The densities of interplanetary micrometeoroids have been inferred by various techniques in the past; a valuable (albeit indirect) technique has been the study of the deceleration profile of radar meteor trails, for example. Impacts on the thin foils of the Micro-Abrasion Package on NASA’s LDEF satellite and the Timeband Capture Cell Experiment on ESA’s Eureca satellite now provide direct in situ measurement of the cross-sections of impacting micrometeoroids and also of space debris particles. Combining these data with impact data from thick-target impact craters, where the damage is mass-dependent, and where such targets have experienced a statistically identical flux, leads to a measure of the impactor density which is only weakly affected by the assumed impact velocity. Comparing the space result with those from simulations shows that the density distribution of interplanetary particles in space has a more significant low density component than the distributions obtained by most other recent methods and that the mean density is in the range 2.0 to 2.4 g cm$^{-3}$ for masses of $10^{-10}$ to $10^{-9}$ kg. The characteristic density—namely, the single value which would characterize the impact behavior of the distribution—is 1.58 cm$^{-3}$. Perforation profiles reveal that a large fraction of the largest particles impacting the satellites are non-spherical but that typical aspect ratios are mostly in the range 1.0–1.5. Flux distributions of the meteoroid population incident on the Earth at satellite altitudes are derived in terms of mass and mean diameter.

Key Words: meteoroids; interplanetary dust; space debris; Earth.

1. INTRODUCTION

The densities of interplanetary dust particles (IDPs) have been estimated previously by several techniques; e.g., the cratering record on lunar rocks (Brownlee et al. 1973, 1975, Smith et al. 1974, LeSergeant D’Hendecourt and Lamy 1980) and returned spacecraft surfaces (Love et al. 1995), the deceleration of radar and visible meteors (Verniani 1973, Babadzhanov 1994), and more direct measurements of particles collected in the stratosphere (Fraundorf et al. 1982, Zolensky et al. 1989, Flynn and Sutton 1991, Love et al. 1993). The recovery of space-exposed thin foils, however, presents the opportunity for further determinations of the density from the perforation signatures of impacting meteoroids. This must, however, be combined with the cratering record of a thick-target for exactly the same pointing history of space exposure in order to eliminate any assumptions of calibration or space environment (flux distributions). Such data are here presented from the LDEF Micro-Abrasion Package (MAP) experiment (McDonnell et al. 1993) which exposed thin foils of thicknesses 1.5–30 μm.

By scanning the flux distribution on thin foils (perforations) and on thick targets (craters) where both have been exposed to the same flux, we can obtain a measure of particle density. Information on particle density arises because different mechanisms are involved in the two target types. For example, in thin foils (of thickness $f$) intermediate sized particles (of diameter $d_p \approx f$) can cause a hole of around 5 times the particle diameter (Horz et al. 1995), while very large particles (say $d_p > \sim 20 f$) effectively “punch out” their cross-sections (size). For a thick target, impact-crater dimensions are more mass-sensitive; the resultant thin-foil damage may also be used to obtain the aspect ratio of the impacting particles.

Previous workers (e.g., Paley 1992, Deshpande 1993, Gardner et al. 1996) have examined such data to obtain empirical conversions between foil perforation diameters ($D_p$) and inferred ballistic limit ($F_{\text{max}}$). The latter is defined as the maximum thickness of foil that the same particle would have been capable of perforating, had that foil been intercepted instead of the target that was, in fact, impacted. Deshpande used such a conversion with the hole growth equation of Carey et al. (1985) (known as the CMD equation) to obtain a density distribution from LDEF data. Unfortunately the CMD equation has severe limitations near the ballistic limit and hence does not characterise well the actual behaviour in this critical region; it also lacks appropriate consideration of the dependence of on projectile and target densities.
Recently, Gardner et al. (1997a) developed an empirical equation (henceforth referred to as the GMC equation), based on hypervelocity impact data for various projectiles, foil thicknesses and materials (McDonnell 1970, Hörz et al. 1995). This relates particle size to hole diameter and when rearranged (below, Section 3) gives the \( D_h \sim F_{\text{max}} \) relationship. The results from using this equation with different impactor densities and velocities will be compared to the results from the LDEF and Eureca satellites. Comparisons such as this, between thick- and thin-targeted data, are significantly better than an absolute conversion to a parameter such as particle mass or diameter, which would be sensitive to the value of the impact velocity used. After the modeling process, the flux distributions are converted to impactor mass and diameter using the parameters from the modeling.

2. EXISTING SOURCES OF DENSITY DATA

a. Depth/Diameter Ratio of Lunar Rock Impacts

Clearly presenting a much longer exposure time than could be attained by spacecraft, the lunar rock samples have been used to obtain projectile densities from the depth/diameter ratio of their microcraters. From these data, Smith et al. (1974) inferred three populations of particles, with densities of 8, 3, and \( 1-2 \) g cm\(^{-3} \), based upon calibrations at \( 1-7 \) km s\(^{-1} \). In contrast, Brownlee et al. (1973, 1975) obtained a single distribution consistent with mean densities of \( 2-4 \) g cm\(^{-3} \). LeSergeant D’Hendecourt and Lamy (1980) concluded that there were only two populations: large (>2 \( \mu \)m) silicate particles with a density of \( 2-3 \) g cm\(^{-3} \) and smaller (<2 \( \mu \)m) metal (~7 g cm\(^{-3} \)) particles. Unfortunately, none of these analyses provide data on the particle shape, as the resultant impact crater is much larger than the impacting meteoroid.

b. Depth/Diameter Ratio of Spacecraft Impacts

Spacecraft thick-target surfaces have also been used to obtain particle densities, based on crater depth/diameter ratios. As with lunar craters this method often involves assumptions about the relationship between depth/diameter ratio and projectile density. More cautiously Love et al. (1995) compare the spread of their observed depth/diameter ratios to the spread in expected impactor densities (from stratospheric particles, see section 2d) and then interpolate from these end-points. They conclude that densities in the range \( 2-5 \) g cm\(^{-3} \) dominate the impact flux.

c. Meteor Trails

Using deceleration profiles from over 5000 radar meteors, Verniani (1973) obtained 0.8 g cm\(^{-3} \) for the density of sporadic and stream meteors an estimate that remained unchallenged for some 20 years. However, Babadzhanov (1994) suggests that the methodology of these early results was inappropriate. Regarding work from 1967, he states, “The main shortcoming ... is that all their results were based on a theory and methods which are applicable only to single non-fragmenting meteoroids.” Instead he considers a quasi-continuous fragmentation model which is then fitted to the observed light curves of optical meteors. From 85 trails he inferred a mean density of \( 3.3 \) g cm\(^{-3} \), but with a wide spread: 25 were below \( 2 \) g cm\(^{-3} \), 32 were between \( 2 \) and \( 4 \) g cm\(^{-3} \) and 28 between \( 4 \) and \( 8 \) g cm\(^{-3} \). The particles in his study typically have masses of between 0.01 and 10 g, corresponding to diameters of between approximately 2 and 20 mm at the mean density of \( 3.3 \) g cm\(^{-3} \). This is larger than the thin-foil impacts on LDEF, which extend to particle diameters of hundreds of microns at most.

d. Captured Stratospheric Particles

Flynn and Sutton (1991) directly measured the densities of 12 interplanetary dust particles (IDPs) after their capture by high-altitude aircraft. When combed with results of Fraundorf et al. (1982) and Zolensky et al. (1989), a bimodal distribution of densities with peaks at 0.6 and 1.9 g cm\(^{-3} \) is obtained. Love et al. (1993) found no such bimodality in their sample of 100 particles which had been “selected to avoid selection effects.” Their results show “... instead a single broad peak around 2 g cm\(^{-3} \) with a high density tail.” They did not find any particles with densities below \( 0.5 \) g cm\(^{-3} \) and conclude that such low densities are rare; we must note that IDP collection is itself a selective process and the most porous or fluffy particles would not be captured intact. High density meteoroids might also be under-represented, due to ablation. Flynn (1994) summarises the results of captured stratospheric IDPs to date and suggests that, due to fragmentation and compression on atmospheric entry “... the in-space densities of IDPs could be lower than those measured on collected particles.” The retrieved stratospheric particles depend upon selective factors, particularly the interplanetary approach velocity, for atmospheric deceleration and capture; particle survival and fragmentation effects are again particle-sensitive and it could well be that lower-density agglomerates fail to survive for analysis. Indeed, Ratcliff et al. (1995) have shown that cometary particles in the size range retrieved are unlikely to survive a direct atmospheric entry.

3. HYPERVELOCITY IMPACT FOIL PERFORATION RESULTS

a. Impact Physics

An impactor passing through a very thin foil will leave a hole only slightly larger than the particle, thus giving a measure of the particle diameter; there is little dependence
on the impact velocity and the particle density. Clearly if this impactor had, instead, impacted a thick-target then a crater would have resulted. The size of the crater, however, would depend on impact velocity and particle density as well as size. The interception by satellites of these meteoroids, and possibly of space debris, above the atmosphere avoids the selection effects that may possibly corrupt or bias IDP analyses.

The cumulative flux of micrometeoroids that penetrate a foil of thickness, \( f \), may be directly determined by a threshold detector or inferred from thick-target cratering data (Newman 1992, Gardner et al. 1996). This flux distribution (expressed in terms of limiting threshold-penetration, i.e., ballistic limit) permits simple comparison between fluxes from different detectors and spacecraft. The flux distribution at different \( F_{\text{max}} \) values thus has good counting statistics and is ideal for comparing with foil perforation (\( D_h \)) flux data, particularly as the GMC hole growth equation incorporates a ballistic limit term. Because thick and thin targets exposed on the same spacecraft surface experience statistically identical fluxes, the flux at a particular hole diameter may be equated with the \( F_{\text{max}} \) flux. In this way the cumulative flux may be used to map any given perforation diameter to a ballistic limit and thus obtain an empirical \( D_h \) to \( F_{\text{max}} \) conversion. Such a conversion, obtained (Gardner et al. 1996) from the 5 \( \mu \)m aluminium foils exposed on the space-pointing face of LDEF, is shown in Fig. 1. As this conversion is due to impacts on the space-pointing face of LDEF, only a very small fraction of impacts can be ascribed to orbital particles (Love and Brownlee 1993). Figure 1 also shows impact data from the 9.2 \( \mu \)m foil exposed as part of the Eureca TiCCE experiment (Gardner et al. 1996) processed in the same manner.

The normal form of the GMC hole growth equation (Gardner et al. 1997a) (Eq. 1) gives the (normalized) size of particle (\( d_p/f \)) which would form the specified (normalized) hole diameter \( D_h/f \).

\[
d_p' = A \left( \frac{10}{9 + e^{D_h/f}} \right) + D_h (1 - e^{D_h/f}),
\]

(1)

where \( d_p' \) and \( D_h \) are normalized parameters, namely \( d_p/f \) and \( D_h/f \).

At the ballistic limit (\( D_h = 0 \)) it can be seen that the value of \( d_p/f \) is simply \( A \), one of the fitting parameters. At this point our foil thickness (\( f \)) is equal to the ballistic limit (\( F_{\text{max}} \)) for the particle under consideration, and thus we find that \( F_{\text{max}} \) is given by \( d_p/A \). Hence a simple rearrangement gives the ballistic limit (\( F_{\text{max}} \)) for the particle that caused a hole \( D_h \) in a foil of thickness \( f \),

\[
F'_{\text{max}} = \left( \frac{10}{9 + e^{D_h/f}} \right) + \frac{D_h}{A} (1 - e^{-D_h/f}),
\]

(2)

where \( F_{\text{max}} \) and \( D_h \) are normalized parameters, namely \( F_{\text{max}}/f \) and \( D_h/f \).

For an aluminium foil, \( A \) and \( B \) are given by Eq. 3 and 4 (derived from Gardner et al. 1997a)

\[
A = 2.35 \left( \frac{V_{\rho_h}}{\sqrt{\rho_i}} \right)^{-0.723} \alpha_i^{0.145} f^{-0.053},
\]

(3)

\[
B = \begin{cases} 
V < 6.0: & -0.004 + 1.85V \\
V > 6.0: & 6.66 + 0.74V,
\end{cases}
\]

(4)

where in the units for the equation, \( \alpha_i = 6.9 \times 10^7 \) Pa, \( \rho_i = 2780 \) kg m\(^{-3}\), \( f \) is the foil thickness in \( \mu \)m and \( V \) is in km s\(^{-1}\).

d. Obtaining Particle Densities from the Conversion between Perforation Diameters and Ballistic Limit (\( D_h \) to \( F_{\text{max}} \))

Figure 2 shows the variation of Eq. (2) with density and velocity. We note that the equation is only marginally affected by the assumed impact velocity, with particle density having a much larger effect. As many of the following graphs are of this form, we state what this graph shows. For a particle that has perforated a foil of thickness \( f \) to produce a hole of diameter \( D_h \), the graph shows (based on the GMC equation) the maximum thickness (\( F_{\text{max}} \)) of foil that this same particle could have perforated (producing a vanishingly small hole). Thus for a small hole (\( D_h/f < 0.5 \)) the particle could not be expected to penetrate a significantly thicker foil, whereas for a larger hole (say, \( D_h/f = 5 \)) then clearly the particle could have penetrated...
Figure 3 shows that the empirical $D_h$ to $F_{max}$ relationship obtained from LDEF’s space face is consistent with a characteristic density of 1.5 g cm$^{-3}$. We use the term *characteristic density* to refer to a single density which, for the equations used here, best represents the observed data; for particulates of a single value of density, the characteristic density is equal to that density but, as will be shown later, the characteristic density is not the mean density of the incident particle distribution. The velocity used (15.5 km s$^{-1}$) was derived (Deshpande 1993, McDonnell et al. 1993) by comparing the meteoroid impact fluxes on the trailing and space-pointing faces of LDEF and is the normal component of the meteroid’s impact weighted average velocity relative to the spacecraft. This velocity compares well with the (impact-weighted) mean velocity (16.6 km s$^{-1}$) obtained by Taylor (1996) following a reappraisal of the results of the Harvard Radar Meteor Project (Southworth and Sekanina 1973). McDonnell et al. (1996) have applied Taylor’s velocity distribution to the space face of LDEF and found an impact-weighted velocity of 16.0 km s$^{-1}$. While this velocity distribution was obtained from significantly larger particles than we consider here, it has been shown (McDonnell et al. 1996) that its use gives very good agreement with the fluxes observed on the different faces of LDEF, a comparison sensitive to particle velocity (Zook 1991).

Although perforations have been analyzed on Eureca TiCCE (Gardner et al. 1996), insufficient impact craters on thick targets have been located to permit such an accurate direct intercomparison as was possible with the LDEF data, requiring instead a smooth line to be fitted through the available flux data from thick targets. As shown in Fig. 4 the bulk of the impacts are also seen to be consistent with particles of 1.5 g cm$^{-3}$, although the smallest ($D_h/f < 3$) impacts suggest a lower density. This low density result is caused by a small step in the observed cumulative $D_h$ distribution which the $F_{max}$ distribution cannot, because of the smoothing (Gardner et al. 1996), duplicate. It is thus unclear, because of the smaller number of data-points available, whether this is a genuine facet of the Eureca data or is an artefact. With the LDEF data, however, the low characteristic density of the impactors is clear.

The curve obtained from Eqs. (2)–(4) has, thus far, been fitted to the impact data. However, it is equally possible...
c. Simulations Using Distributions

Thus far, only a single value of the velocity and density have been considered in the penetration formula. It might well be the mean value, but this would have to be demonstrated, and so the effects of a velocity and density distribution have been considered. Anomalous results could, for example, be produced from a bimodal distribution of particles.

To assess these effects and possible bias in the interpretation of space data, a series of simulations have been performed, where a particle size distribution similar to that observed on the LDEF satellite was modeled impacting on foils and on thick targets, using the modified GMC equation. The density of each particle is (pseudo) randomly selected in such a way that the density distribution of the simulated impacts corresponds to a published density distribution. Simulations were performed using the distributions published by Flynn and Sutton (1991) and Love et al. (1993) and also those obtained from meteor observations by Babadzhanov (1994). As before, an impact velocity of 15.5 km s\(^{-1}\) is used. To maintain consistency with the experimental results, the simulations consisted of 185 particles impacting each of the surfaces (equal to the total of 185 perforations detected on the LDEF MAP space pointing foils). The method of equating fluxes described earlier was then applied to the resultant data and \(D_h\) to \(F_{\max}\) conversions obtained.

As shown in Figs. 6 to 9 results from several simulation runs are consistent with the input data in that the points do not lie outside the range of the input densities. Figure 10, however, shows clearly that the best fit through the data (i.e., the characteristic density) is not the mean density of the sample, but is biased to yield a lower density than the true mean. This bias results simply from the use of a...
FIG. 8. The LDEF fit compared to simulation results using Love et al.’s density distribution. A single velocity of 15.5 km s\(^{-1}\) was used.

non-linear equation \(f(\rho_i)\), since in general \(\bar{f}(\rho_i) \neq f(\bar{\rho})\). The graphs also show, for the published density distributions, that those obtained from intact capture do not match the LDEF data well. Only Babadzhanov’s sporadic distribution is likely to produce results comparable to those for the space face of LDEF if the single velocity is used.

We have also to date used a single velocity in the simulations; however, to be strictly accurate a velocity distribution should be used. For this purpose the results obtained by Taylor (1995) (based on a reappraisal of data from the Harvard Radio Meteor Project) are therefore now used. The meteor (atmospheric entry) velocities are reduced (by 2/3) to obtain normally resolved mean impact velocities.

Further simulations (described in the next section) show the method to be sensitive to small numbers of low density particles. However, it is the low density IDPs which are least likely to survive atmospheric deceleration and capture, thus it is not surprising that the density distribution of Love et al. (1993) (from IDPs) does not compare well with the \textit{in situ} results. Furthermore, any increase of particle densities due to deceleration forces (as suggested by Flynn 1994) would clearly contribute to this effect. The distribution of Flynn and Sutton (1991), in contrast with that of Love et al., shows a lower density than we find on our exposed surfaces; the reason for this discrepancy is not clear. Looking towards the impacts on lunar rocks for information on particle density, we find problems due to secondary impacts and also the velocity spread of the impacting particles. The data most likely to correspond with spacecraft measurements are thus the radar meteor data of Babadzhanov. Caswell et al. (1995) have shown that sporadic meteors cause the bulk of impact damage on spacecraft and thus Babadzhanov’s sporadic distribution is chosen as the most representative, both from the above reasoning and the results of the single velocity distributions. Figure 11 shows the results of simulation calculations using these velocity and density distributions; as can be seen, the simulated data are now very close to the empirical data, although the LDEF results still suggest a lower density in the range 0.5 < \(D_h/f\) < 3. We noted, however, that the meteoroids in Babadzhanov’s sample are significantly larger in scale than the impacts on the satellite (~2 mm in diameter), whereas the \textit{largest} particle impacting the LDEF MAP space face has a diameter of some 200 \(\mu\mathrm{m}\).

d. Quantifying the Bias

To quantify the divergence between the mean sample density and the fitted value two further series of simula-

FIG. 9. The LDEF fit and TiCCE data compared to simulation results using Flynn and Sutton’s density distribution. A single velocity of 15.5 km s\(^{-1}\) was used.

FIG. 10. The results of fitting a single density to the simulated results earlier. The solid line marks the ideal case of equal fitted and mean densities; the data show that a single density fitted to the data is somewhat below the mean particle density; i.e., \(\bar{f}(\rho) < f(\bar{\rho})\). Also shown (dotted line) is the value obtained from fitting to the space data.
FIG. 11. The LDEF fit compared to simulation results using the density distribution from the sporadic meteoroid results of Babadzhanov, combined with the velocity distribution of Taylor. General agreement with the LDEF and TiCCE satellite data is seen. Comparing this graph with Fig. 8 it is seen that including the velocity distribution has only minimal effect.

FIG. 12. Effects of adjusting the mean of a bimodal density distribution, consisting of 1.0 and 7.8 g/cm³ particles. The graph shows that a small component of low density particles has a significant effect on the best fitting density, whereas a small component of high density particles has negligible effect.

FIG. 13. Effects of adjusting the standard deviation of a monomodal density distribution. Neither the sample mean nor the shape of the distribution is seen to affect the graph significantly, in contrast to the effects from a bimodal distribution.

TABLE I

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Mass range (approx.)</th>
<th>Mean density (µ) (g cm⁻³)</th>
<th>Std. Dev (S) (g cm⁻³)</th>
<th>De-rating ratio (R) S/µ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babadzhanov</td>
<td>&gt;10⁻²</td>
<td>3.3</td>
<td>1.8</td>
<td>0.56</td>
</tr>
<tr>
<td>(Sporad)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flynn &amp; Sutton</td>
<td>10⁻¹³–10⁻¹¹</td>
<td>1.1</td>
<td>0.63</td>
<td>0.57</td>
</tr>
<tr>
<td>Love et al.</td>
<td>10⁻¹³–10⁻⁹</td>
<td>2.4</td>
<td>1.1</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Note. The standard deviations of the distributions used earlier in this work are combined with the results shown in Fig. 13 to give an improved estimate of the mean density of particles impacting the space face of LDEF.
mean aspect ratio of $1/\cos(45) = 1.41$, but only for the largest perforations (i.e., $D_h/f > 10$); it cannot, however, account for the irregular perforation shapes of Fig. 14.

The effect of density in decoding perforation data is shown in Fig. 16 on a cumulative impact flux plot. In the case where the perforation is marginal, this clearly represents a particle with an $F_{\text{max}}$ value only slightly larger than the thickness of the sample foil, hence the selection of a different particle density for such a particle has a negligible effect on our conversion. However, as the particle size increases the effect becomes more significant; for the space face, however, the uncertainties in the flux largely mask the uncertainties due to density. We note, once again, that perfect agreement between the thick and thin-target data is not obtained using a single density across the whole size range.

FIG. 14. Impacts on foils from the Eureca TiCCE experiment. The line drawings in the upper portion of the figure show all the impacts detected on a particular sample of foil and are shown at the same (arbitrary) scale. The lower portion of the figure (SEM image) shows the permanent record left by an impactor of its geometrical cross section as it passed through the thin foil.

4. ANALYSIS OF PERFORATION PROFILES

Figure 14 shows a selection of the perforations from the Eureca TiCCE experiment; the line drawings in the upper section of the figure are all at the same (arbitrary) scale and represent all of the detected impacts in a particular sample of foil. While totally spherical particles are uncommon, most of the impacts are not far from this cross-section, with the aspect ratio (length/width) rarely exceeding 2. Extreme ratios, which would be produced by needles or flakes, are not observed. The reentrant morphology of the lower image of Fig. 14 is an unusual example. Figure 15 shows the perforating impacts on the Eureca TiCCE foils with their measured diameters and the results of applying the GMC equation to the hole diameters. It should be noted also that the aspect ratio for a large perforation can also depend on the impact angle; a spherical particle impacting at a grazing angle can, indeed, cause a highly elongated perforation. This effect alone would predict a

FIG. 15. Comparison between major and minor axes of TiCCE impacts. Measurements for perforations and calculated diameters (obtained from the GMC equation with $\rho = 2.0$ and $v = 15.5$ km s$^{-1}$) for the corresponding particles are shown. Measurements are normalized to foil thickness. The graph also shows lines representing aspect ratios of 1.0 and 1.41.
from the shape of the Grün et al. (1985) interplanetary flux model (shown for reference), which is otherwise quite well matched by this data. Foil penetration data from LDEF’s east face, Eureca TICCE (Gardner et al. 1996) and from EUROMIR ’95 ESEF (Shrine et al. in press, Gardner et al. 1997b) is shown.

Application of the method to surfaces such as LDEF’s east face (Fig. 17b) or Eureca TICCE (Fig. 18b) which receive a significant number of impacts due to space debris must necessarily be less conclusive than those where the debris component is small (such as LDEF’s space face). This is due to the variable mixing ratio (as a function of size) between debris and interplanetary particles, as well as the different velocity distributions involved. Further

FIG. 16. (a) LDEF space-face impacts, which are dominated by interplanetary meteoroids. Foil perforations have been converted to Ballistic limits ($F_{max}$) using the GMC equation and a choice of particle densities. The thick-target (cratering) data is shown for comparison. General agreement with a density of 1.5–2.5 g cm$^{-3}$ is illustrated at small to intermediate sizes ($F_{max}$ between 5 and 200 μm), with a trend towards lower densities at larger dimensions. (b) Application of the same method to the thick and thin (5 μm foil) target impacts of the LDEF east face which is readily accessible to space debris. The data does not extend to overlap the region where the interplanetary flux (space face) shows a potential trend towards lower densities.

FIG. 17. LDEF space- (a) and east- (b) facing cumulative flux, as a function of ballistic limit, compared to modeling based on the Grün et al. (1985) flux distribution (reproduced from McDonnell et al. 1996). The agreement between the interplanetary flux and LDEF space face (a) is well within the tolerances of measurement and calibration. The contribution of orbital (space debris) particles on the east face (b) is clearly visible below $F_{max} = 40$ μm, exceeding the natural interplanetary population by a factor of 10 at a penetration thickness of 2 μm.
TABLE II

<table>
<thead>
<tr>
<th>Typical Properties of a Micrometeroid (in the Mass Range $10^{-9}$–$10^{-11}$ kg) Consistent with LEO Impact Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean/characteristic density</td>
</tr>
<tr>
<td>Velocity distribution</td>
</tr>
<tr>
<td>Mean impact velocity—Impact (penetration formula) weighted for all angles</td>
</tr>
<tr>
<td>Source</td>
</tr>
<tr>
<td>Shape</td>
</tr>
<tr>
<td>Aspect ratio</td>
</tr>
</tbody>
</table>

FIG. 18. The LDEF space face perforation fluxes, converted to particle mass (based on a mean density of 2.2 g cm$^{-3}$). The conversion to mass has been performed at 3 velocities (a), and shows generally good agreement with the distribution of Grün et al. (1985). Since the earlier analysis shows a reduced density for the large perforations (mass $> \sim 10^{-7}$ g), the converted MAP data at these sizes should possibly be moved to the left, as indicated by the error bars. (b) Results from foil penetration data from other exposures (LDEF east face) and satellites (Eureca TiCCE and Mir ESEF) are shown. In both (a) and (b) the Grün et al. flux has been adjusted by a factor of 2.0 (McDonnell et al. 1996) to account for gravitational focusing but no attempt is made to correct for exposure geometry or pointing history.

consideration of these effects is given in a recent review (McDonnell et al., in press) of recent and historical near Earth spacecraft measurements, considering meteoroid and space debris.

5. CONCLUSIONS

The use of data from both thick and thin target materials has permitted the characteristic in situ density of interplanetary dust particles to be determined. Simulated results using density distributions show the approach has a high sensitivity to the low density component of the impacting particle flux; this is a likely effect on space exposed thin-foil detectors, and results from the larger area of such impactors. Results are summarized in Table II.

Results from the space face of LDEF (and from Eureca TiCCE) indicate a characteristic micrometeroid density of $\sim 1.5$ g cm$^{-3}$ for most of the impacts, with a lower density for the largest impacts, although the errors at this dimension are significant. Numerical simulations using density distributions from other methods show, despite a good correlation with Babadzhanov’s sporadic distribution, that the distributions obtained from stratospheric collections do not agree well with the space data. Analysis of the method presented here has shown that either a small fraction of low density particles or a large standard deviation in the density spectrum can cause a significant reduction in the characteristic density. Correcting for these effects leads to a detected mean particle density in the range 2.0 to 2.4 g cm$^{-3}$, a value somewhat lower than that obtained by other methods. However, it is noted that the other methods are typically inefficient in sampling low density particles.

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REFERENCES


