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IDE SPATIO-TEMPORAL IMPACT FLUXES AND HIGH TIME-RESOLUTION STUDIES OF MULTI-IMPACT EVENTS AND LONG-LIVED DEBRIS CLOUDS

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IDE OVERVIEW

The purpose of the LDEF Interplanetary Dust Experiment (IDE) was to sample the cosmic dust environment and to use the spatio-temporal aspect of the experiment to distinguish between the various components of that environment: zodiacal cloud, beta meteoroids, meteor streams, interstellar dust, and orbital debris. The experiment, as well as preliminary results, has already been described in some detail elsewhere [ref. 1]. Six panels of detectors were carried on orthogonal faces: Earth, Space, East (ram, or leading edge), West (wake, or trailing edge), North and South faces. Each panel contained detectors with two different sensitivities. Approximately 60% of the detectors on each panel were the more sensitive type (0.4 μm dielectric thickness, refered to as "4"), while the remaining 40% were the less sensitive variety (1.0 μm dielectric thickness, refered to as "10"). Preflight calibrations indicated that the sensors' lower limits of detection, for hypervelocity particles, were roughly 0.2 μm and 0.5 μm diameter, respectively. The upper detection limit for both types of sensors was estimated to be particles approximately 100 μm in diameter. This represents the particle size that would physically break the detector substrate.

The use of the word "spatio-temporal" invokes the fact that, unlike most LDEF (or other) cosmic dust experiments, IDE provides both directional and precise time information on the near-Earth particulate environment. The fact that the collected data appear to contradict the conventional view that impacts occur on a spacecraft in low Earth orbit at a relatively constant rate lends a strong support to the idea that there **must** be an IDE type follow-on to LDEF. We will show that all conventional models of the orbital debris environment are grossly wrong in their predictions of the day-to-day flux.

The flight data were recorded on magnetic tape, which ran out after 49 weeks (thus exceeding the 9-month nominal mission duration). Recorded data include the time, panel, and type of detector for each impact; plus periodic detector status checks, LDEF sunrise time, and various other "housekeeping" items. The time resolution (i.e. clock tick) was 13.1s. More than 15000 impacts were recorded on the 459 detectors in 346 days [Table 1]. On the high-activity panels (East, North, South), the time history was extremely episodic [Figure 1].

The first lesson of this experiment is that the particulate environment at 500 km is extremely clumpy, and this has some profound implications with respect to orbital operations of impact -sensitive surfaces.

Sunrise data permitted a precise calibration of the spacecraft clock. IDE activation occurred at 1984 April 07d 17h 23m 43.8s ± 0.3s UTC. The difference between nominal and observed clock rate amounted to several orbits over the full mission. The estimated accuracy of any individual epoch is ~ 15-20s.

IMPACTS vs. FLUX

Impact counts and times are the real observations in IDE. Areal fluxes must be inferred from a knowledge of active detector area. With the exception of the West 4 set, all detector groups suffered permanent loss of one or more detectors during the course of the mission. The South 4 set, the second hardest hit, eventually lost 16 detectors (33%). This attrition must be accounted for in calculating fluxes. There appears to have been significant hypervelocity impact contamination by the "Shuttle Induced Atmosphere" [ref. 2] during the first few days of the mission. The first 8 days (2.4% of the mission) produced 36% of the mission hits on the Earth 4 set, 14% on West 4, 9% on Space 4, and 5% on East 4 & 10. An interesting detail is that many of the West hits were at slightly less than half an LDEF orbit period after a swarm of East impacts; we seem to have observed the effects of an eccentricity in the Shuttle contamination cloud orbit. For our analysis, we wish to distinguish between a "space environment" and a "spacecraft environment", and the evidence is that manned spacecraft produce their own extremely dirty local neighborhood. We have consequently omitted the first 8.2 days from our data set. We present here [Table 2] the first-order estimate of the areal fluxes for LDEF, based on a linear approximation to the detector failure history.

BETA METEOROIDS

Several interplanetary spacecraft have reported anomalous concentrations of very small cosmic dust grains coming from the general direction of the Sun [ref. 3]. This has been interpreted as evidence for "beta meteoroids", grains so small that, after release from a parent body, they experience a radiation pressure sufficient to modify the apparent mass of the Sun [ref. 4]. Variational analysis shows that the new orbit of the particle is Keplerian, but with increased eccentricity, semi-axes, semi-latus rectum and apsides. If the particle is sufficiently small, the new orbit is parabolic or even hyperbolic, and the particle escapes the solar system. Escape orbit or not, conservation of angular momentum requires that the speed decrease for some range of distances < a_o, increasing elsewhere, depending on release circumstances.

In the LDEF context, West panel should see beta meteoroids near sunset, East near sunrise, Space near noon. When plotted in sun-synodic coordinates, such as time since sunrise, both East and West show strong beta signatures. It appears that West is perhaps even dominated by particles from the solar direction [Figure 2]. The beta phenomenon is not episodic, but persists throughout the year as a broad, diffuse band tracking the Sun in right ascension (Figure 3.). This is apparently the first detection of beta meteoroids from low Earth orbit.

METEOR STREAMS

One of the major original goals of the experiment was the spatio-temporal exploration of meteor streams. Consequently, virtually the first task was to begin a survey of the impact record around times of known meteor showers.

The April Lyrids came only two weeks after launch, but the IDE data around that date provided a surprise: two enormous surges separated by 6 days [Figure 4]. The event of 17 April shows impacts nearly evenly divided on North and East, with essentially none on the other 4 panels. This is almost surely a debris event, but identification requires further study. The event of 23 April falls right at the time of Lyrid maximum. The hourly rate is >100 times the mission mean on both North and Space, with few on East and none elsewhere. Over several days, even North and Space were inactive at times when they could not see the Lyrid radiant. We have been tempted to call this a meteor stream event, but there are problems with this interpretation. The event is too sharp and too strong, and there was a spacecraft launch (1984-041) the preceding day. The bifurcated nature of the burst (see below) may be characteristic of debris events. On the other hand, even with this event removed from the data, there seems to be an increase in the background flux during this period. Other events have been located in the near vicinity of other meteor showers. This does not imply detection and confirmation. A definitive discussion of meteor stream activity cannot be carried out until a "sanitized" data set is produced, with identifiable debris events removed.

MEAN FLUX *vs.* EVENTS, SEQUENCES and CLOUDS

The mean fluxes given in Table 2, lacking a temporal component, do not describe the true nature of the particulate environment very well. The IDE impact record is not a random scatter diagram. It is so clumpy that long-term averages may be primarily useful for predicting mean equipment lifetimes [see Figure 1]. We are in the process of compiling a comprehensive catalogue and atlas, for which we propose the following terminology:

- Each individual detection is an *impact*, and a detection not obviously a member of a larger class is an *isolated impact.*
- Detections often occur in bursts, during which numerous impacts arrive within a short time at a rate well above the surrounding flux. We designate this as an *event.* Obviously, this is a subjective definition that depends on the time resolution with which one looks at the data. With hourly resolution, Figure 4 shows two events.
- At finer resolution, the 23 April event is bimodal and can be considered as two related events [Figure 5]. We shall call several apparently related events a *multi-event sequence*. Many of the bursts that we see in the data have similar bimodal structure to that of the 23 April encounter, and this may be a clue to understanding the spreading of orbital debris clouds.
- We find several instances of events separated by low-order multiples of one-half the LDEF orbital period. These we will call *multi-orbit event sequences* . This phenomenon has already been mentioned in the context of the Shuttle contamination event. Figure 6 shows a sequence of at least 25 events spread over about 1.6 days (4-5 June 1984), at intervals of one (or occasionally two) LDEF orbit(s).

A multi-orbit event sequence can only occur if the particulates are themselves in Earth orbit, intersecting that of LDEF. Each time that LDEF comes back to the same place in its orbit, it hits the same cloud, again and again and again. We are sampling chords through this cloud, time after time, over a day and a half. This rules out serious consideration of extraterrestrial origin. These are orbital debris clouds, and they can be seen clearly in 3-dimensional (two angles and time) representations [Figure 7]. Goldstein and Randolph (ref. 5) saw the same phenomenon, which they called rings, at larger particle sizes with groundbased radar in 1989; within the limitations of the two observation sets, a ring is only a particular type of cloud, and the data do not permit an experimental distinction.

Multi-orbit event sequences -- debris clouds (or rings) -- comprise a major fraction of the particulate environment seen by IDE. The first six clumps that we identified contain about 25% of all impacts recorded during the mission. The "May swarm" and the 4-5 June event together contain more than 80% of all impacts recorded during those two months. The first pass, alone, on 4 June contained 131 hits in about 2 minutes, 0.8% of the mission impacts in 0.0004% of the duration of the mission, 3 orders of magnitude above the average flux. The spacecraft whose instruments are subjected to such an encounter during the first weeks of its mission will experience a drastically enhanced rate of impact induced degradation over that predicted (and planned for) based on the assumption of a random distribution of impacts with time. One of the major lessons to be learned from the IDE data , and hence from the LDEF, is that orbital debris is far from isotropic, unlike the assumptions of most current models.

More sophisticated analysis of the June 4 multi-orbit event sequence may extend the sequence, and indeed Figure 6 suggests that it was longer than1.6 days. We suspect that the same cloud was re-encountered about 54 days later, after a full LDEF precessional rotation. Since the sequence begins near the equator, there are two possible ways to use precessional dynamics to infer information on the orbit of the dust cloud. The most direct way is to determine the slope of the locus of events in right ascension-declination space [N.B. to non-astronomers: right ascension is the celestial equivalent of terrestrial longitude, but measured from the equinox; declination is identical with terrestrial latitude]. It is clear from Figure 7 that the locus crosses the equator at about 30° right ascension, and that the angle of the locus is about 70°. That is only approximately the inclination of the cloud orbit, since both orbits are precessing backwards along the equator at rates determined by their inclinations [Figure 8]. A relatively simple iterative calculation will give the true orbital debris inclination since the inclination of the LDEF orbit is known.

The other approach begins with the re-encounter, which can only occur after a precessional beat period of the two orbits. In principle, this permits calculation of the cloud's precession period, from which a determination of the orbit inclination can be made. This then permits a geometric calculation of the node from mutual geometry with LDEF's orbit. When both approaches are possible, they are complementary and can provide a consistency check on the results. Analysis of this striking event is not yet complete, but the ascending node is definitely about 30°, inclination in the range 70-85° (i.e. near-polar). We are looking at candidate sources. By contrast, the "May swarm" appears to have a moderate (~30-35°) inclination, but the equator crossing is probably indeterminate from these data.

NATURAL COSMIC DUST vs. ORBITAL DEBRIS: WHICH DOMINATES THE ENVIRONMENT?

The total number of artificial Earth satellites in orbit is growing exponentially, and it is an important question to know how this affects the particulate environment. Related to this issue are the relative proportions of artificial and natural material that together compose that environment. From the LDEF Interplanetary Dust Experiment data, Singer *et al.* [ref. 1] argued that the ratio of transverse flux (mean of North and South panels) to Space panel flux, coupled with kinematic constraints, suggests a ratio of artificial to extraterrestrial particulates of about 5:1. That conclusion has not been changed by the use of mean fluxes from Table 2, replacing the raw counts of Table 1. Taking foil penetration thickness at minimum particle diameter as equivalent to IDE dielectric thickness, we obtain a ratio of about 4-6:1 from a comparison of the IDE East panel fluxes with an extrapolation of the interplanetary component predicted for that panel [e.g. ref. 6].

By contrast, it is commonplace to encounter the statement that cosmic dust predominates. Which view should prevail? An examination of the East panel predictions cited above shows that the statement is oversimplified. McDonnell shows clearly that current models predict that natural cosmic particulates should dominate strongly for sizes (d) > 100 μm, but should only slightly exceed debris for 100 μm > d > 25 μm. Man-made matter strongly dominates for d < 20 μm. This latter is the range that forms the bulk of IDE impactors.

Another element in the argument is highlighted by the discovery of multi-orbit event sequences and their characterization as orbital debris clouds. The comprehensive catalogue of IDE events and sequences is not yet available, but it is clear that clouds contain an important fraction of all the impacts detected. In addition, the direction distribution of flux makes it clear that the majority of these particulates are in Earth orbit. Even if one wishes to postulate an *ad hoc* ring of captured comet and asteroid dust [ref. 6, ref. 7], there is no convincing way to construct something like the May swarm. The clouds must be orbital debris.

The evidence supporting the idea that the debris population density has not changed over the years is based primarily on the use of 1963 data [ref. 6, Figure 3], which exerts a long lever arm over a 15 year empty gap. If only the spacecraft data since 1970 are used, the debris levels arguably track the exponential growth of the satellite population, at least within the error bars on the data.

By contrast, the IDE West fluxes, which should contain essentially no debris after removal of the initial Shuttle contamination event, are higher than an extrapolation of McDonnell's predicted trailing edge curve by a factor of 3.3. This might be explained if the prediction contained no beta meteoroid model. If that were indeed the explanation, then IDE suggests a beta meteoroid flux of about 7×10^{-5} m^{-2} s^{-1} at both sensitivity levels.

CONCLUSIONS

There are several major lessons to be drawn from these results, even though we are far from having exploited the IDE data to their fullest:

- The introduction of precise time and even rudimentary directionality as colateral observables in sampling the particulate environment in near-Earth space produces an enormous qualitative improvement in the information content of the impact data.
- The orbital debris population is extremely clumpy, being dominated by persistent clouds in which the fluxes may rise orders of magnitude above background. This aspect of the environment cannot be reflected in any model based on isotropic assumptions.
- The unexpectedly intense temporal aspect, and the fact that these data are already 7 years old, lend support to the idea that there should be a follow-on IDE type experiment to obtain updated information and to test the secular trend in the debris population.
- The IDE data suggest a strategy to minimize the damage to sensitive spacecraft components, using the observed characteristics of cloud encounters. Such a strategy based on an observing program that we designate SYNMOD (Synoptic Monitoring of Orbital Debris) and incorporating either automatic or interactive instrument control, will be detailed in a future publication.

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Table 1. LDEF/IDE Impact Totals and Directional Ratios from April 1984 through March 1985. **Trans** denotes transverse (mean of North and South). Standard deviations are estimates based on the square-root of the number of hits. **N.B.**: The ratios are to be considered as **impact ratios** only. Ratios involving the Space panel have been normalized to reflect the smaller number of sensors on that panel.

LDEF Face	0.4 μm counts	# of sensors	1.0 μm counts	# of sensors
Earth	44	48	29	32
Space	380	35	155	24
North	2467	48	1081	32
South	3029	48	1200	32
East (Ram)	4540	48	1542	32
West (Wake)	455	48	186	32
Total Hits:	10915	275	4193	184
	Ratio	**Std. Dev.**	**Ratio**	**Std. Dev.**
Space/Earth	11.7	1.8	7.2	1.4
North/Space	4.8	0.2	5.2	0.4
South/North	1.2	0.03	1.1	0.05
East/West	10.0	0.5	8.3	0.06
East/Trans	1.8	0.04	1.4	0.05
Trans/West	5.4	0.3	6.1	0.5

Table 2: Preliminary mean flux values for the 338-day period beginning 1984 April 16d 0h UT, based on a first-order evaluation of the time history of active sensor area. The first 8.2 days of the mission have been omitted to eliminate the effects of Shuttle contamination, which was particularly severe on the Earth, Space, and West panels. Estimated errors are subjective.

	Sensors	# of hits	Ave. # of sensors	Ave. area (0.001 m^2)	Flux ($m^{-2}s^{-1}$)	+/- %	ratio 0.4μm to 1.0μm
Earth	0.4μm	28	45.5	89.3	.000011	20	0.7
	1.0	29	31.5	61.9	.000016	20	
Space	0.4	347	34.5	67.7	.00018	5	1.6
	1.0	150	23.5	46.1	.00011	5	
North	0.4	2408	45.0	88.4	.00093	10	1.5
	1.0	1077	30.0	58.9	.00063	10	
South	0.4	3012	40.0	78.5	.0013	20	1.9
	1.0	1198	30.5	59.9	.00069	10	
East(Ram)	0.4	4308	44.5	87.4	.0017	10	2.0
	1.0	1470	30.5	59.9	.00084	10	
West(wake)	0.4	391	48.0	94.2	.00014	5	1.4
	1.0	183	31.5	61.9	.0001	5	

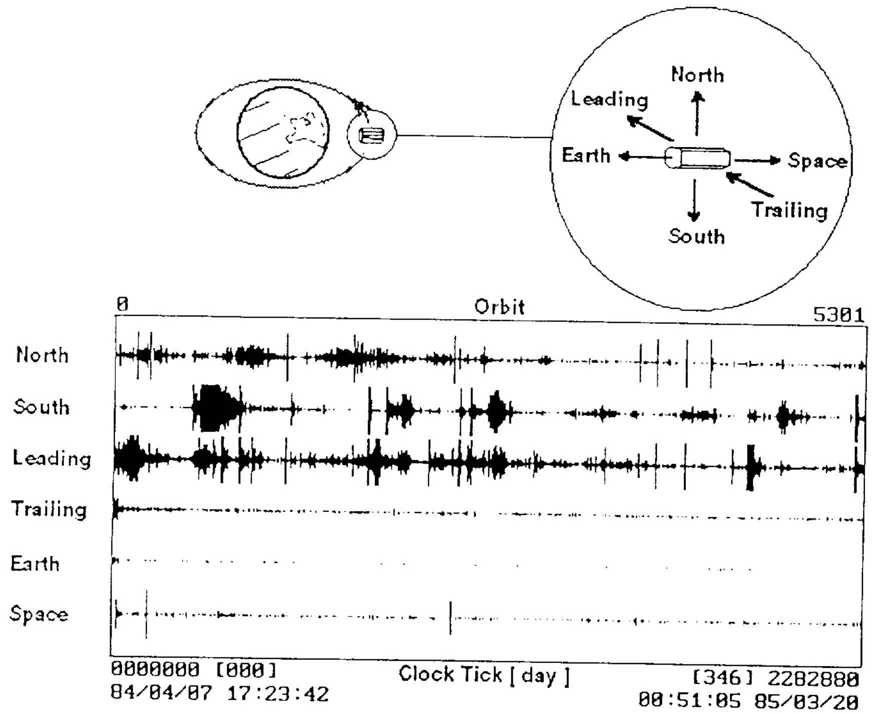

Figure 1: Time history of impacts on the 0.4μm panels over the entire 346 day period of active IDE data recording. In this "seismograph" plot, the vertical extent of each trace indicates the impact rate as a function of time. The display has been truncated in the vertical direction in the most active portions to avoid overlap between adjacent traces.

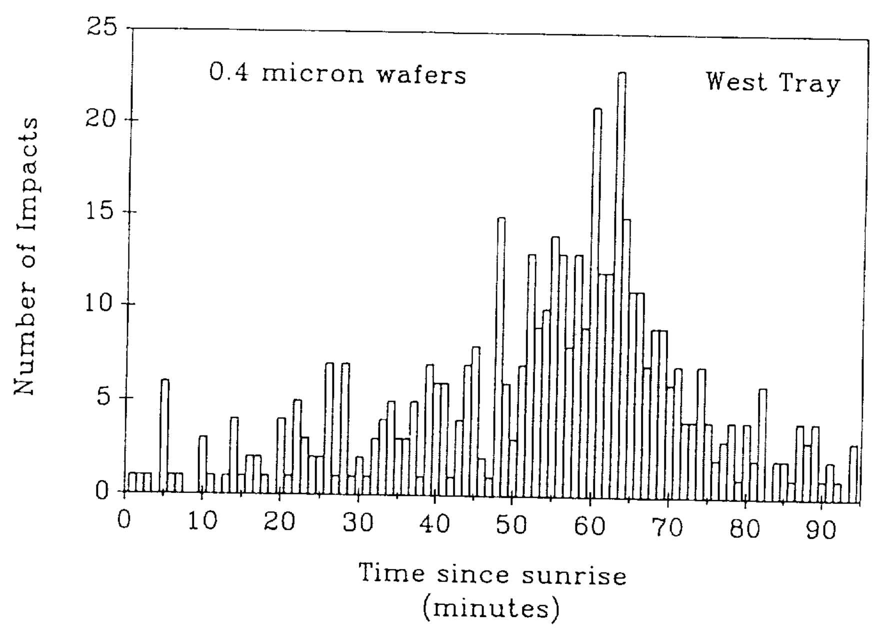

Figure 2: All 0.4μ data from West (trailing edge) panel plotted to show day-night asymmetry. West panel will most nearly face the Sun at evening quadrature, about 53 min after sunrise; sunset is about 6 min later. The 1.0μ data show the same features.

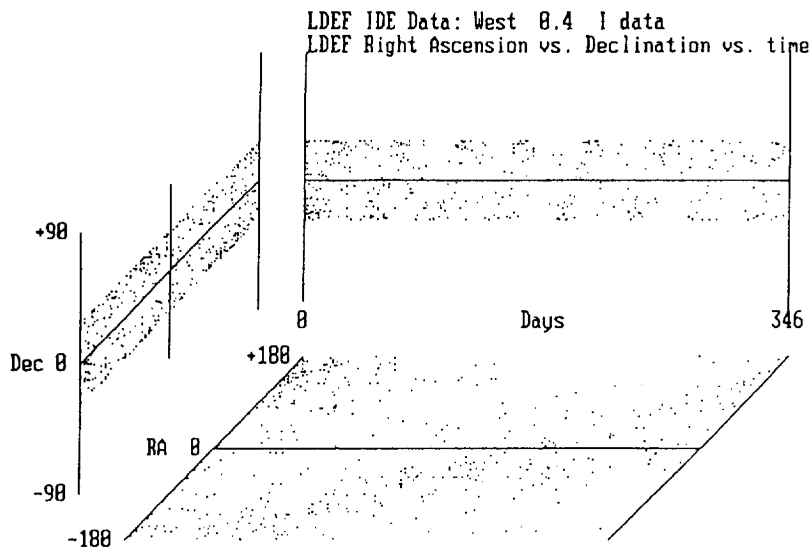

Figure 3: Three-dimensional (two angles and time) view of the sky as seen by the high-sensitivity trailing edge detectors. The RA *vs.* time plot clearly shows a large fraction of the impacts in a broad zone that tracks the Sun, with zero crossing in mid-December. Most of the West panel impacts came from near the solar direction, consistent with an important beta meteoroid population.

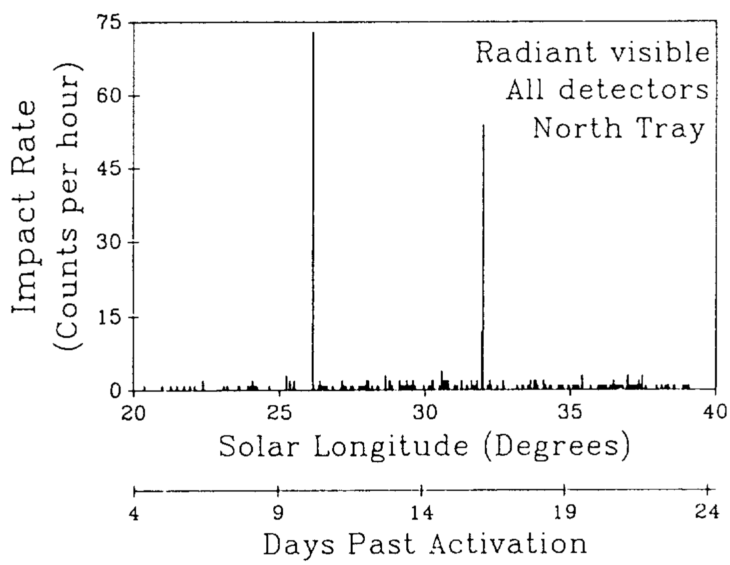

Figure 4: Apparent hit rate (counts/hr) in the vicinity of the April Lyrid meteor stream, North panel. The time of the Lyrid maximum corresponds to the later spike (23 April); that 6 days earlier is surely a debris event. Both are remarkable by their sharpness, and by the high values (10 and 14 respectively) of the detection ratio 0.4μm/1.0μm, suggesting a preponderance of submicron particles. The North flux averaged over the entire mission was roughly 0.5 impacts per hour.

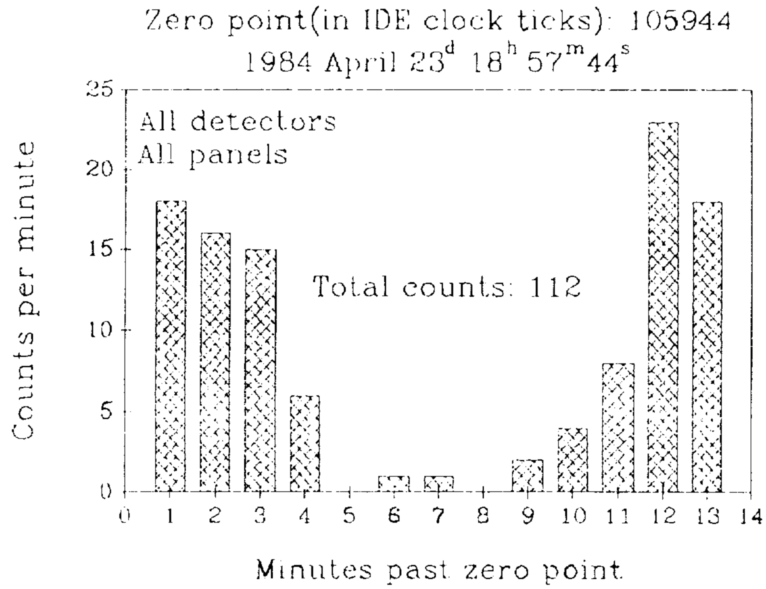

Figure 5: This is the postulated "Lyrid" event of Figure 5, but binned by minutes. It is clearly bimodal, and can be considered as two separate but related events.

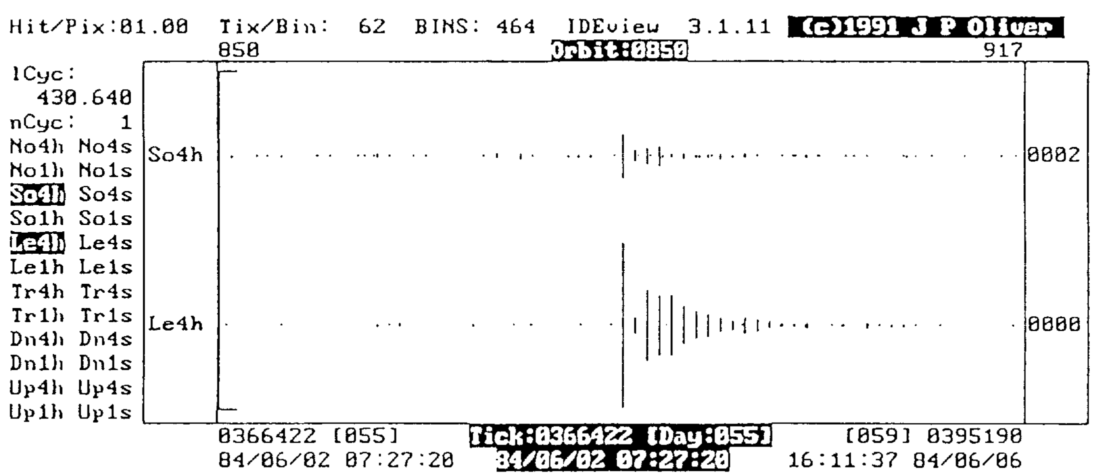

Figure 6: The "June 4" multi-orbit event sequence. Each time LDEF moved southward across the equator, it encountered a cloud of particles rising northward in a different orbit. These collisions took place on at least 25 passages through the descending node over the course of 1.6 days. Only East (and to a lesser degree South) were hit. The first event in the sequence contained 131 impacts, or 0.8% of the mission total, in less than 2 minutes.

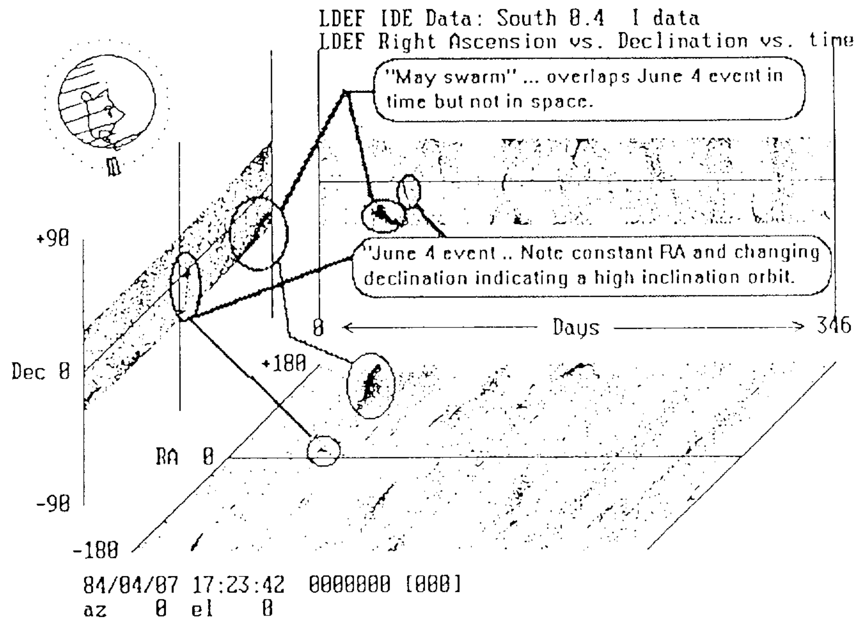

Figure 7: This 3-D plot shows all impacts recorded on the South 4 set of IDE detectors during the active phase of the mission, in right ascension-declination-time space. Clearly, a large fraction of the impacts recorded are grouped in highly episodic events and sequences, implying clouds of material in Earth orbit. Two specific examples are annotated.

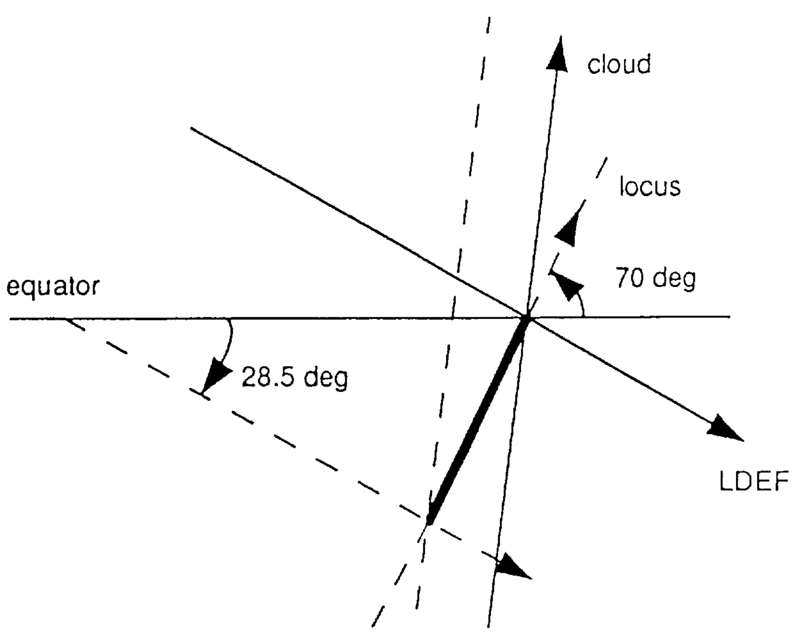

Figure 8: Both the spacecraft and the debris cloud are precessing backwards along the equator, at rates determined solely by the inclinations of their respective orbits. The locus of events in the right ascension-declination plane of events in a multiple orbit sequence is a resultant of these two precessions, and the locus characteristics thus provide a means of iteratively determining the orbital inclination of the dust cloud. The diagram shows the "ideal" case (satisfied by the 4-5 June sequence) of a locus in the equatorial zone.