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LDEF INTERPLANETARY DUST EXPERIMENT (IDE) RESULTS

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ABSTRACT

The Interplanetary Dust Experiment (IDE) provided high time resolution detection of microparticle impacts on the Long Duration Exposure Facility satellite. Particles, in the diameter range from 0.2 microns to several hundred microns, were detected impacting on six orthogonal surfaces of the gravity-gradient stabilized LDEF spacecraft. The total sensitive surface area was about one square meter, distributed between LDEF rows 3 (Wake or West), 6 (South), 9 (Ram or East), 12 (North), as well as the Space and Earth ends of LDEF. The time of each impact is known to an accuracy that corresponds to better than one degree in orbital longitude. Because LDEF was gravity-gradient stabilized and magnetically damped, the direction of the normal to each detector panel is precisely known for each impact. The 11 1/2 month tape-recorded data set represents the most extensive record gathered of the number, orbital location, and incidence direction for microparticle impacts in low Earth orbit.

Perhaps the most striking result from IDE was the discovery that microparticle impacts, especially on the Ram, South, and North surfaces, were highly episodic. Most such impacts occurred in localized regions of the orbit for dozens or even hundreds of orbits in what we have termed Multiple Orbit Event Sequences (MOES). In addition, more than a dozen intense and short-lived "spikes" were seen in which impact fluxes exceeded the background by several orders of magnitude. These events were distributed in a highly non-uniform fashion in time and terrestrial longitude and latitude.

1. INTERPLANETARY DUST EXPERIMENT

The Interplanetary Dust Experiment (IDE) was conceived to permit a discrimination between cosmic dust and orbital debris, and to characterize the dust in terms of mass, velocity, time, and trajectory[1]. The IDE experiment occupied portions of six trays, one each on the leading and trailing edges, the Earth and space ends, and the "north" and "south" edges. Five of the trays carried 80 active detectors, while the spaceward tray bore only 59. The total detector area was slightly less than one square meter. Each detector was a 50-millimeter diameter metal-oxide-silicon (MOS) semiconductor capacitor («B_Ref287687536 * mergeformat »). Each detector was charged by a bias voltage supply through a current limiting resistor. An impacting microparticle with sufficient energy could vaporize the dielectric layer and cause a transient discharge of the capacitor. The associated electronics counted and time-tagged each discharge. The thickness of the oxide determines the energy required to trigger a discharge of the capacitor. The thinner dielectric requires less impact energy, providing higher sensitivity. The thickness of the oxide dielectric of 60 % of the detectors on each panel was 0.4 microns; it was 1.0 microns for the remaining 40%. Pre-flight calibration indicated that the sensors lower limits of detection, for hypervelocity particles, were roughly 0.2 microns and 0.5 microns diameter, respectively[2]. The upper hypervelocity particles, were roughly 0.2 microns and 0.5 microns diameter, respectively[2]. The upper detection limit for both types (representing the particle size expected to physically break the detector substrate) was 100 micron in diameter. Identical detectors were flown on Explorer 46 (the Meteoroid Technology Satellite - MTS) in 1972.

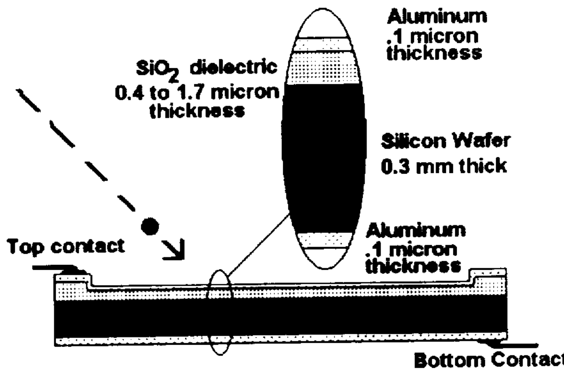

Figure 1. Cross-section of typical MOS impact detector. The IDE sensors used 0.4 and 1.0 micron thick dielectric.

An on-board tape recorder was included to record the time of each impact, identified by panel and by wafer thickness, but not by specific detector. The time resolution of the IDE clock was about 13.1 seconds. About every 2.4 hours, there was also a dump to the tape of the status (illuminated or dark) of six sun sensors, the status (active or shorted) of each detector, and other "housekeeping" information. Sunrise and sunset information from the sun sensors allowed calibration of the IDE clock. IDE activation occurred at 1984 April 07d 17h 23m 43.8s ± 0.3s UTC.

Tape was only supplied for the nominal nine-month mission, and it ran out on day 346. Post-flight verification shows that there was only one recording anomaly during this time and no significant data were lost. About 15,000 impacts were recorded on the 459 detectors during the active phase of the mission. For the remaining 4.7 years of flight, the detectors continued to receive impacts which left physical craters, but no time-resolved information was recorded.

2. TIME-RESOLVED DATA

Much of the information on orbital debris and cosmic dust in the near-Earth space environment has come from the examination of surfaces recovered after exposure in orbit[3,4,5]. While such information has provided valuable information on mean fluxes, it has been deficient in detailing the near-Earth micrometeoroid and space debris environment in two crucial ways. First, most of these spacecraft have not maintained their orientation in an Earth-centered reference frame. Thus the measured fluxes have been averaged over a range of directions relative to the orbital velocity vector and to the celestial sphere. Second, since the time of occurrence of each impact cannot be determined, it is not possible to investigate variations in particle flux with position and time; that is, spatio-temporal information cannot be obtained from such data analysis.

In contrast with these earlier studies, the controlled orientation and high time resolution of the IDE data provide, for the first time, a detailed, extensive data set well adapted to analysis of the spatio-temporal characteristics of orbital debris in near-Earth orbit. An examination of the IDE data

(«B_Ref287584489 * mergeformat ») shows immediately that the detected particle fluxes were neither uniform in time nor in space. All impacts on the 0.4 micron IDE detectors are displayed in this "seismograph" plot. The entire 346-day active data recording phase of the mission is represented along the horizontal axis. The impact rate on each of the six orthogonal surfaces is indicated by the vertical amplitude of each trace. Note that the impact rates represented in this figure are raw rates, uncorrected for effective area. This does not significantly change the appearance of the plot.

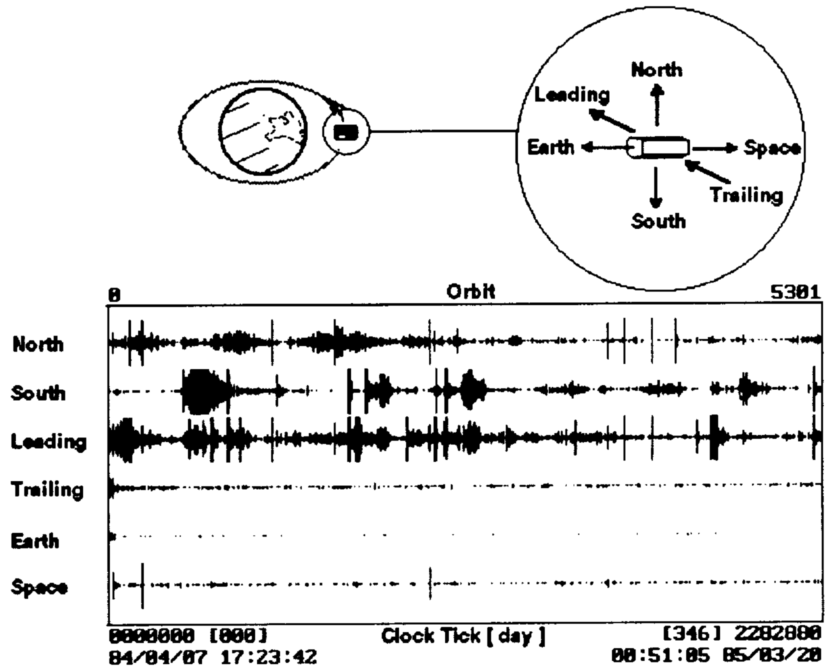

Figure 2. All impacts recorded on the 0.4 micron dielectric thickness (high sensitivity) IDE detectors during the 346-day time-resolved phase of the mission.

Examination of «B_Ref287584489 * mergeformat » suggests a number of interesting points:
•· activity on the northward and southward facing surfaces was very different,
· all surfaces except trailing and Earth exhibited occurrences of short transient "spikes",
· the north, south, and leading edges exhibited extended periods of increased activity which were unseen on the other three surfaces,
the trailing edge, which should be shielded from orbital debris by the body of the spacecraft, showed most of its activity during the early portion of the mission,
· and the Earth facing surface (which should be very well protected by the proximity of the Earth) also showed activity during the first week of the mission.

The activity shown on the trailing edge and the Earth end is almost certainly due the shuttle orbiter. It is well established that the shuttle will be surrounded by a "Spacecraft Induced Atmosphere"[6]. The orbiter moved away from LDEF almost immediately after deployment, partly to avoid contaminating LDEF. The (approximately) one week duration of the impact activity seen on the shielded surfaces of LDEF suggests that a significant amount of material was distributed by the shuttle in orbits which allowed "catching up" with the LDEF from behind and from beneath.

3. MULTIPLE ORBIT EVENT SEQUENCES AND SPIKES

Closer examination of the data shows that in addition to being non-uniformly distributed in time, the IDE impact data are non-randomly distributed in both time and space. In Figure 3, a portion (taken from the leading edge high sensitivity detector data) of the IDE data set is examined at increasing time resolution. The upper trace in this figure represents the same information as the leading edge trace of Figure 2. The data of 4 June 1984 are selected out and displayed in the middle trace.

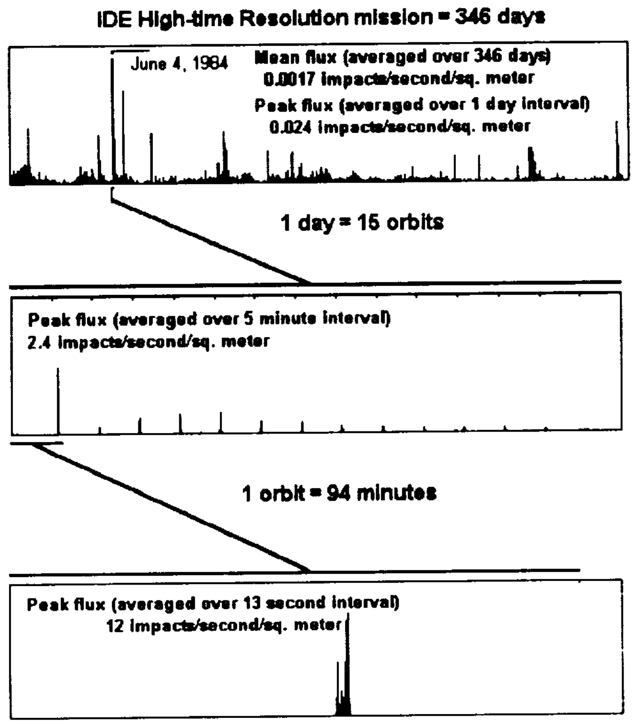

Figure 3. Observed activity on the leading (ram) edge of LDEF as recorded by the high sensitivity (0.4 micron dielectric) detectors of IDE. Note that **every** impact is displayed. The lack of impacts between the obvious events is real.

The regular spacing of the impacts matches the LDEF orbital period of approximately 94 minutes. The final trace of this figure displays a single 94-minute segment of the 4 June data. All the impacts during this segment occurred during a period of less than five minutes. As may be seen in these figures, the IDE data set contains many impacts which occurred in "bursts", during which numerous impacts were recorded in a short time. Such a burst we have designated an event. At the finest resolution, events may show structure. For example, the 4 June event illustrated here appears to be double. A number of these multi-event sequences appear in the IDE data set. As illustrated in Figure 3, events may be seen to reoccur each time the LDEF returned to the same point in its orbit. These we call multi-orbit event sequences (MOES).

A significant conclusion resulting from the high time resolution of LDEF IDE data displayed in Figure 3 is that the instantaneous fluxes observed are much greater than the mean fluxes. As shown in the text imbedded in the figure, the mean flux calculated from the 346-day data set is 0.0017 impacts/second/sq. meter. The peak flux, observed with the IDE time resolution of 13 seconds, was 12 impacts/second/sq. meter, almost 4 orders of magnitude greater! While long-term fluxes may be useful for engineering structures and similar purposes, there are circumstances where peak fluxes may be more useful. The IDE results indicate that an optical surface such as a window (which could be degraded by small particle impacts) could need replacement far sooner than would be predicted by mean fluxes.

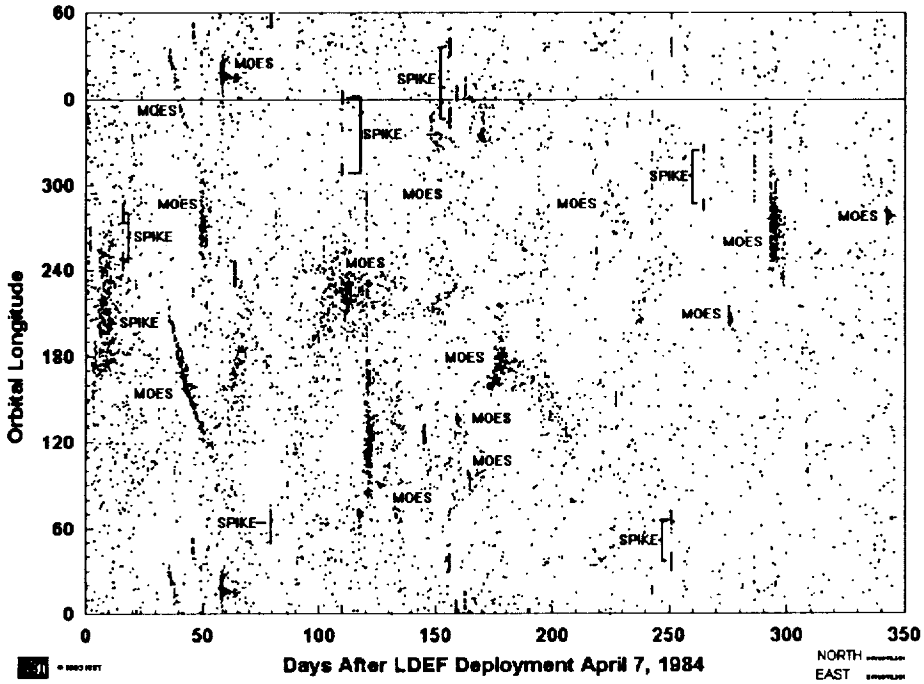

Figure 4. Impacts on the high activity surfaces as a function of LDEF orbital position and time for the 346 day time-resolved data set. Note that the orbital longitude axis partially repeats at the top.

While the structure of an individual MOES is illustrated in Figure 3, the distribution of the observed MOES with orbital location and time is best illustrated in a plot such as Figure 4. In this figure, all impacts on the high sensitivity detectors mounted on the North, Ram, and South LDEF surfaces are plotted as a function of LDEF orbital longitude and time. A number of MOES are indicated. Also indicated are "spikes", defined as sudden bursts of impacts which occurred on only a *single* orbit. These spikes were the most intense individual events observed by IDE. In addition to their lack of multiple-orbit repetition, spikes differ from the events of an MOES by frequently appearing as pairs of events, separated in orbital longitude by 10 to 30 degrees. This "bifurcated" structure of spikes is visible in Figure 4.

Most of the 15,000 impacts recorded by IDE occurred in MOES. It is natural to assume that such events result from the intersection of the orbit of the LDEF with that of a concentration of orbital debris. An examination of a typical MOES (*e.g.* the June 4 event shown in Figure 3.) shows two important characteristics:

1) the orbital debris particle orbits are eccentric; if they were circular, the IDE detectors would register the group twice each orbit since a circular orbit *must* intersect LDEF's orbit (which is essentially circular) at two points, and

2) the particles must be "smeared out" along the orbit in some ring-like or torus structure. If the particles were concentrated in a "clump", the encounters with LDEF would not occur over an extended sequence of consecutive orbits, unless the period of the particle orbit was the same as that of LDEF, an unlikely circumstance in general.

In order to deduce as much as possible about the orbit of the impacting particles in an MOES, we have developed the "method of differential precession".[7] The goal of this method is to obtain the orbital characteristics of the particles which struck the IDE detectors during a MOES by an analysis of the time variation of the LDEF position over the series of encounters. This analysis makes use of the fact that the non-sphericity of the Earth induces the pole of an object's orbit to precess, resulting in a cyclic change in the position of the line of nodes of the orbit (in the case of LDEF, the period of this precession is approximately 53 days). The oblateness of the Earth also causes the line of apsides of the orbit to precess, the point of perigee advancing if the orbital inclination is low and regressing otherwise. In general, bodies in different orbits will have different rates of these precessions, and should two of these orbits intersect, the differences in the precession rates will cause the point(s) of intersection to vary with time. If the characteristics of one of the intersecting orbits are known, the migration of the point of intersection may be used to determine the precession rates and orientation of the unknown orbit, which then may be used to calculate a family of candidate orbits.

4. DISTRIBUTION OF SPIKES IN TIME AND LOCATION

Spikes are not directly subject to analysis by the method of differential precession since, by definition, they appear to be single events (albeit bifurcated). Never-the-less, the observed spikes show interesting patterns in their times of incidence that may yield useful clues as to their origin. Most spikes occurred on the North and Ram LDEF surfaces. Three spikes occurred primarily on the Space surface. Virtually no spike activity was visible on the South surface.

A plot of all spikes observed on the North LDEF surface as a function of the sub-LDEF terrestrial latitude and longitude is shown in Figure 5. These events were almost all concentrated above the northern hemisphere, and between longitudes 80 and 200 degrees east. An examination of launch activities has shown no correlation between Soviet or other launches and the occurrence of spikes.

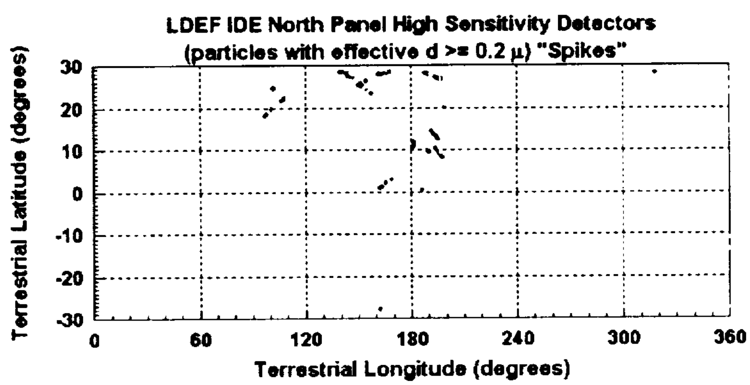

Figure 5. Location of LDEF ground track (sub LDEF terrestrial latitude and longitude) during spikes.

In the process of studying the event times of spikes, it was realized that many, especially those that exhibited bifurcation, appeared to have a 15.5 day periodicity (see Figure 6). This could be explained if the source of the spikes was a highly concentrated clump of material in an orbit whose beat frequency with LDEF was 15.5 days. Unfortunately, the short lifetimes of micron sized orbital debris particles does not allow such a clump to have a lifetime measurable in days, much less months. It appears more likely that the spikes result from material leaving some long-lifetime orbiting object. Again, this hypothetical source object must have an orbit which has a 15.5 day beat frequency with LDEF. One possibility that we have examined is the Solar Maximum Mission satellite (SMM). SMM was in virtually the same orbit as LDEF, differing only in semi-major axis. After deploying LDEF in April, 1984, the shuttle Challenger then increased its altitude by about 20 km. and undertook the repair of the SMM. The beat frequency between the LDEF orbit and that of an object 19.3 km. above (or below) is 15.5 days. The spikes do not, however, coincide with the times of closest approach between LDEF and SMM, as calculated from the appropriate orbital elements. It seems likely, however, that material from SMM is involved in the IDE spikes. The terrestrial latitude and longitude concentration shown in Figure 5 would then presumably be a coincidence.

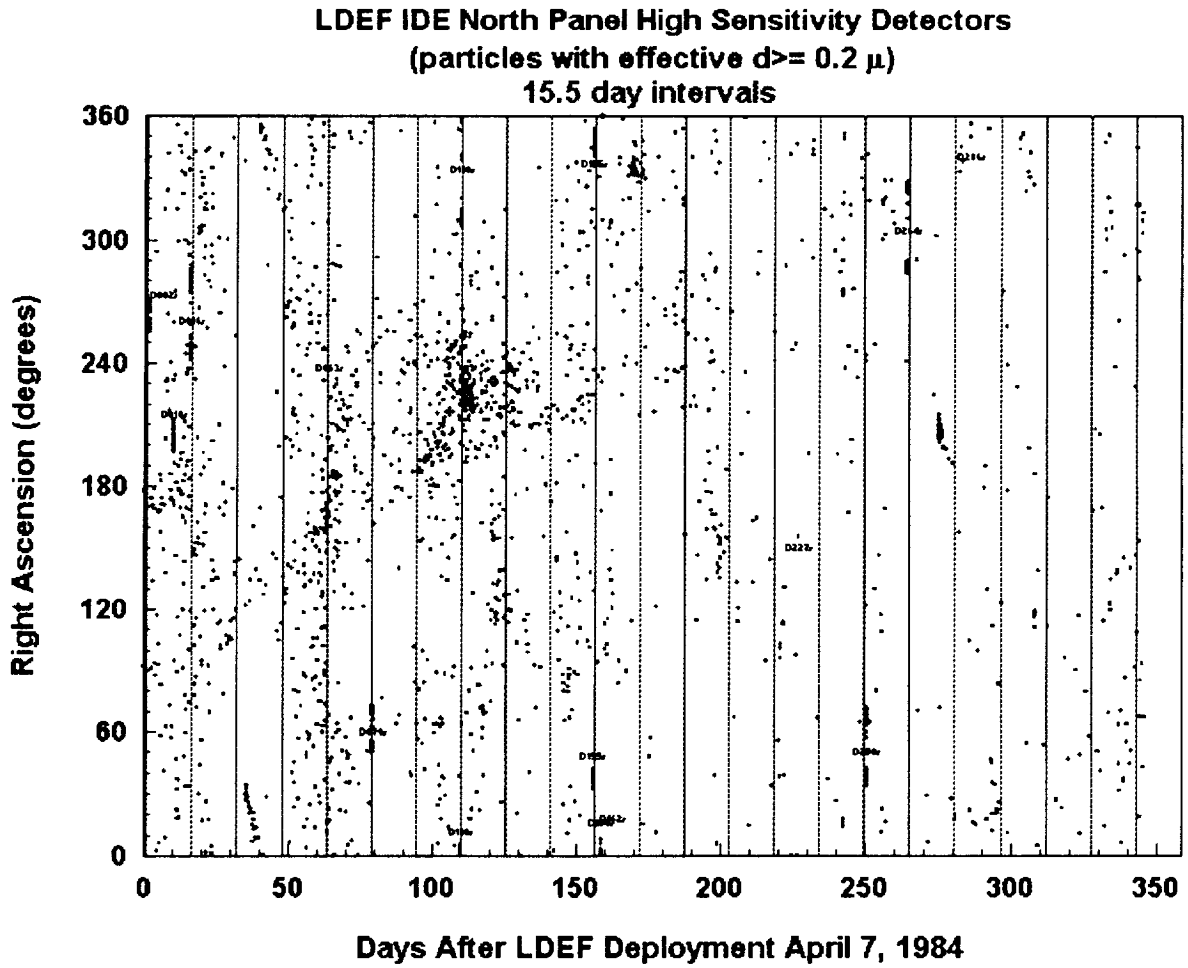

Figure 6. Spikes on LDEF North surface as a function of time. Note that many spikes occurred very near to some multiple of 15.5 days (as indicated by the vertical plot divisions).

5. SUMMARY

The LDEF IDE experiment detected many discrete events which can be associated with orbital debris. Indeed, the majority of micron sized particles detected by IDE were contained in the MOES debris cloud events. Many of these events were long-lived enough that they could be analyzed in terms of the impactor orbital elements. This longevity, in itself, suggests that much of the microparticle orbital debris environment results from material being released from longer-lived larger objects. Discrete events termed spikes were observed that may be the result of material released from the Solar Maximum Mission satellite.

6. ACKNOWLEDGMENTS

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