that **the overall flux rates measured by the IDE matched those measured by other LDEF experiments.** With this knowledge, the temporal history of the flux measured by IDE can be assumed to be accurate with high confidence.

The highly variable microparticle impact flux on the West, or trailing edge (row 3) of LDEF observed by IDE is confirmed by the 0.74 year and 5.77 year FRECOPA data. IDE and FRECOPA recorded first year microparticle impact fluxes (for craters in Al that are 2-3  $\mu\text{m}$  in diameter and larger) on the West side of  $0.99$  and  $0.86 \times 10^{-4} \text{ m}^{-2}\text{s}^{-1}$ , respectively, and 5.77 year (full mission) fluxes of  $0.26$  and  $0.22 \times 10^{-4} \text{ m}^{-2}\text{s}^{-1}$ , respectively. (The MAP experiment also showed a full mission integrated flux of  $0.23 \times 10^{-4} \text{ m}^{-2}\text{s}^{-1}$  for craters in Al  $\geq 4 \mu\text{m}$ .) The calculated flux for the time period after the IDE recording tape ran out (days 347-2106) is  $0.12 \times 10^{-4} \text{ m}^{-2}\text{s}^{-1}$ , or a factor of 8.3 times lower than the first year flux. The consequences of this high variability are discussed further in the next section.

The one point of apparent inconsistency among the IDE, MAP and FRECOPA data occurs on the South side (row 6). The MAP data for penetrations in a  $2.0 \mu\text{m}$  thick Al foil (equivalent to craters  $\geq 3 \mu\text{m}$  in dia.) yield a 5.77-year integrated flux of  $6.0 \times 10^{-4} \text{ m}^{-2}\text{s}^{-1}$ , which is 1.6 times higher than the IDE 5.77-year integrated flux of  $3.8 \times 10^{-4} \text{ m}^{-2}\text{s}^{-1}$  on the South side. Penetration counts in a slightly thicker ( $3.1 \mu\text{m}$ ) MAP foil (equiv. to craters  $\geq 4 \mu\text{m}$  in dia) yield an integrated flux of  $2.2 \times 10^{-4} \text{ m}^{-2}\text{s}^{-1}$ . Additionally,  $4.8 \mu\text{m}$  thick MAP foils mounted on both the South and North (row 12) sides of LDEF yield verified integrated fluxes of  $1.5$  and  $1.3 \times 10^{-4} \text{ m}^{-2}\text{s}^{-1}$ , respectively. Also, the North side MAP and IDE data showed fluxes of  $3.7$  and  $3.9 \times 10^{-4} \text{ m}^{-2}\text{s}^{-1}$ , respectively. Thus, it appears that the penetration counts in the thinnest MAP foil mounted on the South side are positively biased by secondary impacts or by non-impact induced penetrations or ruptures.

This apparent positive bias to one point of the South side MAP data is also supported by the self-consistency of the IDE data, which showed similar fluxes for all long-term time periods on the North and South sides, as would be expected by their near equivalent positions on LDEF. Thus far there is no indication that the IDE data were negatively biased due to loss of detector sensitivity (as described in the previous section), and McDonnell and Stevenson have been careful to point out the possibility of positive bias in the thinnest MAP foils (ref. 9). Therefore, at this time we must assume that it is the MAP data that is biased. However, this issue can be readdressed after the MAP team has examined the suspect foil microscopically.

#### Evidence for Temporal Structure at All Finite Averaging Times

Figure 1 puts into striking relief the fact of extreme temporal variation in the orbital debris environment over long time periods. This is the first evidence that this variability exists at all averaging intervals. We have already shown (see refs. 6 and 7; ft. notes 2 and 3) important variation from minute to minute and from week to week. This is further illustrated in Figures 2a and 2b where the East and West fluxes and East/West flux ratios for the high and low sensitivity IDE detectors are shown as a function of time. The points plotted are the result of a 5-day running average smoothing function.

Figure 1 shows the same effect from year to year for the low sensitivity IDE detectors. East has comparable values for 0.95 yr and 5.77 yr, while North, South, and Space show an excess factor of 1.6 to 1.9 for the first year, whereas Earth shows a deficit factor of 1.9 for the first year. The first year on West shows 3.7 times the flux of the full mission. These values can be compared to the IDE flux values calculated for days 347-2106 and listed in Table 1.

Although there is no microparticle impact flux reported to date that can be directly compared to the IDE data from the East, or leading, edge of LDEF (row 9), the IDE data show that there was essentially no long-term change in the measured fluxes on this location (see Table 1 and Fig. 1). The MAP team reported an East/West ratio (leading/trailing) of 33 for somewhat larger impacts (equivalent to  $\geq 7 \mu\text{m}$  diameter craters in Al) for the entire mission. The IDE low sensitivity detectors also measured an East/West ratio of 33 for the same time period for impacts that would form craters in Al  $\geq 3 \mu\text{m}$ .



Although these ratios are consistent, the East/West microparticle impact flux ratios measured by the same IDE detectors during days 1-346, and days 347-2106 are 8.5 and 73, respectively.

The extreme range for the long-term integrated flux ratio measured by the IDE low sensitivity detectors is due entirely to the variability in impact flux on the trailing edge of LDEF (Fig. 1), whereas the short term variability in the ratio is due to activity on both sides, as shown in Fig. 2. The relative activity levels on the IDE detectors can provide information on the mass distribution of microparticles, and the variabilities of the short-term impact flux ratios among the various sides of LDEF can yield important information on the characteristics of orbital debris clouds and natural dust sources. **However, for theoretical and practical applications, the extreme variability of long-term East/West microparticle impact flux ratios must be taken into account.** For some applications, it may be more appropriate to use impact flux values, and respective ratios, for the 4.82 year period represented by LDEF orbital days 347-2106. These values represent the modal ratio (that was prevalent during ~85% of the LDEF mission), whereas the 5.77 year integrated values represent the mean ratio for the entire mission. We are continuing our investigation of these observed variabilities of impact flux ratios.

In an effort to understand the high variability of impact flux recorded by the IDE detectors on the trailing edge (West), we have investigated the effect of spurious discharge activity. As described above, this activity is most notable just after IDE activation. We have looked at this question in several ways. Such discharges can occur, as described above, but in large measure only within the first few hours after activation -- much less than a day. From optical scans of all West panel low sensitivity IDE detectors we found an average of <1 contaminant- or defect-caused inflight spurious discharge per sensor on this panel. If all of these discharges had occurred during the first year, the total number of recorded impacts would have to be adjusted from 186 to 156, for an average first-year East/West flux ratio of 9.7. Even this does not account for the large variation in ratios.

We also looked at whether the East/West ratio is "front-loaded" by high activity associated with the deployment and activation of the IDE. Figure 2b shows that 5-day means of the ratio vary by two orders of magnitude about the mean value of 8.5 for essentially the entire year. These data, and additional data in preparation, are a striking reminder of the variability and episodic nature of microparticle impacts in low Earth orbit.

### The Earth Side Mystery

One of the more puzzling aspects of the IDE data comes from the LDEF side that was originally considered the least interesting -- the Earth end. We remind the reader that, since this face was only 0.07 Earth radii from the surface, it was expected on kinematic grounds to be largely shielded from both natural and artificial particles (ref. 1). In reality, the 5.77-year flux on the Earth end was comparable to that on West, which itself was higher than expected. Here also, as on several other faces, there was a significant difference between the first-year flux and the full-mission flux. The long-term microparticle impact flux was roughly double the first-year flux. In addition, the optical survey gives no evidence of large particles and no evidence of highly-oblique impacts.

Could the averages be skewed by a single event after day 346? We cannot answer this question directly, but there are some intriguing coincidences. For example, in a 1986 SDI-sponsored test a Delta rocket vehicle launched its third stage into such an orbit as to collide with its own second stage at 3 km/s (ref. 12). The collision was at about 200 km altitude. The resulting debris cloud is known to have had a large outward component, and the recent ground-based Oscar-22 disruption test suggests strongly that that cloud had a very high number density of micron-sized particles (ft. note 5). An ASAT weapon test on September 13, 1985 resulted in a 7 km/s collision between the weapon and an 850 kg P78-1 satellite at about 500 km altitude, the same altitude as LDEF (ref. 12). We repeat: we can draw no conclusions from the information now available to us. Had the IDE magnetic tape been longer, or had there been downlink telemetry on LDEF-1, explicit answers could be given to the questions raised by the Earth side IDE panel.

## SUMMARY

The Interplanetary Dust Experiment continues to yield new discoveries about the microparticle population in low Earth orbit. The latest findings indicate that the long term (multi-year) average microparticle impact fluxes on all sides of LDEF, except East (ram) varied widely during the mission. Measured long-term microparticle impact fluxes on the North, South, West, Space and Earth sides of LDEF during the first year were 0.5 to 3.7 times the 5.77 year fluxes. We have presented the comparisons and contrasts among the IDE optical survey impact data, the IDE first-year timed impact data, and impact data from other LDEF micrometeoroid and debris experiments.

The following observations were reported.

- 1) The 5.77 year long-term integrated microparticle impact fluxes recorded by IDE detectors matched the integrated impact fluxes measured by other LDEF investigators for the same period.
- 2) IDE integrated microparticle impact fluxes varied by factors from 0.5 to 8.3 for LDEF days 1-346, 347-2106 and 1-2106 (5.77 years) on rows 3 (trailing edge, or West), 6 (South side), 12 (North side), and the Earth and Space ends.
- 3) IDE integrated microparticle impact fluxes varied less than 3% for LDEF days 1-346, 347-2106 and 1-2106 (5.77 years) on row 9 (leading edge, or East).

These results give further evidence of the accuracy and internal consistency of the recorded IDE impact data. This leads to the further conclusion that the utility of long-term flux ratios for impacts on various sides of a stabilized satellite in low Earth orbit (LEO) is extremely limited. These observations, and their consequences, highlight the need for continuous, real time monitoring of the dynamic microparticle environment in LEO.

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