DETERMINATION OF HYPERVELOCITY IMPACTOR SIZE FROM THIN TARGET SPACECRAFT PENETRATIONS

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ABSTRACT

Analysis of space-flown experimental surfaces requires the use of calibration data, usually in the form of an empirically derived penetration equation. These equations necessarily have limits on their applicability, some more than others. A recently published equation, and its applications, are discussed and the equation is then used to analyse thin foil impact data from the LDEF, Eureca and Mir spacecraft.

1. INTRODUCTION

As is becoming increasingly known, even among the general public, spacecraft receive impacts from debris and natural particles, which can cause surface degradation or, for large impactors, catastrophic damage.

Whilst large objects may be tracked from the ground, the population of particles below 1 mm in diameter is best studied by in-situ detectors, which may be either active or passive in nature, both requiring careful calibration. Active sensors clearly have advantages in terms of time-resolution and (for some detector types) sensitivity. Passive sensors, however, have an important role to play due to their simplicity, low mass, and the high area-time product possible for such detectors, especially when "detectors of opportunity" such as structural surfaces(Ref. 1) and solar cells(Ref. 2) are considered. Passive sensors do, of course, require retrieval.

Foil penetration experiments provide a simple method of impact flux determination and have been flown on many space missions, for example: early shuttle missions (Ref. 3); NASA's LDEF and ESA's Eureca satellites (Ref. 4, 5); and the MIR space station (Ref. 6). Unfortunately the foil penetration formulae previously in use have inherent limitations, in terms of the range of hole sizes that may be interpreted (most of the equations fail to model the correct behaviour near marginal perforation) and the limited range of targets and projectiles from which they were derived. These limitations can lead to a significant divergence between the equations and experimental data (Ref. 7). A recent effort in overcoming them has led Gardner et al. (Ref. 8) to the construction of a new equation.

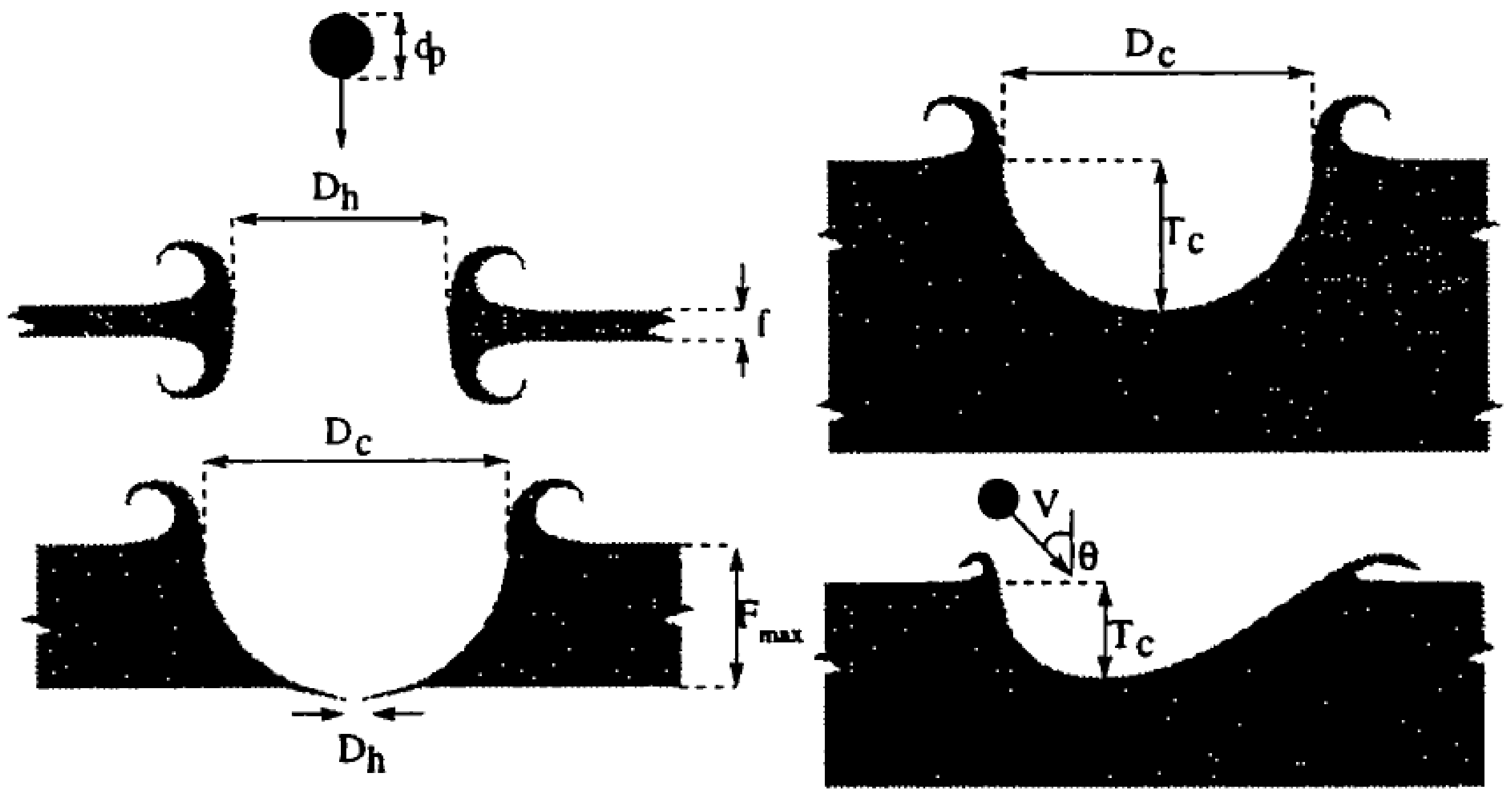

Figure 1: Measurements taken from a hypervelocity impact.

2. NOTATION AND MEASUREMENTS

d_p	particle diameter	f	foil thickness
D_h	hole diameter	T_c	crater depth
D_c	crater diameter	F_{max}	ballistic limit
V	Velocity	θ	Impact Angle
ρ	density	σ	yield strength

All measurements are relative to, or in, the original surface plane, except for D_h which is measured at the smallest diameter and θ which is relative to the surface normal. The ballistic limit, F_{max}, is defined as the maximum thickness of foil that the particle would perforate. Measurements are shown in Fig. 1.

3. THE GMC EQUATION

The equation of Gardner, McDonnell and Collier (Ref. 8) (or GMC equation) is unusual in that rather than giving the hole diameter caused in a given foil by a known particle, it gives the diameter of the particle that caused a known hole. This approach better represents the situation with the analysis of space-flown foils and also greatly simplifies the mathematics.

The equation (shown in Fig. 2 compared to equations of Nysmith and Denardo (Ref. 9), Sawle (Ref. 10), Maiden et al. (Ref. 11) and Carey et al. (Ref. 12)) takes the form:

$$\frac{d_p}{f} = A\left(\frac{10}{9+e^{\frac{D_h}{fB}}}\right) + \frac{D_h}{f}\left(1 - e^{-\frac{D_h}{fB}}\right) \quad (1)$$

where A and B are dependent on the projectile and target materials and parameters. The values

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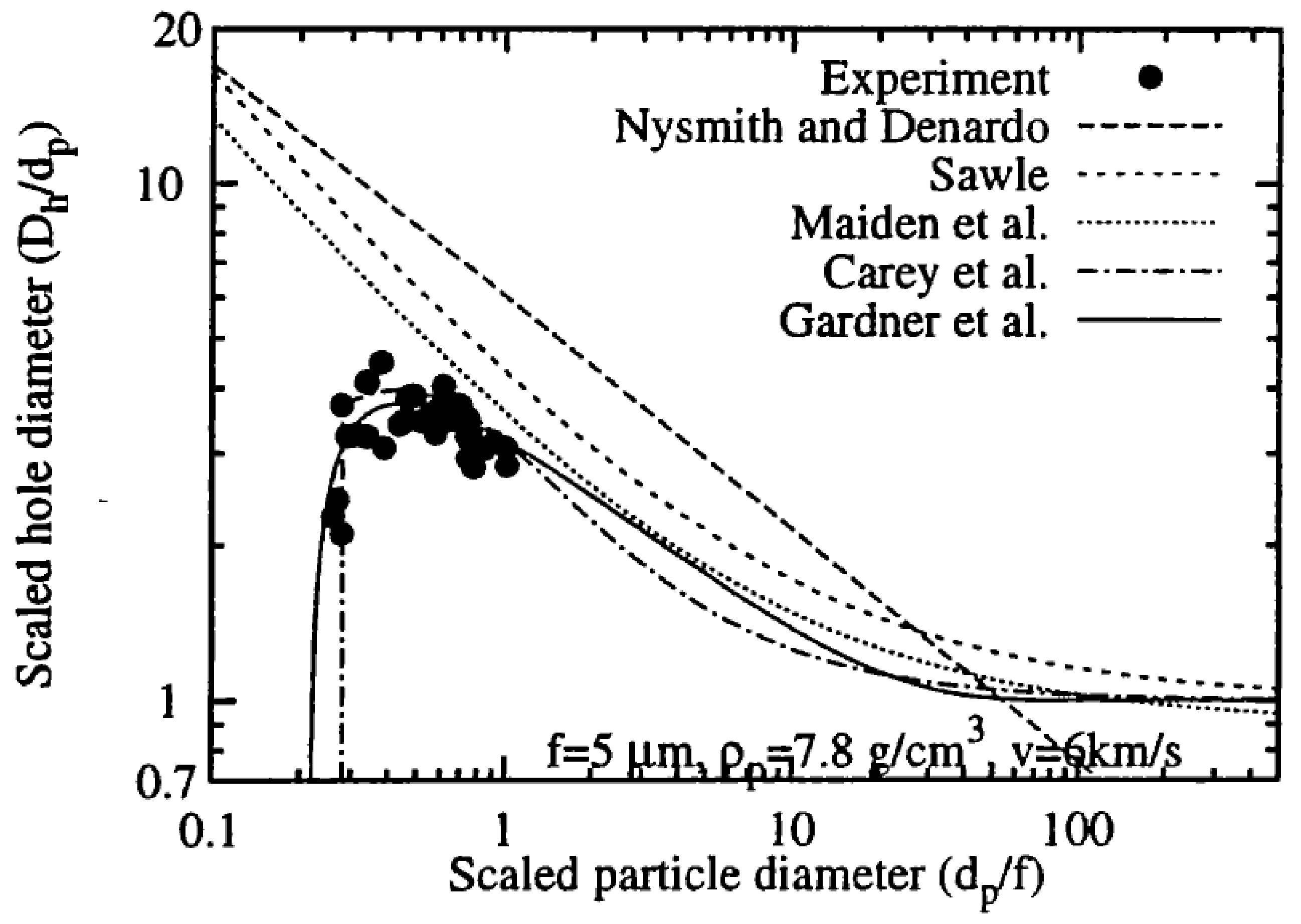

Figure 2: the GMC equation compared to other hole growth equations. 15

of A and B (for an aluminium target) are given in Eqs. 2 & 3. Where f is in μm and all other units are in SI.

$$A = 6.97 \left(\frac{V \rho_p}{\sqrt{\sigma_t \rho_t}} \right)^{-0.723} \left(\frac{\sigma_t}{\sigma_{Al}} \right)^{-0.217} f^{-0.053} \quad (2)$$

$$B = \begin{cases} V \leq 6.0\,\mathrm{km/s} : 1.85 \times 10^{-3} V - 0.004 \\ V > 6.0\,\mathrm{km/s} : 0.74 \times 10^{-3} V + 6.66 \end{cases} \quad (3)$$

4. APPLICATION TO SATELLITE IMPACT DATA

Impact data from foils exposed on the three satellites of interest in this work have been published elsewhere (Ref. 4, 5, 6, for example) as hole diameter and/or perforation limit fluxes. Here we apply the GMC equation to the data and thus obtain particle diameters and masses. Before this is possible it is first necessary to identify a range of values for the velocity and density of the impacting particles.

The possible impact velocity range is dependent on whether the particle is orbital or interplanetary. Comparisons between impacts on LDEF and Eureca (Ref. 13) have shown that the averaged impact flux on LDEF is dominated by interplanetary particles in the range $30 < F_{max} < 1000\,\mu$m ($1000\,\mu$m representing the largest impacts on the surfaces considered). Using their modelling techniques and the velocity distribution of Taylor (Ref. 14), McDonnell et al. (Ref. 15) have found the (impact weighted) mean particle velocity of meteoroids on LDEF's space face to be 24.6 km/s. The mean impact velocity can be shown to be 2/3 of this value.

The use of the GMC equation in a comparison between thick and thin targets (Ref. 16) has revealed that the impact data suggests a mean density of 2.0–2.4 g/cm^3, a result also consistent with those obtained by other approaches, such as analysis of crater depth to diameter ratios (Ref. 17) (2–5 g/cm^3).

Particle Velocity m/s	A kg/m^3	B
31.6×10^3	0.240	22.2
24.6×10^3	0.287	18.8
19.6×10^3	0.338	16.3

Table 1: Values of A and B used to obtain particle diameters from hole diameters. A is given for a 1 μm foil and a 2.2 g/cm^3 particle.

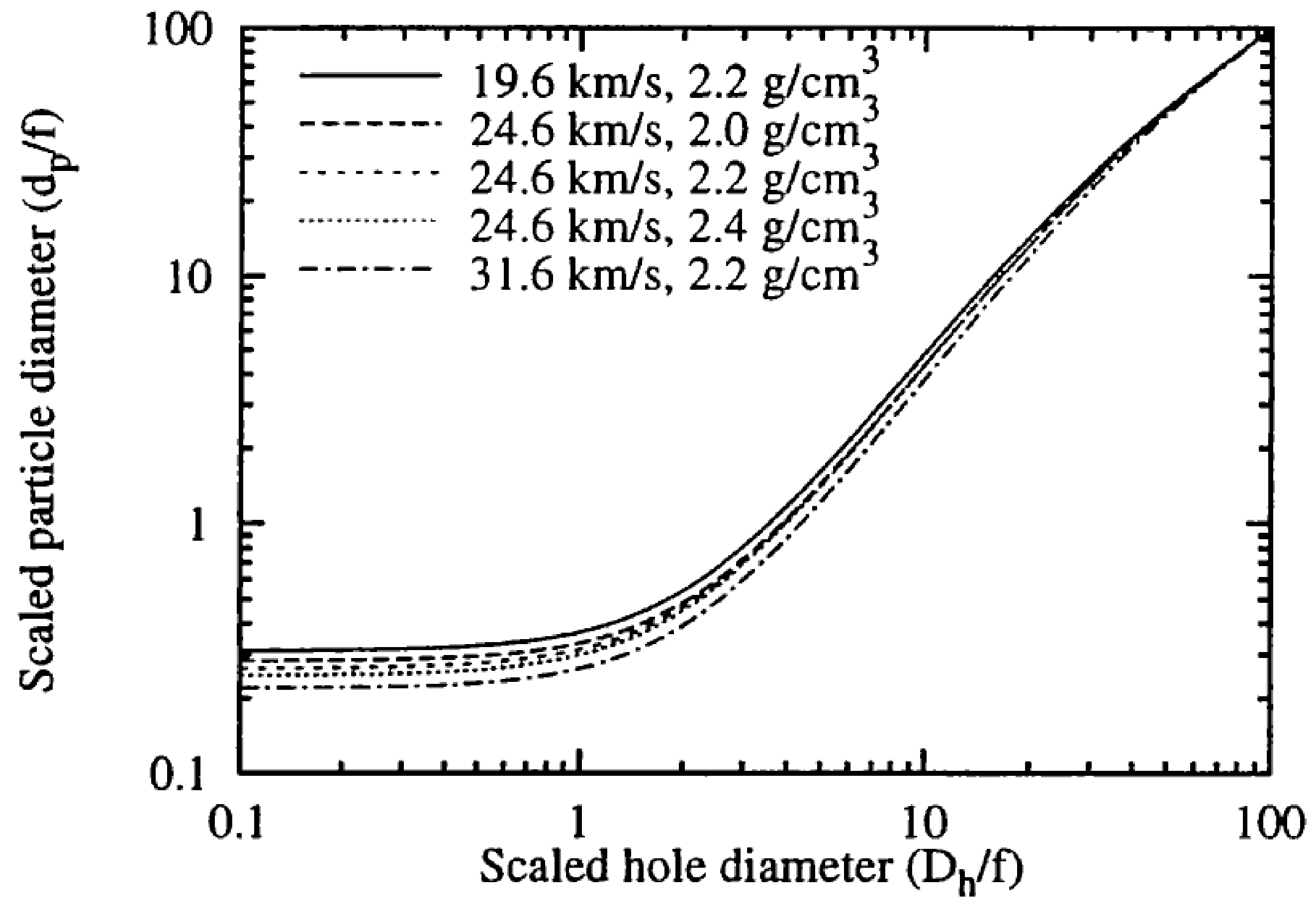

Figure 3: Effect of impact velocity and density on function used to convert hole diameters to particle diameters.

In this analysis, therefore, we take the simplest approach and apply these mean velocities and densities to the perforation data. To show the effect of velocity we use a ±5 km/s bracket. A full comparison would demand the use of modelling techniques to find the characteristic velocities and densities to be used for the different surfaces (i.e. the single values that represent the distribution best), which is beyond the scope of this paper.

Table 1 shows the parameters A and B for these three limiting cases. Fig. 3 shows the relationship between D_h/f and d_p/f for these three cases and also for densities 2.0 and 2.4 g/cm^3. It is observed that above $D_h/f \simeq 5$ the particle density has little effect compared to that of the impact velocity, which is significant until $D_h/f \simeq 100$.

Figs 4 and 5 show the perforation data after application of the relationship as particle diameters and masses respectively. The interplanetary flux of Grün et al. (Ref. 18) (assuming 2200 kg/m^3 particles for Fig. 4) is also shown as a reference. An enhancement factor of 2.0 (Ref. 19) has been applied to account

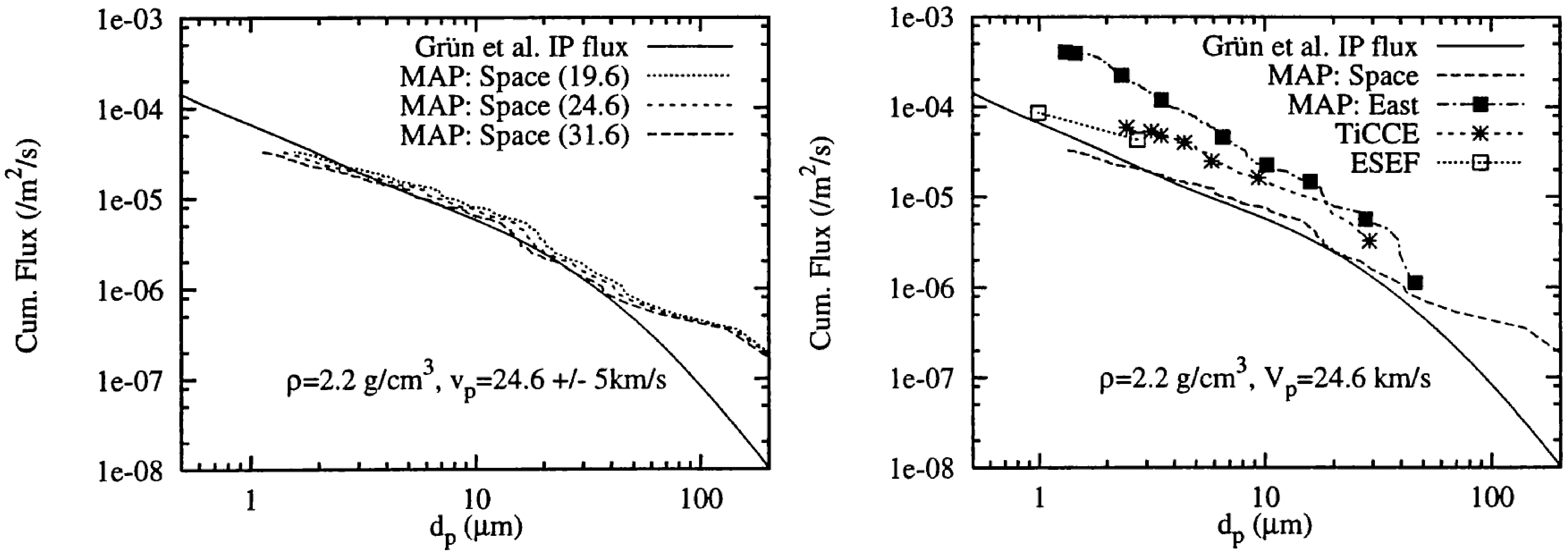

Figure 4: Particle diameter fluxes obtained using the functions of Fig. 3. The Grün et al. IP flux has been multiplied by 2.0 to account for gravitational enhancement.

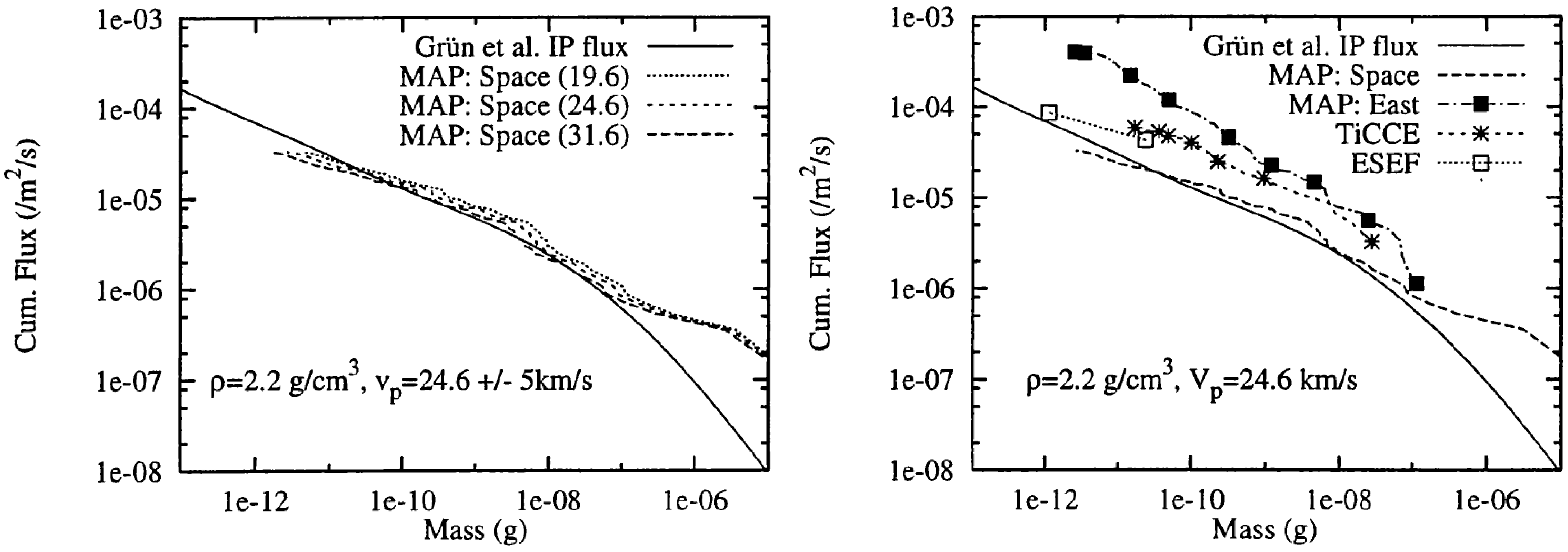

Figure 5: The Particle diameter fluxes of Fig. 4 are here shown as masses.

for gravitational focusing.

As would be expected the fluxes for TiCCE and MAP east face are higher than that of Grün et al., as no attempt has been made to account for spacecraft movement or the flux enhancement towards the Earth's apex of motion.

One somewhat anomalous result is that ESEF (which was nominally Earth pointing and thus should have received a very low flux) records an impact flux that is of similar order to that of TiCCE (Earth-ram direction). A partial explanation for this is that MIR performed a number of manœuvers during the exposure time, giving the detectors access to more favorable exposure geometries. We also note that the active sensors of ESEF (Ref. 20) detected a localized debris cloud in a size range capable of perforating the foils.

5. CONCLUSIONS

The equation of Gardner et al. has many applications in de-coding satellite impact data, a few of which have been discussed here. One notable result is that by using the equation particle diameter fluxes (and thus mass fluxes) may now be obtained from foil perforation data. This in turn has permitted (somewhat simplistic) comparisons between a number of different exposures to be made.

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