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THE GEOCENTRIC PARTICULATE DISTRIBUTION: COMETARY, ASTEROIDAL OR SPACE DEBRIS?

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ABSTRACT

Definition of the Low Earth Orbit (LEO) particulate environment has been refined considerably with the analysis of data from NASA's Long Duration Exposure Facility (LDEF). Measurements of the impact rates from particulates ranging from sub-micron to millimetres in dimension and, especially, information on their directionality has permitted new scrutiny of the sources of the particulates. Modelling of the dynamics of both *bound* (Earth orbital) and *unbound* (hyperbolic interplanetary) particulates intercepting LDEF's faces leads to the conclusion that the source is dominantly interplanetary for particle dimensions of greater than some 5 microns diameter; however the anisotropy below this dimension demands lower velocities and is compatible with an orbital component. Characteristics of the LDEF *interplanetary* component are compatible with familiar meteoroid sources and deep space measurements. Understanding of the orbital component which exceeds the interplanetary flux by a factor of 4 is less clear; although the very small particulates in orbit have been asscociated with space debris (Lawrance and Brownlee, 1986) this data conflicts with other measurements (McDonnell, Carey and Dixon, 1984) at the same epoch. By analysis of trajectories approaching the Earth and its atmosphere, we have shown that a significant contribution could be captured by *aerocapture*, i.e. atmospheric drag, from either asteroidal or cometary sources; such enhancement is unlikely however to provide the temporal and spatial fluctuations observed by the LDEF Interplanetary Dust Experiment (Mullholland et al. 1992). A further new mechanism is also examined, that of *aerofragmentation capture*, where an atmospheric grazing trajectory, which would not normally lead to capture, leads to fragmentation by thermal or mechanical shock; the microparticulates thus created can be injected in large numbers, but only into short-lifetime orbits. The concentration in one particular orbit plane, could explain the temporal fluctuations seen on LDEF; space debris could also explain the phenomenon.

THE LEO ENVIRONMENT FROM LDEF'S IMPACT DATA

The successful retrieval of LDEF in January 1990 after 5.75 years in orbit has provided a vast and unique amount of data on the LEO particle population. Extensive analysis of craters and perforations seen on the various experiments, and on the vehicle, has been performed. Impacts reveal the crater size distribution and directional characteristics from sub-micron dimensions to millimetres, representing more than nine magnitudes in mass.

Computer modelling of various particulate distributions intercepting LDEF in orbit shows that the majority of the intermediate and large particles (>5μm) are compatable with a distribution of interplanetary origin, with a geocentric approach velocity of 17.4 ± 3 km/s (Sullivan and McDonnell, 1992). However, using modelling of Zook (1991 and 1992) a value of 20 km/s results. The anisotropy of the smaller particulates reveals the presence of a significant orbital component; further, the IDE experiment also revealed time-dependence in the flux of these smaller particles.

PERSPECTIVE OF LDEF DATA IN THE INTERPLANETARY SCENE.

Interplanetary flux data at 1 AU (Grün et al, 1985) are compatable with the LDEF penetration data observed on the West (trailing) and Space faces. With their similar velocities orbital components cannot access these faces. On the forward faces, however, the orbital component clearly exceeds the interplanetary flux. We will examine how, with aerodrag the interplanetary component could effect this, but must note that space debris could readily provide a source (ESA SP Space Debris, 1988). Impact comminution from rockets and satellites, flecks from the erosion of satellite paint and also Al_2O_3 spheres from rocket motor burns are prime candidates for this micro-debris population.

We note early fears of the existence of the "Earth's dust belt" (Whipple, 1961). Prompted by unreliable satellite and rocket measurements, its 'lifetime' was short lived and dismissed by Nilsson (1966) and other workers. The studies now reported refer to very much smaller masses, where higher drag altitudes and hence greater scale heights pertain; LDEF data also calls for much smaller enhancements than the 3 or 4 magnitudes previously investigated.

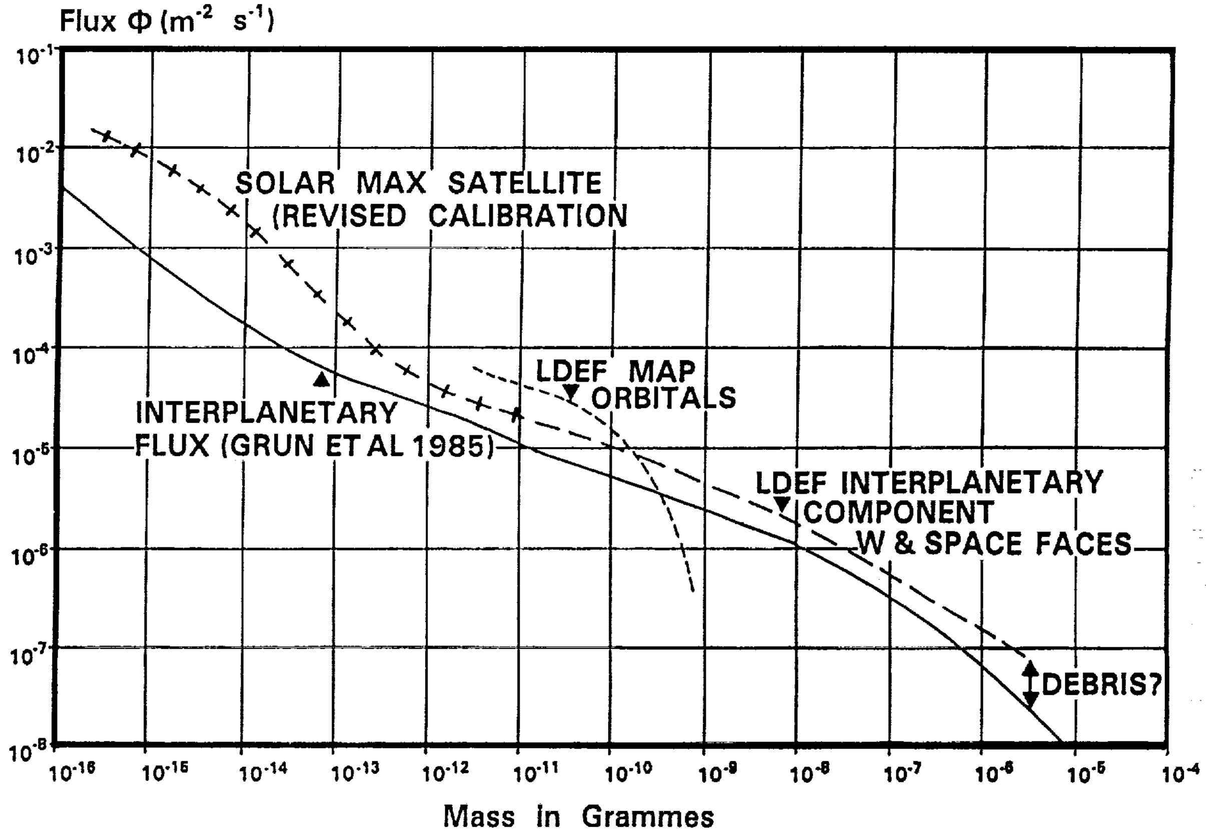


Figure 1 LDEF flux data from the West (trailing) and space-pointing faces, corrected for Earth shielding and gravitational focussing, yielding the expected flux at 1 A.U. heliocentric distance (McDonnell et al., 1991). They compare favourably with (though a factor of 2 higher than) deep space measurements. In contrast the excess orbital component on LDEF's leading face (orbitals) dominates the interplanetary unbound component at LDEF's altitude for particles < 10^{-10}g mass.

Aerocapture of Interplanetary Particulates.

Interplanetary particles that penetrate below a certain height in the Earth's atmosphere, known as the critical atmospheric height, will lose too much kinetic energy to remain on a hyperbolic orbit, and will eventually be absorbed by the atmosphere. Figure 2 shows schematically the trajectories studied by computer using the standard atmosphere and a 7th order "gear" method for numerical trajectory integration. Those that penetrate just below this height will be captured into orbit, and may complete several orbits before capture, while those that penetrate deeper on the first pass will be directly absorbed. For spherical particles of a given density, the critical atmospheric height is a function of the particle mass and geocentric velocity; the relationship established by these is shown in Fig. 3.

The relative probability of capture (i.e. normalised to the probability of absorption) for particulates of 1μm, 10μm and 100μm diameter is also shown (Fig. 4) as a function of geocentric velocity. The probabilities are generally low, indicating that the orbital particles will not dominate the directly intercepted IP flux in LEO, unless the particles are able to complete a large number (>100) of orbits, which is not the case. The majority of all captured particles are absorbed after <10 orbits, as is shown e.g. by the circular orbit lifetimes stated in Fig. 5. Longer lifetimes are only possible for particles with high initial perigees, which is limited to the particles with very low geocentric velocities since the critical atmospheric height defines the maximum possible initial perigee - unless the possibility of orbital pertubations thereafter can be invoked.

The orbital residence time of aerocaptured particles can be long due to the high initial apogee and hence will enhance, but not dominate the natural material in LEO. We note that capture is effective only for small particles with very low values of V_∞, low (solar) eccentricity and low inclination orbits. Thus, the capture of asteroidal material is favoured above that of short period comets, and even more strongly favoured over that of long period comets. These strong selection effects must caution us regarding a likely bias towards asteroidal sources in the results expected from the study of intact residue studies on LDEF.

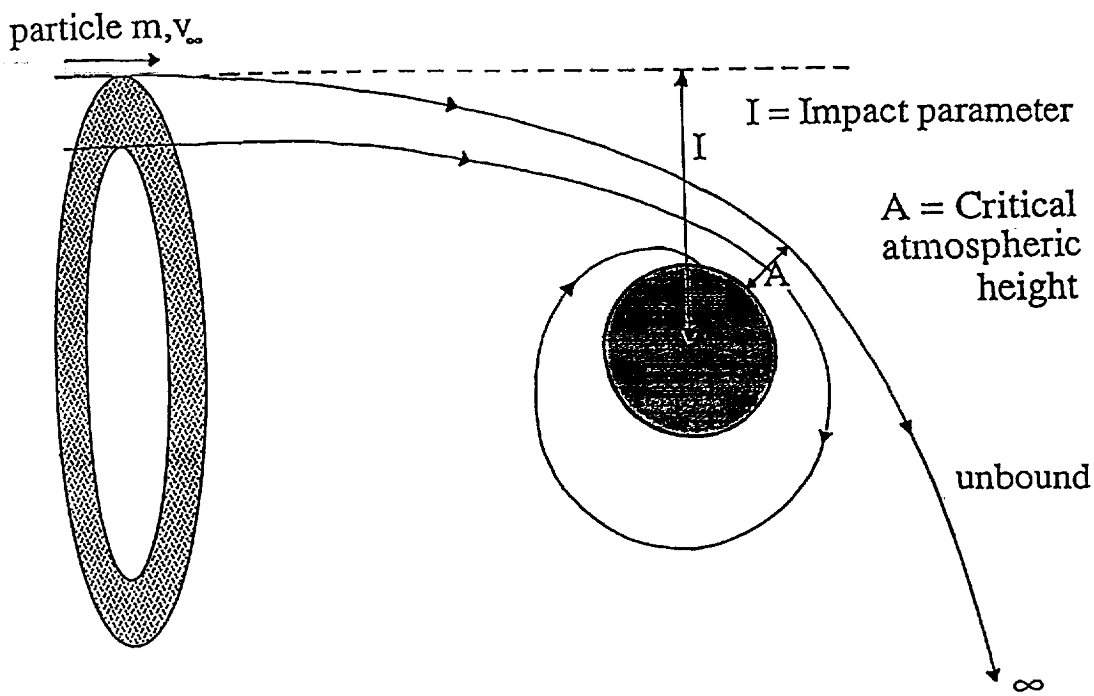
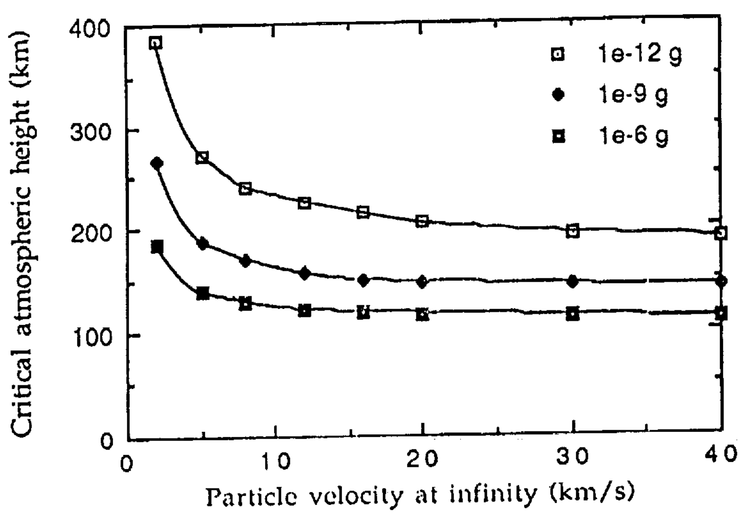


Figure 2. Schematic for computer trajectory analysis performed to identify the fraction of interplanetary particulates captured into Earth-bound orbits relative to the total number approaching from within the critical impact parameter I. The fraction captured is shown in Figure 4. The lifetime in Earth orbit results from a folding of the number of subsequent perigee passages before reentry, and the (decreasing) orbital period. The capture mechanism strongly favours low values of V_∞.

Figure 3. Critical atmospheric height at perigee for the first passage of unbound particulates as a function of V_∞ for particulate diameters 1μm (10^{-12}g), 10 μm (10^{-9}g) and 100 μm (10^{-6}g). LDEF 's mean orbital altitude of 458 km is comparable to that of slow micron dimension particles.



Aerofragmentation Capture. In order for either larger or faster particles to be captured, they must lose a larger amount of kinetic energy on the first pass than is required for the smaller, slower particles. This can result in the particles experiencing very large temperatures and pressures which may result in fragmentation of the particle, particularly if the particle is a large fluffy agglomerate. This is frequently seen in meteor streams. Particles on an initially marginally hyperbolic orbit may also be fragmented, whereupon the fragments, by virtue of their smaller critical atmospheric height, will be captured into orbit. This process is unlikely to be efficient in terms of the fractional number of particles so fragmented, and the captured fragments are unlikely to be in long-lifetime orbits, but the total number of particles that can be generated from the fragmentation of one 1g particle is very large e.g. *potentially* 10^{11} if all converted to micron dimensions, and will form an extended swarm in orbit, possibly consistent with the observed spatial and temporal anisotropy.

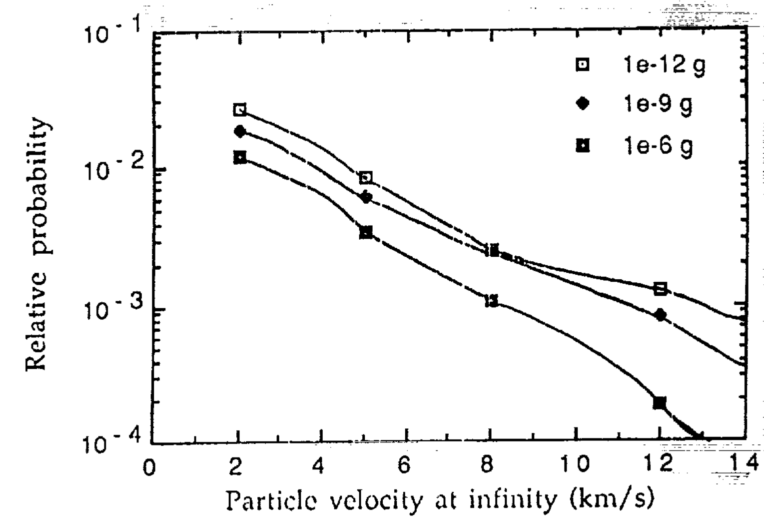


Figure 4. Fraction of interplanetary particulates captured into Earth orbit from initially hyperbolic orbits as a function of the approach velocity V_{∞}.

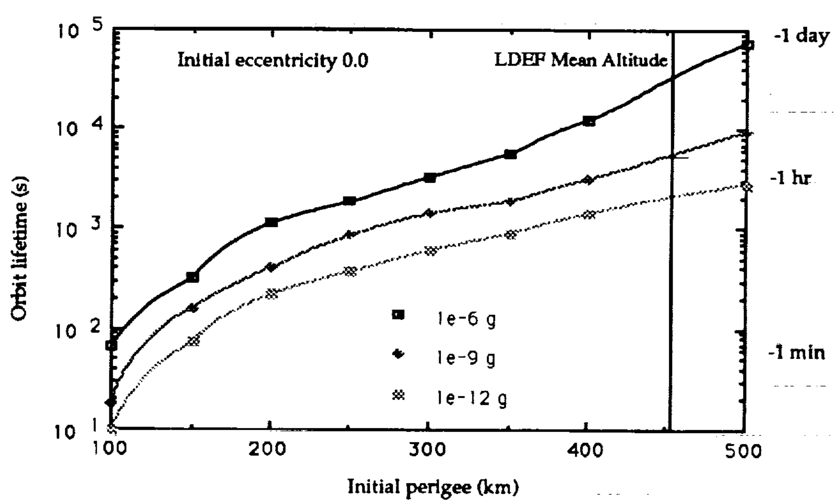


Figure 5. Circular orbit lifetimes of particles as a function of initial perigee for the 3 candidate particulate sizes. LDEF's mean altitude of 458 km is shown, along with the circular orbital period at this altitude. We see that 10 μm diameter (10^{-9}g) particles complete only one orbit; for eccentric orbits they survive several perigee passages. The orbitals which LDEF intercepts are generally only a transient population, en route towards atmospheric capture.

In figure 6 (a) we show the peak pressures expected for our candidate particulates on marginally hyperbolic orbits. For fragile agglomerates (perhaps with a crushing strength of only some 1 Nm^{-2}) we see that particulates of greater than 10μm could be fragmented. In figure 6 (b) for the same conditions, we plot the temperatures experienced. Again for 10μm or greater a rise of some few hundred degrees imposes conditions which could release the bonding forces of agglomerates. In fragmentation from any of these conditions, we see that particles released from larger masses will not have an initial perigee as high as is possible for direct aerocapture, and it is difficult to envisage a shower duration of much more than one orbit. We should note, however, the high availability of mass in the meteoroid range 10^{-7} to 10^{-5} g.

Intact capture on LDEF. Unbound orbits have a minimum value of the Earth's escape velocity at LDEF's altitide, viz. 10.8 km/s. For targets which are not 'under-dense' e.g. multi layer insulation or foams, the impact pressure will exceed the strength of all known projectile materials. This has the interesting consequence that if intact residues of cosmic origin are discovered on LDEF, they must arise from an aerocaptured interplanetary particle; the search to identify these fragments could therefore yield evidence on these mechanisms.

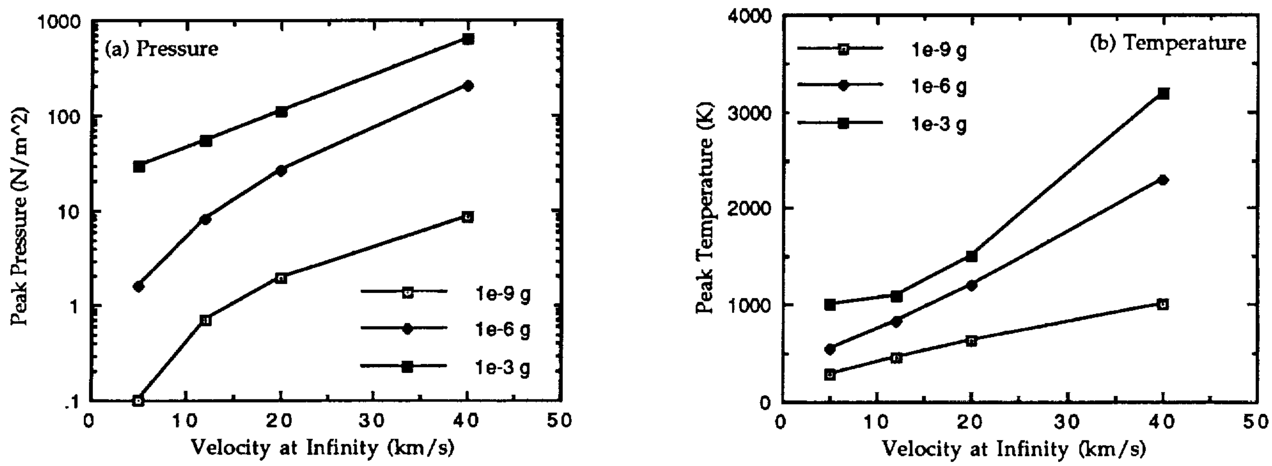


Figure 6. For the particulate sizes at their respective but different critical hieghts (see fig. 4) peak aerodynamic drag pressures are shown (a). For the for the same conditions the peak temperatures under radiative (black body) equilibrium are established, 6 (b).

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