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THE ORBITAL CHARACTERISTICS OF DEBRIS PARTICLE RINGS AS DERIVED FROM IDE OBSERVATIONS OF MULTIPLE ORBIT INTERSECTIONS WITH LDEF

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SUMMARY

During the first 346 days of the LDEF's almost 6 year stay in space, the metal oxide silicon detectors of the Interplanetary Dust Experiment (IDE) recorded over 15,000 impacts, most of which were separated in time by integer multiples of the LDEF orbital period (called *multiple orbit event sequences,* or MOES). Simple celestial mechanics provides ample reason to expect that a good deal of information about the orbits of the impacting debris particles can be extracted from these MOES, and so a procedure, based on the work of Greenberg[1], has been developed and applied to one of these events, the so-called "May swarm". This technique, the "Method of Differential Precession," allows for the determination of the geometrical elements of a particle orbit from the change in the position of the impact point with time. The application of this approach to the May swarm gave the following orbital elements for the orbit of the particles striking LDEF during this MOES: a = 6746.5 km; $0.0165 < e < 0.025$; $i = 66^\circ.55$; $\Omega_0 = 179^\circ.0 \pm 0^\circ.2$; $\omega_0 = 178^\circ.1 \pm 0^\circ.2$.

INTRODUCTION

For 346 days after the deployment of the LDEF satellite on April 7, 1984, the tape recorder belonging to the Interplanetary Dust Experiment (IDE) stored information on over 15,000 impacts made by submicron and larger-size particles on its metal oxide silicon (MOS) detectors[2]. These detectors were mounted on trays facing in six orthogonal directions — LDEF ram and trailing edge, the poles of the LDEF orbit (north and south), and radially inward (towards the Earth) and outward (towards space). The 13.1 second time resolution provided by the IDE electronics, combined with the high sensitivity of the MOS detectors and large collecting area (~ 1 m^2) of the experiment, conclusively showed that the small particle environment at the LDEF altitude of 480 km was highly time-variable, with particle fluxes spanning over four orders of magnitude[3].

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[1] Greenberg, R., *Orbital Interactions: A New Geometrical Formalism*, Astronomical Journal., **87**, pp. 184-195 (1982)

[2] "IDE Spatio-Temporal Impact Fluxes and High Time-Resolution Studies of Multi-Impact Events and Long-Lived Debris Clouds", J.D. Mulholland, S.F. Singer, J.P. Oliver, J.L. Weinberg, W.J. Cooke, P.C. Kassel, J.J. Wortman, N.L. Montague, W.H. Kinard, LDEF - 69 Months in Space: First LDEF Post-Retrieval Symposium, (NASA CP-3134), January, 1992, pp. 517-528

[3] See "LDEF Interplanetary Dust Experiment (IDE) Results", J.P. Oliver *et al.*, this volume.

It is highly desirable to learn as much as possible about the orbital characteristics of the particles which struck the IDE trays. At a minimum, these characteristics can determine whether the particles were interplanetary in origin or debris from a satellite or spent rocket. If the particles can be identified as debris, then it becomes possible to determine their parent body, which gives a clue as to which objects in Earth orbit are major contributors to the orbital debris population. Unfortunately, the IDE data permit the unique determination of only the position of the impacted particle (which is the same as that of LDEF at the time of impact), whereas an unambiguous determination of the particle's orbit requires a knowledge of both the position and the particle velocity. The IDE sensors were threshold detectors[4], triggered by any particle with sufficient energy to damage the detector dielectric, and so were rough indicators of particle energy, not velocity. It is therefore impossible to use the IDE data to obtain an orbit for a single impacting particle. This situation improves, however, for an impacting group of particles which have the same orbit. In this case, the particles will strike multiple IDE trays, permitting a rough determination of the direction of the group's velocity, which, when combined with the position information, yields a family of possible candidate orbits for the particles. The situation improves even more if the orbit of the group is such that it encounters LDEF multiple times, for then the change in the LDEF position at the encounter times can be used to produce a family of possible orbits, which can be further constrained by the velocity direction information.

Fortunately, most of the 15,000 impacts recorded by IDE occurred in such groups, which we term *events*. These events were of two types — the *spikes*, which were single, isolated events of high intensity and the *multiple orbit event sequences* (MOES), which were series of events with the events separated in time by integer multiples of the LDEF orbital period. The spikes are discussed in another paper in these proceedings; here we shall concentrate on the multiple orbit event sequences, as they were produced by particles with orbital characteristics such that the group had multiple encounters with LDEF. Even though the spikes were generally more intense, the MOES could be quite long-lived, some lasting for many days. As discussed in the previous paragraph, it is these MOES which can yield the most information about the particles' orbit.

Figure 1 is a "seismograph" plot of a typical MOES; time increases to the right along the horizontal axis, and the intensities of the events are roughly indicated by the extent of the vertical lines. A cursory glance reveals two important bits of information about the particle orbits involved in MOES:

1) the particle orbits are eccentric; if they were circular, the IDE detectors would register the group twice each orbit, as a circular orbit would 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 at integer multiples of the LDEF orbital period, unless the period of the particle orbit was the same as that of LDEF, a highly unlikely circumstance.

[4] For details on the IDE detectors, see "Long-term Particle 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", C.G. Simon, J.D. Mulholland, W.J. Cooke, J.P. Oliver, P.C. Kassel, LDEF - 69 Months in Space: Second Post-Retrieval Symposium, (NASA CP-3194), April, 1993, pp. 693-704

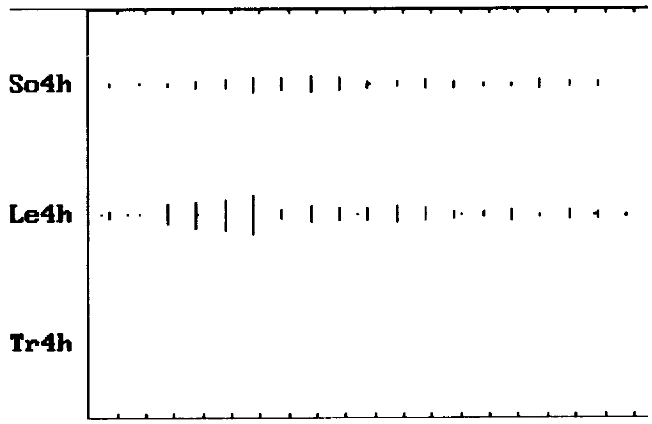

Figure 1: Typical MOES (not the May swarm). Impacts on the south (So4h), ram (Le4h), and trailing (Tr4h) surfaces are shown. The tick marks along the top and bottom are spaced at intervals of a LDEF orbital period.

This information is about all that can be determined from a visual inspection of the MOES in the IDE data set. Clearly, it is necessary to develop a technique that will extract additional information about the particles' orbit. We have arrived at such a technique, the "Method of Differential Precession", which shall be summarized and applied in the following pages.

THE METHOD OF DIFFERENTIAL PRECESSION

Overview

The goal of the Method of Differential Precession 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.

This concept is illustrated more clearly in figures 2 and 3, which depict the geometry of the situation with regard to LDEF. Following conventional notation, Ω_L represents the position of the ascending node of the LDEF orbit (which is known) and Ω_p represents the ascending node of the unknown orbit of the impacting particles. The position of the perigee of the unknown orbit is represented by ω; LDEF's orbit is essentially circular ($e \sim 10^{-4}$) and so has no perigee. The inclinations of the two orbits are i_L and i_p, and u_L and u_p denote the arguments of latitude of the point of intersection, measured counterclockwise along the orbits from the respective ascending nodes. We are using the argument of latitude rather than the more conventional true anomaly, ν, due to the fact that one of the orbits is circular. In the case of an elliptical orbit, the two quantities are related by $\nu = u - \omega$. Figure 2 shows that, for any given time, the known quantities Ω_L and i_L determine the location of the unknown orbit's node, Ω_p, provided that the inclination of the unknown orbit is specified. Similarly, figure 3 shows that Ω_L, i_L and u_L determine u_p if i_p is specified. As time progresses, the orbits will precess at different rates, resulting in the movement of the point of impact (intersection), with a corresponding change in u_L and u_p.

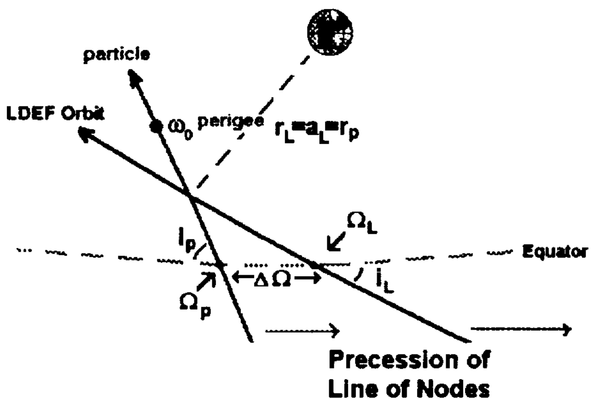

Figure 2: Differential precession of the lines of nodes

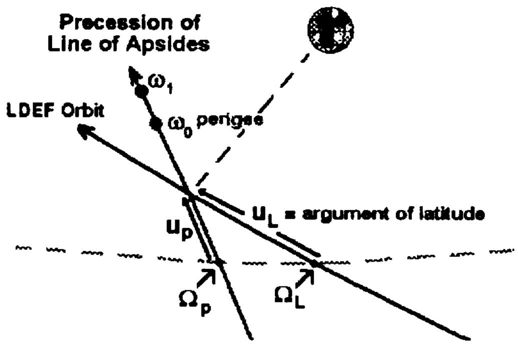

Figure 3: Precession of the line of apsides

Assuming that the inclination of the particle orbit is known, our knowledge of the LDEF orbit enables us to compute Ω_p and u_p for each impact occurring in a given MOES. The variation in Ω_p with time directly yields the precession rate of the line of nodes of the particle orbit, $\dot{\Omega}_p$, which can then be used to construct a family of possible candidate orbits by means of the well-known relation

$$\dot{\Omega} = \frac{-3n}{2} J_2 \left[\frac{R_e}{a(1-e^2)} \right]^2 \cos i_p, \tag{1}$$

where R_e is the radius of the Earth and J_2 is the second gravitational harmonic. The semi-major axis and eccentricity of the particle orbit are denoted by a and e, while n is the mean motion of the particles. The family of candidate orbits will have values of a and e specified by equation (1), and can be constrained by the simple fact that any candidate orbit must intersect that of LDEF at some point. Information about the direction of the particle velocity obtained from the numbers of impacts on the IDE trays during the MOES can also be employed to derive the vector intercept of the particles, which further constrains the range of allowed orbits. It should be noted that even though this technique can completely determine the orientation of the particle orbit (i_p, Ω_p, and ω), the lack of velocity information still prohibits a unique determination of the orbit's size and shape.

Unfortunately, the inclination of the particle orbit is not known, forcing the adoption of an iterative scheme in order to achieve a solution. One starts by assuming a reasonable value for the particle inclination, which will enable the determination of the u_p's and Ω_p's at the times of impact, and, consequently, $\dot{\Omega}_p$. It is also necessary to obtain the rate of the perigee advance of the particle orbit. This can be done by realizing that, at each impact, the position of LDEF must be the same as that of the particle, thus

$$r_L - \frac{a(1-e^2)}{1+e\cos(u_p - \omega)} = 0 \tag{2}$$

Equation (2) implies that $\dot{u}_p = \dot{\omega}$, and we see that the time variation of the argument of latitude of the impact point, measured along the particle orbit, is equal to the rate of the advance of the perigee. The ratio $\dot{\Omega}_p/\dot{\omega}$ can now be formulated and compared to the theoretical value, which is given by

$$\left(\frac{\dot{\Omega}_p}{\dot{\omega}}\right)_t = \frac{-2\cos i_p}{5\cos^2 i_p - 1} \tag{3}$$

If the ratios are not equal, then a new i_p is calculated according to Newton's method or some similar scheme, and the process repeated until the values agree. In addition to the assumption of no non-gravitational forces, this method also requires that all particles striking LDEF during the MOES share the same orbit, which is perfectly reasonable in light of the short duration of each event belonging to a MOES.

Methodology

Based on the above discussion, one may obtain the family of possible particle orbits by proceeding as follows:

1) Obtain the arguments of latitude (u_L) of LDEF at all impact times in the MOE. This is a simple matter, given the LDEF orbital elements and an orbit propagation code.

2) Assume an inclination (i_p) for the orbit of the particles. Good starting values are 30º, 65º, or 82º, as these are representative of most satellite orbits.

3) The difference between the right ascension of the particle orbit ascending node (Ω_p) and that of LDEF (Ω_L) is determined by the argument of latitude of LDEF at the time of impact (u_L), the inclination of the particle's orbit, and the inclination of LDEF's orbit (i_L). The relevant expressions are[5]

$$\begin{aligned} \Delta\Omega &= \Omega_p - \Omega_L \\ u_L &= \tan^{-1} \frac{-\sin\Delta\Omega}{\cot i_p \sin i_L - \cos\Delta\Omega\cos i_L} \end{aligned} \tag{4}$$

At each impact time, equations (4) may be solved for $\Delta\Omega$ (and hence, Ω_p) via Newton's method or some other scheme.

[5] Greenberg, R., *Orbital Interactions: A New Geometrical Formalism*, Astronomical Journal., **87**, p. 186. (1982)

4) The slope of a line fit to the Ω_p's and their associated impact times gives the rate of regression of the nodal line of the particle orbit, $\dot{\Omega}_p$.

5) Once the $\Delta\Omega$'s have been determined for the impacts, the corresponding arguments of latitude for the particle orbit are found from

$$\cos u_p = \cos u_L \cos\Delta\Omega + \sin u_L \sin\Delta\Omega \cos i_L$$
$$\sin u_p = \frac{\sin u_L \sin i_L}{\sin i_p} \tag{5}$$

6) In the absence of non-gravitational forces, the semi-major axis (a) and the eccentricity (e) of the particle orbit remain constant over time. Therefore, equation (2) requires that $u_p - \omega$ must also be constant, or $\dot{u}_p = \dot{\omega}$. The slope of a line obtained by a linear regression performed on the u_p's and their associated times yields the progression or regression of the line of apsides, $\dot{\omega}$.

7) Compute the ratio $\dot{\Omega}_p/\dot{\omega}$ and compare to the theoretical ratio obtained from equation (3), which is a function of only the inclination of the particle orbit. If the two are not equal to within a specified tolerance, compute a new i_p by means of Newton's method and repeat steps 3 through 6 until the values agree.

8) Use the values of i_p and $\dot{\Omega}_p$ to determine a family of possible candidate orbits in (a,e) space by means of equation (1). Constrain the range of potential candidates by imposing the requirements that the particle orbit must intersect that of LDEF and must not enter the atmosphere (i.e., the perigee must be greater than 200 km).

Application to the May Swarm MOES

One of the most prominent multiple orbit event sequences observed by IDE began on May 13, 1984, and so has become known as the "May swarm." This MOES can be characterized as being of low intensity (~3 impacts per orbit) and long duration, lasting for over 20 days (300 LDEF orbits), with several hundred impacts recorded on the IDE trays facing in the LDEF ram direction and towards the south pole of the orbit, the majority occurring on the south-facing tray. The long duration of this MOES made it an especially suitable choice for analysis by the differential precession technique, the only drawback being the low intensity of the events. To avoid contamination by the occasional "random" impact, the times chosen were those in which the high sensitivity (0.4 micron dielectric thickness) IDE detectors on the south tray recorded multiple impacts within the same IDE clock "tick" (13.1 seconds). This resulted in a total of 38 points for use in the analysis, spanning a time interval of some 18 days.

The procedure outlined in the previous section was then applied to these data, with the inclination converging to a value of 66°.55 after only a couple of iterations. Table 1 lists the resulting longitudes of ascending node and arguments of latitude of the impact points for the particle orbit, along with the times of impact (in decimal days from LDEF deploy) and the LDEF arguments of latitude of the impact points.

Impact time	u_L (°)	Ω_p (°)	u_p (°)
40.03233	221.90	226.6	339.7
40.1638	227.25	232.0	337.5
40.2922	215.89	217.9	342.2
40.5546	223.27	224.7	339.1
40.6842	218.59	218.4	341.1
40.7499	221.48	221.3	339.8
40.9452	219.09	217.2	340.8
40.9463	224.94	224.0	338.4
41.0106	219.68	217.4	340.6
41.1417	223.38	220.8	339.1
41.2063	219.80	216.2	340.5
41.4682	224.69	220.1	338.5
41.5339	226.96	222.3	337.6
41.7942	223.49	216.5	339.0
41.8599	225.76	218.7	338.1
41.9906	226.95	219.2	337.7
42.0554	224.20	215.5	338.7
42.1856	222.89	213.1	339.3
43.0342	224.80	209.6	338.5
43.0343	225.64	210.5	338.2
43.1635	218.47	201.3	341.1
43.6219	227.67	208.9	337.4
43.8179	228.63	208.7	337.0
43.9480	226.48	205.3	337.8
44.2092	228.04	205.3	337.2
44.3403	230.91	207.8	336.2
45.1233	231.53	203.2	336.0
45.8412	232.45	199.4	335.6
46.0377	236.77	203.2	334.2
47.2122	236.89	195.4	334.2
47.4733	237.80	194.7	333.9
47.5380	235.06	191.0	334.8
47.7988	234.15	188.1	335.1
50.0854	250.65	192.3	330.6
50.1505	249.59	190.6	330.8
50.4769	250.98	190.0	330.5
52.5007	257.84	184.4	329.4
55.3086	271.25	180.9	328.7

Table 1: May swarm times of impact (days from LDEF deploy) and the corresponding LDEF arguments of latitude, with the values of the longitudes of the ascending node of the particle orbit and the particle arguments of latitude for $i_p = 66°.55$.

The two linear regressions (see figures 4 and 5), involving the impact times, Ω_p, and u_p, yielded

$\Omega_{p0} = 179°.0 \pm 0°.2$ (Initial longitude of ascending node for the particle orbit)

$\dot{\Omega}_p = -3°.26 \pm 0°.05 \text{ day}^{-1}$

$\omega_0 = 178°.1 \pm 0°.2$ (Initial argument of perigee for the particle orbit)

$\dot{\omega} = -0°.85 \pm 0°.05 \text{ day}^{-1}$

These four quantities, along with i_p, uniquely specify the orientation of the particle orbit at any given time. Note that the initial value of the argument of the perigee indicates that these particles are striking LDEF near apogee, a somewhat surprising result.

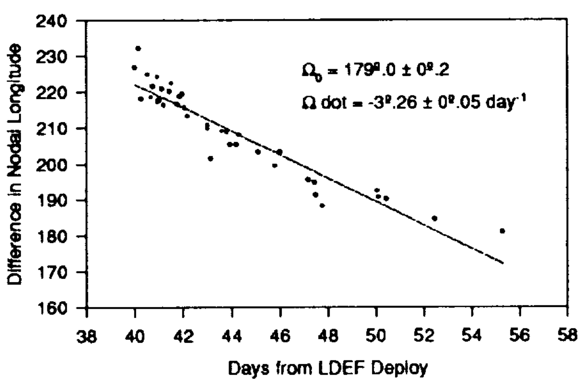

Figure 4: Linear fit to determine nodal line properties

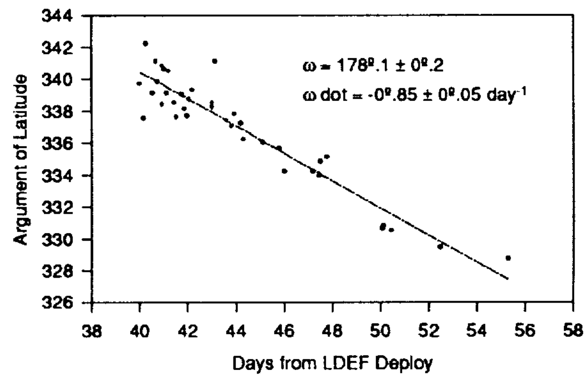

Figure 5: Linear fit to determine apsidal line properties

Next, the precession rate of the particle orbit line of nodes was used in equation (1) to determine the family of possible candidate orbits. These results are displayed in figure 6. Note that the semi-major axis varies little with the eccentricity; in this case, the variation in a is so small that we could confidently set a = 6746.5 km, regardless of the eccentricity. The dual requirement that the candidate orbits have perigees of greater than 200 km in altitude and intersect the LDEF orbit placed strict limits on the allowed values of the eccentricity, which must lie in the range $0.0165 < e < 0.025$.

One of the candidate orbits (e = 0.017) was then chosen for a series of checks on the results of the method. The first check involved the computation of the particle velocity of impact over the duration of the May swarm. These velocities were then resolved into components along the LDEF body axes in order to determine the impact speeds on the IDE trays. For this particular orbit, only the south tray and the ram-facing tray were struck, with the south impact speed being larger than that for the other tray (see figure 7). This is in good agreement with the IDE observations of the May swarm, in which these same two trays recorded large numbers of impacts, with the south tray receiving the most hits. The second check consisted of a comparison of the sky track of the points of closest approach between the two orbits to the sky positions of the individual impacts comprising the May swarm. As can be seen from figure 8, the agreement is excellent, with the sky track of close approach passing neatly through a diffuse band of impact positions.

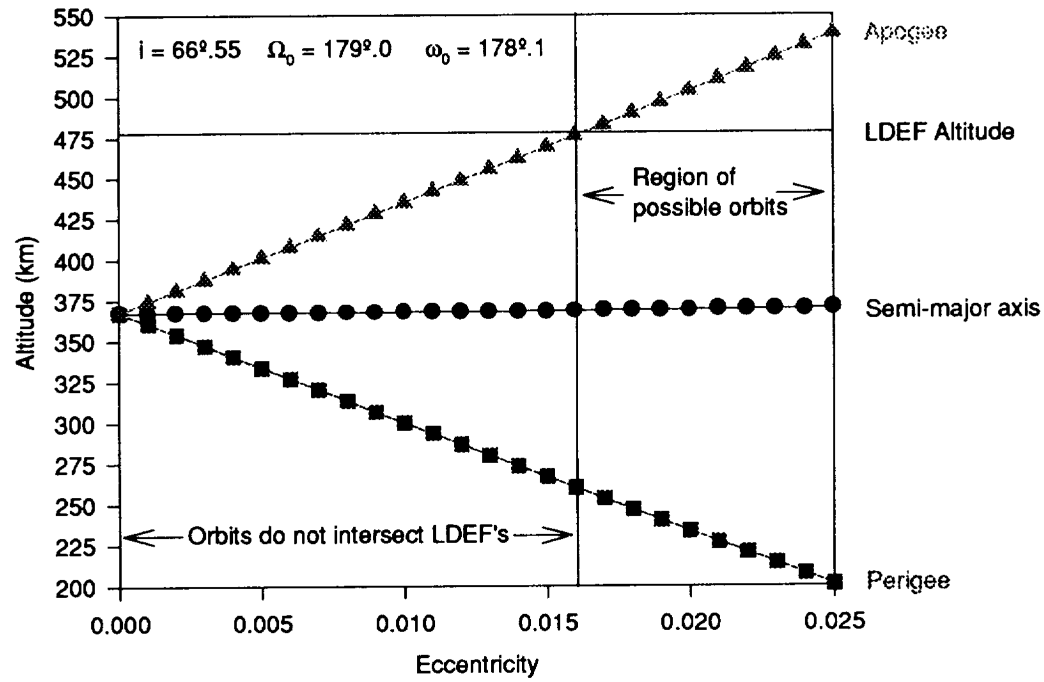

Figure 6: Candidate orbits for the May swarm

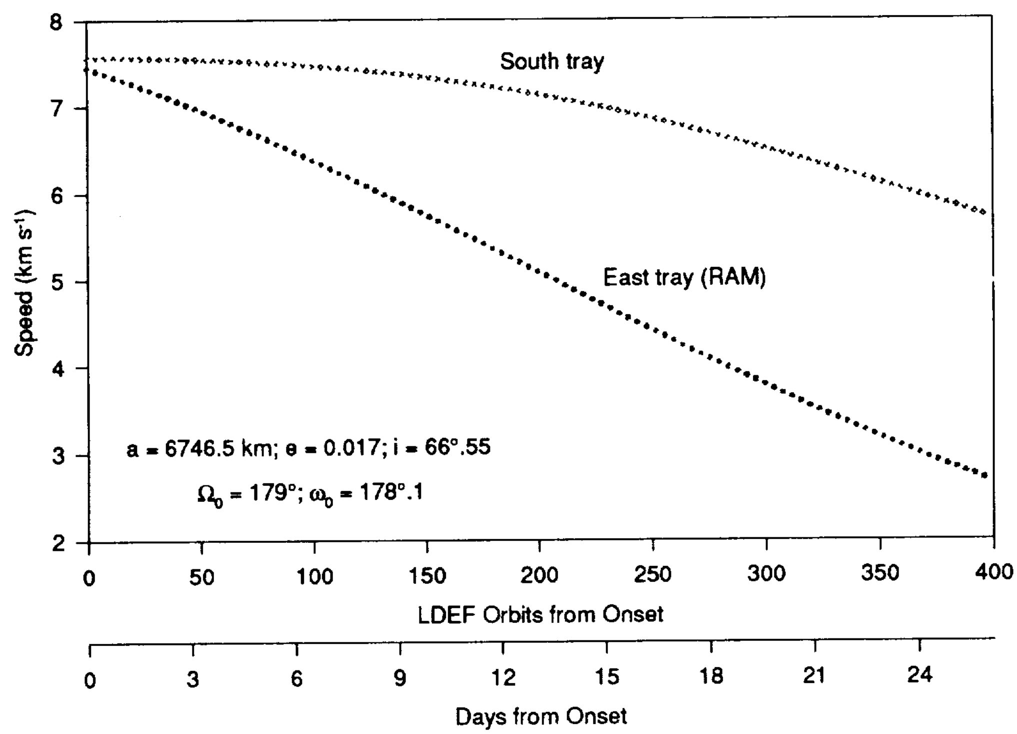

Figure 7: Particle impact speeds along IDE tray normals for test orbit.

In summary, it would seem that the particles impacting LDEF during the May swarm MOES have an orbit that can be characterized by the following parameters:

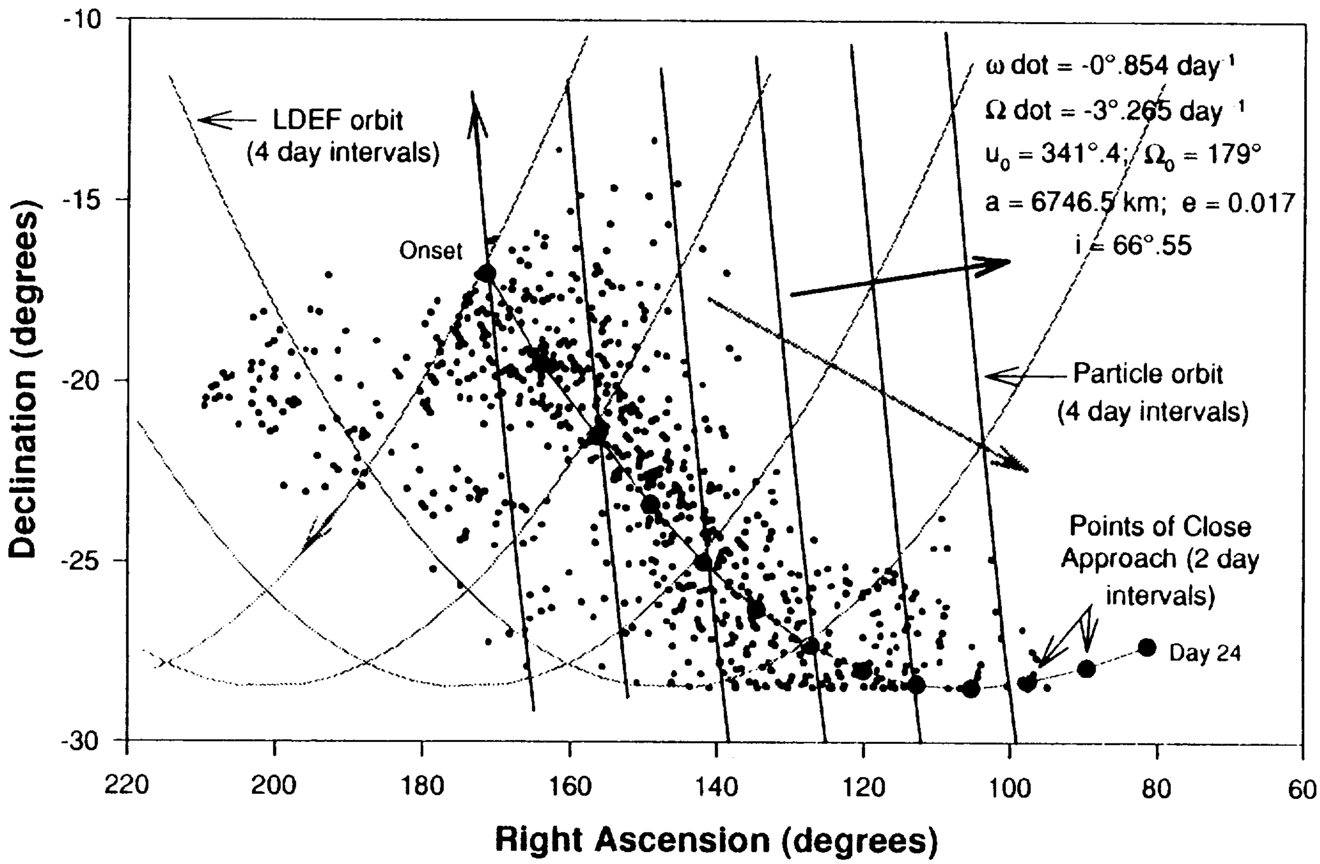

Figure 8: Sky track of close approach between the test orbit and that of LDEF. The particles are moving in a northerly direction, whereas LDEF is moving along its orbit from left to right. At the onset of the May swarm, the impacts are located at the position labeled "Onset", with the impact positions gradually moving towards the lower right as time progresses.

$\Omega_{p0} = 179°.0 \pm 0°.2$ $\quad$ $i_p = 66°.55$

$\dot{\Omega}_p = -3°.26 \pm 0°.05 \text{ day}^{-1}$ $\quad$ $a = 6746.5$ km

$\omega_0 = 178°.1 \pm 0°.2$ $\quad$ $0.0165 < e < 0.025$

$\dot{\omega} = -0°.85 \pm 0°.05 \text{ day}^{-1}$

CONCLUSION

It has been pointed out numerous times in the literature that the surface area to mass ratio of a micron-sized particle (the size of many of the LDEF impactors) is large, thus causing the particle to experience significant perturbations from forces such as radiation pressure and atmospheric drag. Indeed, numerical calculations indicate that radiation pressure can cause a one micron diameter particle, initially in an orbit similar to that of LDEF, to enter Earth's atmosphere after only a very few (<10) orbital revolutions. Such calculations leave us hard-pressed to explain how a MOES like the May swarm, which we postulate to be caused by a ring of micron and sub-micron particles, can persist for many days. The only reasonable explanation is that the ring must be replenished by debris from some source during the time spanned by the MOES.

To obtain the geometrical characteristics of this ring, the technique of differential precession looks at the time evolution of the point of intersection with the LDEF orbit. It does not matter that the particles exist in the ring for only a short time; the only requirement is that the orbit shared by the particles at the times of impact with LDEF be similar. In general, this orbit would not be the same as that of the source of the debris particles, for non-gravitational forces would have rapidly acted to alter the particles' orbit from that of the parent body. It should be realized that if the parent body (whose orbit is presumably stable) continually produced particles of similar properties, these particles would have experienced the same perturbations as their predecessors and would therefore have undergone a similar orbital evolution. If any of the future orbits intersected that of LDEF, a MOES would have been observed by IDE, this MOES lasting as long as the source produced particles, or until the geometry of both orbits changed such that there was no longer a point of contact.

The IDE data set is rich, with many MOES of varying characteristics that await analysis by some procedure. The method of differential precession is such a technique, one that appears to be able to extract a good deal of information about the particle orbit involved in a MOES. We fully expect that its application to the other MOES will not only shed some light on possible sources of orbital debris, but will also yield quite a few surprises.

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