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ORBITING PARTICLE CLOUDS-- PROPERTIES, PREVENTION, AND PROTECTION

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ABSTRACT

A surprising result of the LDEF Interplanetary Dust Experiment (IDE) was the discovery of artificial debris in the form of orbiting clouds of micron-sized particles **[ref 1,2]**. A year's data from sensitive impact detectors gives some indication of the spatial and temporal distribution of the particles. The episodic nature and orbital properties of the particle clouds provide some suggestions about their origin; but they also mandate the need for synoptic observations--from satellites of different altitudes and orbital inclinations--in order to better characterize the clouds **[ref 3]**. In particular, one would like to study the development of clouds following the initial event, and their decay as the result of drag and other non-gravitational forces. [An *APPENDIX* describes an estimate of the mass of a debris cloud.] With such data in hand one can then set up a sensible and effective program of *prevention*--although it is already fairly certain that the burning of solid rockets will discharge smoke particles into bound orbits that have an appreciable lifetime. Based on such studies it should then be possible to develop appropriate *protection* protocols that minimize the damage produced by particle clouds. While the impact of a micron-sized particle is not lethal to satellites or space stations, the resultant cratering can degrade their performance by spoiling optical surfaces, degrade the efficiency of solar cells, and change the emission characteristics of surfaces and thus disturb the thermal balance of the spacecraft. Synoptic data can be used to predict the occurrence in time and space of particle fluxes and the timing, direction, and intensity of impacts. With this foreknowledge it should be possible to take appropriate *countermeasures*--by changing the orientation of the spacecraft, or by interposing shields to protect sensitive surfaces, or by changing the schedules of certain operations, like manned extravehicular activity, that should not be exposed to additional hazards.

1. THE LDEF-IDE RESULTS

I want to concentrate my discussion on a new phenomenon, the orbiting particle clouds detected in the Interplanetary Dust Experiment (IDE) on the LDEF satellite. [The five display graphs below present the basic information on LDEF; the IDE; the experimenters; the IDE detectors; and a general summary of IDE results.]

Long Duration Exposure Facility

- Placed in Orbit April 7, 1984 by Space Shuttle Challenger
- Circular Orbit at 257 Nautical Mile Altitude, 28.5 Inclination
- Planned Mission Duration About 12 Months
- Actual Mission Duration, 69 Months
- Retrieved In December, 1990 by Space Shuttle Columbia
- Orbit Had Decayed By Retrieval; 179 Nautical Miles Altitude
- Gravity Gradient Stabilization; One End Always Towards Earth, One Side Always Forward in Orbital Direction

Interplanetary Dust Experiment (IDE)

- **Active, High Time-Resolution, Monitoring of Dust Impacts on the Long Duration Exposure Facility**
- **Time Resolution 13 seconds = 0.8° Orbital Longitude**
- **346 Days of Continuous Data Recording**
- **Detectors on Six Orthogonal Surfaces of LDEF**
- **Particle Size Discrimination Provided by High Threshold (>.5μ) and Low Threshold (> .2μ) Detectors**
- **More Than 0.9 Square Meters Active Detection Area**

LDEF Interplanetary Dust Experiment

- Instrument Flight Investigators:
  S. Fred Singer and John E. Stanley, Univ. of Virginia
  Jim J. Wortman, North Carolina State Univ.
  Phillip C. Kassel and William H. Kinard, NASA LaRC
- Data Analysis Investigators:
  Jerry L. Weinberg, J. Derral Mulholland, John P. Oliver and Charles G. Simon, ISST

  William J. Cooke and Nancy L. Montague, ISST

IDE Detectors

- Metal-Oxide Semiconductor (MOS) Capacitors
- Particle Impacts Vaporize Material, Cause Temporary Discharge
- Thin Dielectric = High Sensitivity to Small Particles

  0.4 micron thickness; Detected Particles 0.2 microns and Larger

  1.0 micron thickness; Detected Particles 0.5 microns and Larger
- Upper Limit to Particles Detected ≈ 100 microns
- Mix of Both Sensitivities For Total Area of 0.15 Sq. Meter Per Panel
- Panels Located On Leading (Ram), Trailing (Wake), Space, Earth, North, and South Surfaces of LDEF

Summary of IDE Observations

- 346 Days of Continuous Data
- More than 15,000 Impacts Recorded

	0.4μ	1.0μ		0.4μ	1.0μ
Ram:	4540	1542	Wake:	455	186
Space:	380	155	Earth:	44	29
North:	2467	1081	South:	3029	1200

- Impacts Extremely Episodic In Both Time and Space
- Peak Fluxes More Than 10,000 Times Mean Fluxes
- Impact Arrivals Not Randomly Distributed

We can reasonably assume that these are particles of micron size, as judged from the ratios of impact rates observed by IDE detectors of different sensitivities **[ref 1]**. These particles are almost certainly generated by human activity, perhaps by a rocket burn in low earth orbit (LEO). These debris particles are different from the orbital debris that has been discussed widely in the last few years, which consists of particles and objects large enough so they can be detected by ground-based radar or even by optical means from a spacecraft **[ref 4,5]**. [The display graph below summarizes the LDEF/IDE observations of debris clouds.]

Orbital Debris Clouds

- **Greatly Increased Impact Rates Localized In Time and Space**
  - **Events Occur Every 94.1 Minutes**
  - **Typical Event Duration; 3 to 5 Minutes (1500 to 2500 Km)**
- **Events Occur in Same Place Each Orbit**
  Relative Activity on Differing Surfaces
  May Yield Apparent Source Direction
- **Precession Allows Mapping In Space**
- **May 13th Swarm . . . ≈30° Orbital Inclination**
- **June 4th B Event . . . ≈65° Orbital Inclination**

The chief characteristics of the particle clouds observed by LDEF are their episodic nature and the high impact rates, thousands of times greater than the background. In other words, the clouds exhibited unusual spatial and temporal distributions that were not predictable. The LDEF detectors would traverse a cloud repeatedly before it "disappeared." The average IDE impact rate observed was 50 per day; most of the 15,000 hits recorded were associated with debris clouds **[ref 6]**. Similar phenomena have been reported from the Munich Dust Counter flown on the Japanese satellite HITEN (MUSES-A) **[ref 6]**. The average impact rate recorded was 0.5 per day, but varied by four or five orders of magnitude, indicating "groups" or "swarms," as found in previous experiments **[ref 7,8]**. But it was the high count rates and good statistics of IDE that allowed us to identify the existence of orbiting clouds.

My discussion is in three parts, the first dealing with the science, particularly the orbital mechanics, of these micron-sized debris clouds; the second, dealing with the effects of such clouds on spacecraft--both by impact and by light-scattering--and what one might do about this; the third, discussing the need for a better understanding of the occurrence and behavior of such clouds using synoptic surveys, such as the SYNMOD program proposed by our group.

2. ORBITAL MECHANICS

It should be immediately obvious that we are dealing here with a very complicated problem, since we cannot specify the source or sources of these particles. Ideally, we would like to know their mass distribution and also their velocity distribution at the point of their release, so that we can calculate their orbits and subsequent distribution in phase space, i.e. in the space around the earth and in velocity space.

In the absence of such information, we can resort to model calculations. We can assume, for example, that particles are emitted isotropically--either with a unique velocity or with a velocity distribution--from an object (say a spacecraft or rocket) in orbit about the earth. For sake of definiteness, let us assume that a particle cloud is emitted isotropically from a satellite in an inclined circular orbit. It should be apparent that all the particles contained within a certain "loss cone" will be immediately absorbed by the earth's atmosphere; only particles outside of the loss cone can survive.

The solid angle of the loss cone can be easily calculated, and depends on the altitude of the emitter and the velocity of the emitted particles. In the vicinity of the earth, the loss cone is very important; but by the time one reaches the geosynchronous orbit (GEO) the loss cone becomes unimportant--except in a certain restricted velocity range. [For derivation see **ref 10**.]

The fate of the particles that are outside of the loss cone depends primarily on the particle mass. For the larger particles, say of the order of tens of microns or greater, the lifetime may be long enough so that the particles are allowed to disperse along their orbit parameters, and are affected by the gravitational perturbation of the earth's equatorial bulge. As a result, we may end up with a cloud in the form of a toroidal "napkin ring" surrounding the earth. (Such dispersions have been studied in various model calculations **[ref 11]**; they also play an important role in theoretical solar-system astronomy where they have been used to discuss the origin of planetary satellites.)

Even more interesting is the fate of the smallest particles, say in the submicron range. Their lifetime is limited in the first instance by atmospheric drag, since they are sensitive to even the very low densities of the earth's exosphere. But as is well known, such particles are also subject to nongravitational forces--specifically, radiation pressure and electromagnetic forces, such as Coulomb drag **[ref 12,13,14,15]**. The general effect of such forces will be to reduce lifetime by forcing the particle orbit deeper into the earth's atmosphere. There could be exceptional cases where perturbations cancel each other in such a way as to increase lifetime--but these are rare. (One such possibility was discussed in 1961 **[ref 13]** in connection with the Westford experiment, which released a cloud of copper needles into earth orbit to test their utility for radio communication.)

3. EFFECTS OF PARTICLES ON SPACECRAFT

Oliver has discussed the optical effects of debris particles **[ref 16]**. By scattering sunlight as they pass close to a spacecraft, they could generate optical signals that can confuse optical sensors searching for and trying to lock in on guide stars, or performing other such search functions. Once we become aware of this possibility, however, it should be possible to design the spacecraft guidance system to ignore such optical perturbations. For the time being, it is necessary to gather more data about this phenomenon to that sensible precautions can be developed.

With respect to the impact of debris particles on the surface of spacecraft, and particularly on sensitive instruments, we should note that micron-sized particles of the kind we are discussing here would not normally disable the spacecraft. We are not concerned here with the problem of penetration or structural integrity. We are concerned, however, with the problems of scouring and erosion, which can change the optical and radiative properties of surfaces, and which can degrade the performance of optical surfaces used by scientific instruments.

A word of caution: It is quite possible that larger debris objects are released into the same or similar orbits in the generation event. In this case the micron-particle debris cloud can serve as an indicator and warning of the presence of a lethal-sized object.

The problem of *protection* divides into two parts: prediction and mitigation.

From general principles, one would predict that the relative (impact) velocity between a particle in an orbiting cloud and a spacecraft is of the order of the circular orbital velocity (whose square varies inversely as distance to the earth center). Flux is the product of concentration and the impact velocity; but damage relates (roughly) to the energy transferred in the impact **[ref 17]**. As a result, total damage depends on some high power, close to 3, of the orbital velocity--and therefore inversely as the 3/2 power of distance. This means that the greatest damage will occur for spacecraft in LEO and that damage in GEO should be much reduced. (Of course,the preponderance of debris sources further increases the debris flux close to the earth **[ref 18,19]**.)

Mitigation can best be done in response to knowing about the existence and properties of a particle cloud. In the absence of such knowledge, it is prudent to assume--in accord with LDEF data--that damage will be greatest on the leading surface of the spacecraft and least on the trailing and earth-facing surfaces. Shielding should therefore be provided on the leading surface. Optical surfaces should be properly placed and protected. This protection can take one of two forms: (1) permanent shielding by means of baffles, and (2) the use of moveable shields or shutters to be applied when the spacecraft enters the region of the particle cloud.

4. SYNOPTIC MONITORING OF ORBITAL DEBRIS (SYNMOD)

After examining the LDEF data and discovering the existence of debris clouds, it became immediately apparent that we needed a synoptic view of debris clouds. Fortunately, it is not necessary to have dedicated satellites flying at different altitudes and inclinations to obtain such a data base. The IDE instrumentation is simple and lightweight, and makes so little demand for power and telemetry, that it can be "piggybacked" on other satellites **[ref 3]**.

SYNMOD has been extensively discussed in the past two years and plans are afoot to fly the Orbital Debris Environmental Monitor (ODEM) instrument on a number of satellites designed for other purposes **[ref 20]**. The prospects look good, therefore, that in the next few years we will have a much better understanding of the occurrence of debris clouds--which in turn will give us a better means of avoiding their creation and protecting against their effects.

5. ACKNOWLEDGEMENTS

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The next launch of a spacecraft equipped with an array of MOS impact detectors is scheduled for January 1994. The OMDC (Orbital Meteoroid and Debris Counter) will fly aboard the Clementine-1 (DSPSE) transfer stage vehicle in a highly elliptic orbit, inclined at 67 degrees, with an apogee of 167,000 km and a perigee of 350 km. Orbital lifetime is anticipated to be 450 days.

7. APPENDIX: ESTIMATES OF THE MASS OF DEBRIS CLOUD

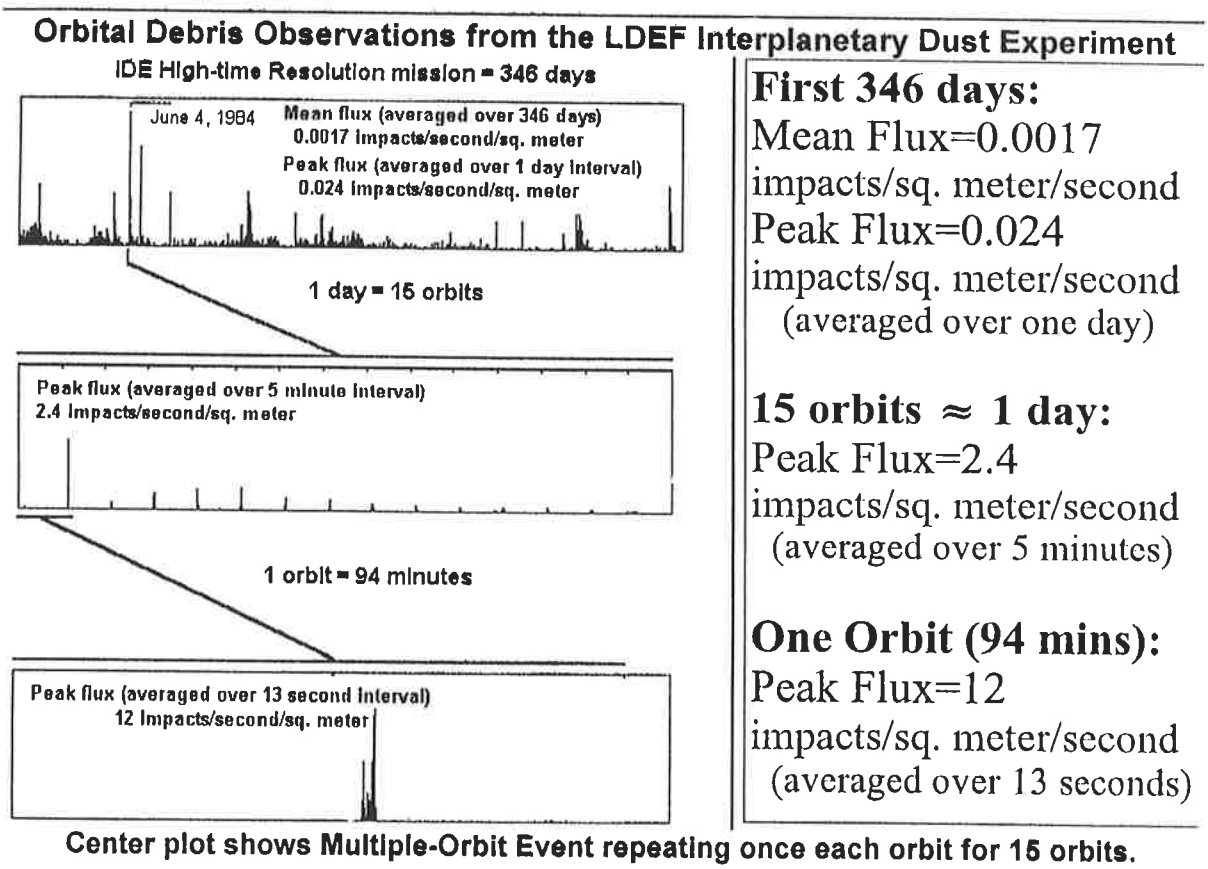
Even though there are not enough data to characterize the debris clouds encountered by LDEF, it may be useful to attempt some rough estimates of their mass. We will estimate the mass of the June 4, 1984, event [see display graph below], assuming that particles are shed from an orbiting object with low relative velocities:

1. Peak flux is of the order of 10/sq.meter/second. With an encounter velocity of about 10 km/sec, particle concentration is about 10^{-3}/cu.meter.

2. From the duration of the event and an LDEF velocity of 7 km/sec, we estimate minimum cloud volume as a ring of (2 pi)x(7000 km)x (1000km)x(10km), or about 4×10^{8}cu.km. Therefore, the peak number of particles is 4×10^{14}. A more reasonable estimate might be 10^{14}.

3. A 0.4-micron-sized particle has a mass of about 10^{-16} kg, so that the debris cloud mass is of the order of 10 gram.

4. Not knowing the altitude of release of the cloud and the initial distribution of particle velocities, we can only guess at the original mass; as an upper limit, assume an explosion at 800 km, a radial extent of 1000 km, and a loss cone of 80% of the solid angle. This would make the initial debris mass released about 500 times greater. This large uncertainty well illustrates the need for synoptic observations of the particle clouds.



Center plot shows Multiple-Orbit Event repeating once each orbit for 15 orbits.