DYNAMIC MODELLING TRANSFORMATIONS FOR THE LOW EARTH ORBIT SATELLITE PARTICULATE ENVIRONMENT

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ABSTRACT. A simple dynamic model to investigate the relative fluxes and particle velocities on a spacecraft's different faces is presented. The results for LDEF are consistent with a predominantly interplanetary origin for the larger particulates, but a sizable population of orbital particles with sizes capable of penetrating foils of thickness <30μm. Data from experiments over the last 30 years do not show the rise in flux expected if these were space debris. The possibility of a population of natural orbital particulates awaits confirmation from chemical residue analysis.

1. Dynamic modelling

The Long Duration Exposure Facility (LDEF) has provided an unprecedented source of information on extraterrestrial particulates after almost 6 years in low Earth orbit. Some initial results are presented by McDonnell et al (1990; 1991). Any instrument to detect interplanetary or orbital particles will not immediately reveal the true space density or flux in Earth orbit. The *detected* flux is dependent on the spacecraft's orbital velocity and the instrument pointing history. Because of the range of possible particle orbits the problem cannot be uniquely solved by inversion techniques. A model particle distribution must be produced, used to predict the observed flux, and modified until a match is obtained. Most previous penetration experiments yielded no directional information, but LDEF, with its controlled attitude with respect to the orbital radius vector, provides valuable constraints on the contribution to the observed fluxes of interplanetary and orbital populations.

In order to determine the particulate population in Low Earth orbit, a detailed model of the distribution of trajectories of incoming interplanetary particles and the geocentric orbits of bound particles (natural or debris) is required. In practice, valuable results may be obtained from a simple model, employing the same methodology, which does not implicitly distinguish between interplanetary or orbital particles, but utilises the very low probability of impact of an orbital particle on LDEF's space-pointing and trailing (West) faces. In the geocentric reference frame the flux distribution is defined by a particle mass distribution having an isotropic velocity distribution with a single (average) velocity (V_p) at each mass. The resultant velocity vectors (V_{face}) impacting normal to a face of a spacecraft with orbital velocity (V_s) are then calculated taking into account shielding by the Earth, from which a mean V_{face} can be determined. The foil perforation fluxes observed in a capture cell experiment such as LDEF A0023 MAP (Micro-Abrasion Package) are a function of this normal velocity (foil thickness marginally penetrated, $f \propto V_{face}^{\beta}$ - see McDonnell et al, 1990 for details).

For the case of an isotropic velocity distribution and the known spacecraft orbital velocity, altitude and effective atmospheric altitude, a geometry factor K can be defined for

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each spacecraft face such that $K_{face} = n_{face}(V_s) / n_{face}(0)$ i.e. the ratio of the number of particles impacting that face, travelling through the particle population with velocity V_s, to that seen when it is at rest. Due to Earth shielding, certain trajectories are forbidden, so a further ratio, the Earth shielding correction Ω is required where $\Omega_{face} = n_{face}(0) / n(0)$. n(0) is the number of particles impacting a stationary plate with no Earth shielding.

Capture cell experiments do not in general provide information on particle velocities. It is possible however, for LDEF data, to derive the mean velocity V_p which is consistent with results obtained from different faces (i.e. different pointing directions) of the spacecraft. Figure 1 illustrates the technique on a plot of log particle flux (Φ) vs log foil thickness (f). α is the cumulative particle mass distribution index, Φ_1 and Φ_2 are foil penetration fluxes observed on faces 1 and 2 with (initially unknown) normal impacting velocities V_1 and V_2. The flux ratio at constant foil thickness ($\varepsilon|_f$) can be directly obtained from the figure. However, the flux ratio at constant mass ($\varepsilon|_m$) is of more interest since it relates to the actual population of particles and their mean velocity. The transformation of data from one face (1) to the other (2) consists of two components: i) $\Delta\log f|_m = \log[(V_2/V_1)^\beta]$ accounts for the difference in mass sensitivity due to the difference in impacting velocity, ii) $\Delta\log\Phi|_m = \log[K_2\Omega_2/K_1\Omega_1]$ accounts for the geometrical factors described above. Since both the K factors and the normal velocities V depend on the initial particle velocity V_p its value can be derived by application of the model.

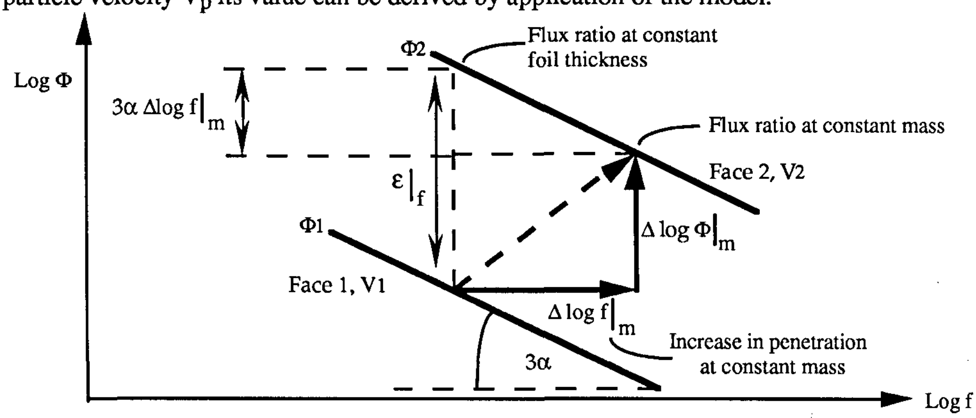

Figure 1. Method of transposition of the cumulative flux plot from face 1 to that of face 2. The flux ratios at constant crater size (or foil thickness, given as the enhancement at constant foil thickness, $\varepsilon|_f$) and at constant mass $\varepsilon|_m$ are indicated. See text for details.

2. Model Results and Application to LDEF Data

Using LDEF's orbital velocity (7.64 km s^{-1}) and mean altitude (458 km) and an effective atmospheric height of 185 km, the following relationships for LDEF's SPace, West (trailing) and East (Leading) faces have been derived from fits to results (for $v_p > 10$ km s^{-1}) from the isotropic single velocity model:

$V_E = 0.713V_p + 4.19$ $\quad K_E = (V_p+7.71)/(V_p-1.38)$ $\quad \Omega_E = 0.676$
$V_{SP} = 0.671V_p - 0.370$ $\quad K_{SP} = (V_p-7.57)/(V_p-7.35)$ $\quad \Omega_{SP} = 1.0$
$V_W = 0.710V_p - 5.32$ $\quad K_W = (V_p-7.92)/(V_p+1.32)$ $\quad \Omega_W = 0.676$

These relationships can be applied to LDEF data (McDonnell et al 1991) for the Space and West faces which are likely to consist only of interplanetary particles. A particle velocity V_p of 16±2 km s^{-1} is required to satisfy both data sets, consistent with unbound particles. If there were no orbital particles impacting LDEF this velocity should also satisfy the data detected on all other faces. Figure 2 shows LDEF foil penetration data (or equivalent - see McDonnell et al, 1991) for East, West and Space. Using V_p=16 km s^{-1} the West data have been transformed to produce a predicted East flux. Although this is close to the observed East data at foil thicknesses > 30 μm, an additional component is required for thinner foils. Since the East face is readily accessible to orbital particulates (but not the Space or West faces) this may be considered to be the result of the presence of a population of orbital particulates. If this additional population of bound particles is a result of man-made space debris, it would be expected to have increased over the period in which experiments have been deployed in Low Earth Orbit.

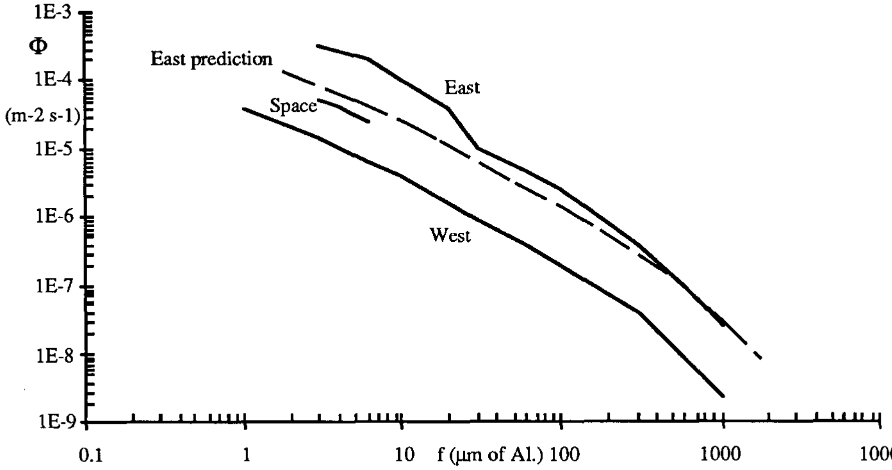

Figure 2. The predicted LDEF East flux is shown (dashed line) using a constant geocentric particle velocity of 16 km s^{-1} obtained from the fit to the West and Space fluxes. This is compared with LDEF data of the East face (full line) (see McDonnell et al 1991).

3. Temporal Stability of the Near Earth Particulates

Spacecraft data from experiments which employ the same detection technique, (thereby avoiding intercalibration problems) are plotted in Figure 3. In the mass range considered, temporal changes in the observed flux over some 30 years are less than a factor of ±2. In

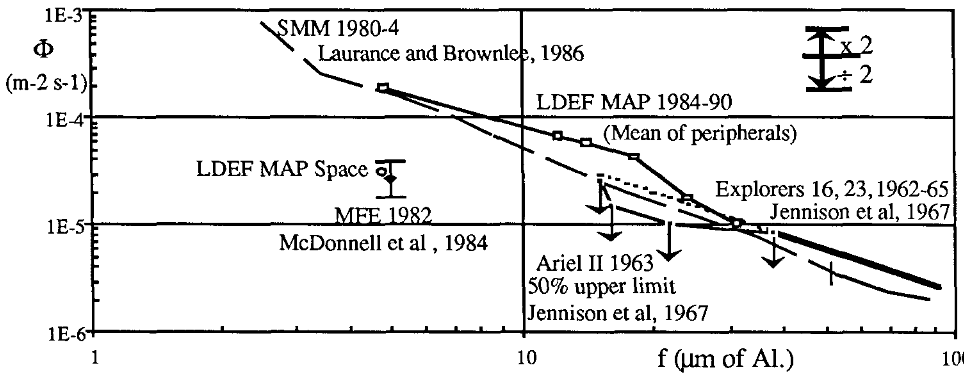

Figure3. Flux measurements from perforation experiments scaled to their equivalent aluminium foil thicknesses. All data are corrected for Earth shielding (Ω = 0.631 for Solar Max Mission, SMM). SMM data is identified as space debris (dashed) and natural particulates (full line).

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this same period space launches and the potential debris source have increased fairly steadily at a mean rate of 110 to 120 objects per year from 1961 to 1989, including the removal of objects by re-entry (NASA Ref 2 in Report of the ESA Space Debris Working Group).

4. Conclusions

Application of a simple dynamic model to LDEF data indicates a predominance of interplanetary particulates at large masses but a sizeable population of orbital particles for foils <30μm thick. Contrary to the possibility of this being space debris, foil penetration experiments do not show an appreciable increase in flux over a 27 year period, despite rapidly increasing space traffic.

The possibility of an Earth orbital component of extraterrestrial captured material has been proposed before (Whipple 1961, McCracken et al 1961) and dismissed many more times (Singer 1961, Nilsson 1966)! This "Dust Belt", as proposed, applied to considerably larger dimensions (of nanogram mass) than is now considered. Although arguments based on particulate dynamics demonstrate the low efficiency of capture in orbit by the Earth for interplanetary particulates (due to the spread of inclination and eccentricity) it should be noted that the "excess" of orbitals we now suspect is both much smaller and at much smaller particle masses than previously postulated. A trend to lower values of i and e for interplanetary orbits at these smaller dimensions would increase the capture efficiency. SMM chemical residue analysis by Laurance and Brownlee (1986) for smaller particles was consistent with terrestrial sources. Clearly, resolution of this problem awaits chemical analysis of the impact residues on LDEF.

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