

INTER-AGENCY SPACE DEBRIS COORDINATION COMMITTEE



IADC Action Item 24.1

Comparison of Meteoroid Models

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Table of Content

TABLE OF CONTENT	3
1. INTRODUCTION AND OBJECTIVES OF IADC AI 24.1	4
1.1. OVERVIEW AND SCOPE OF ACTIVITIES	5
2. SELECTION OF MODELS AND TEST CASES	5
2.1. SELECTION OF MODELS FOR COMPARISON	5
2.2. DEFINITION OF TEST CASES	5
3. MAIN MODEL FEATURES	6
3.1. GRÜN ET AL. INTERPLANETARY FLUX MODEL	6
3.2. DIVINE MODEL	7
3.3. DIVINE-STAUBACH MODEL	8
3.4. IMEM/DIKAREV MODEL	9
3.5. MEM MODEL	10
4. MODEL PREDICTIONS	11
4.1. EARTH ORBITS	11
4.1.1. Fluxes	11
4.1.2. Velocities	13
4.2. INTERPLANETARY DISTANCES	17
4.2.1. Fluxes	17
4.2.2. Velocities	18
5. CONCLUSIONS	21
6. REFERENCES	24

1. Introduction and Objectives of IADC AI 24.1

Any assessment of particle impact risks to spacecraft in orbit requires reliable meteoroid population models. Over the last decade, new models for the sporadic interplanetary meteoroid flux have been developed. These models cover the full velocity range and particle diameters from sub-microns to cm.

At present several meteoroid models exist which were developed by different organisations, use different approaches, and often lead to different results. This can be confusing for the comparison and verification of flux predictions and for impact risk assessments of spacecraft. The issue was discussed within IADC Working Group 2 and there was a general agreement that existing meteoroid models should be analysed in more detail.

During the 24th IADC meeting in 2006 Working Group 2 proposed an IADC Action Item to compare the existing interplanetary meteoroid population models, to identify their basic assumptions and to address potential future developments. The IADC Steering Group accepted the proposal in October 2006 as new IADC Action Item 24.1.

The objective of this AI 24.1 is to: 'Identify differences in present meteoroid population models'.

The following specific tasks were foreseen under this AI 24.1:

- Compare the latest existing meteoroid population models.
- Identify differences of the models and if possible the underlying reasons for these differences.

A Final report and a recommendation for a route forward were the expected outputs.

Participants of AI 24.1 were:

- Italian Space Agency (ASI)
- European Space Agency (ESA)
- Japan Aerospace Exploration Agency (JAXA)
- National Aeronautics and Space Administration (NASA)

The activity was lead by ESA.

1.1. Overview and Scope of activities

WG 2 started work on AI 24.1 during the 25th IADC meeting in 2007. The following specific tasks were identified:

- Preparation:
 - Selection of models for comparison
 - Definition of test cases
- Identification of main features of selected models
- Model predictions
- Conclusions
 - Summary
 - Route forward

2. Selection of models and test cases

2.1. Selection of models for comparison

The following meteoroid models were selected for the model comparison:

- **Grün et al interplanetary model ([Ref. 1], 1985, with different velocity distributions)**
- **Divine Model ([Ref. 2], 1993)**
- **Divine-Staubach Model ([Ref. 3], 1996)**
- **Interplanetary Meteoroid Engineering Model (IMEM)/Dikarev ([Ref. 4], 2003)**
- **Meteoroid Engineering Model (MEM) ([Ref. 5], 2004/2007)**

It was agreed that NASA would perform the calculations for the MEM model while ESA would run the other models.

2.2. Definition of test cases

The following orbits, types of targets, mass ranges and analysis parameters were selected for the model comparison:

Earth orbits

- Epoch (if needed): March 21st
- Circular orbit at 400 km altitude, inc = 51.6 deg (ISS type orbit), averaged over right ascension of the ascending node (Ω).
- Circular sun-synchronous at 1500 km altitude, inc = 102 deg, averaged over Ω
- Circular GEO at 36000 km altitude, inc = 0 deg

Interplanetary

- Epoch (if needed): March 21st
- Sun-Earth L2 (heliocentric, circular, inc = 0 deg)
- Fluxes at approximate sun distances of Mercury, Venus, Earth, Mars (heliocentric, 0.4, 0.7, 1, 1.5 AU, circular, inc = 0 deg; gravitational focusing effects are ignored)

Targets and other parameters to be analysed

Sphere (Earth-orbiting and interplanetary)

- Flux [$\text{N}/\text{m}^2/\text{yr}$] (average flux to outer surface of sphere, not cross-sectional flux)
- Velocity distribution

Cube (Earth-orbiting)

- Fluxes ($\text{N}/\text{m}^2/\text{yr}$) on the 6 surfaces of a cube (ram, anti-ram, starboard, port, zenith, nadir)
- Velocity distribution on each surface

Mass range: 10^{-9} , 10^{-8} , ... 10 g (or applicable range of models)

In some cases smaller masses were studied as well.

Velocity range: 0 to 72 km/s (2 km/s increment)

To reduce the number of calculations, model comparisons were performed for a representative subset of the specified parameters only.

3. Main Model Features

3.1. *Grün et al. interplanetary flux model*

Applicable regime:

- Interplanetary space around 1 AU from the sun
- Mass range: 10^{-18} – 100 g

Basic features:

It is an isotropic model. It is assumed that relative to the surface of the Earth meteoroids arrive isotropically from all directions and with the same velocity.

The model is based on data from lunar craters, zodiacal light and in-situ measurements.

The model is represented through an analytical fit using mass as variable parameter.

A fixed velocity of 20 km/s was assumed to derive fluxes.

A material mass density of 2.5 g/cm^3 was assumed.

Additional information:

The average total fluxes predicted by this model for near Earth space are well verified. Interplanetary flux models developed more recently usually fitted the average fluxes near Earth to this Grün model.

However, the assumption of a fixed velocity and material density introduces ambiguities.

The Grün model itself [Ref. 1] does not include a velocity distribution. In the past the model has usually been used with either of the following assumptions for the velocity:

- A fixed velocity (usually taken as 20 km/s, the value applied for deriving the fluxes).
- The velocity distribution from SSP 30425 ([Ref. 6])
- The HRMP (Harvard Radio Meteor Project) velocity distribution [Ref. 7]

For the following comparison of the various meteoroid models, the HRMP velocity distribution is usually used. The distribution from SSP 30425 is a simplification and is only applicable for Low Earth Orbits (LEO).

3.2. Divine model

Applicable regime:

- Between 0.1 and 20 AU from the sun
- Mass range: $10^{-18} - 1 \text{ g}$

Basic features:

Divine's model determines particle numbers in a heliocentric position/velocity space. Meteoroid densities depend on probability densities for the perihelion distance, eccentricity and inclination of the heliocentric keplerian meteoroid orbits. The meteoroid environment was separated into 5 different populations, each having its own characteristics:

- Asteroidal population
- Core population
- Halo population
- Inclined population
- Eccentric population

The selection was done under the premise that the core population covers the major part of the overall population, while the other minor populations represent subsets of common characteristics.

The model is available as computer based tool.

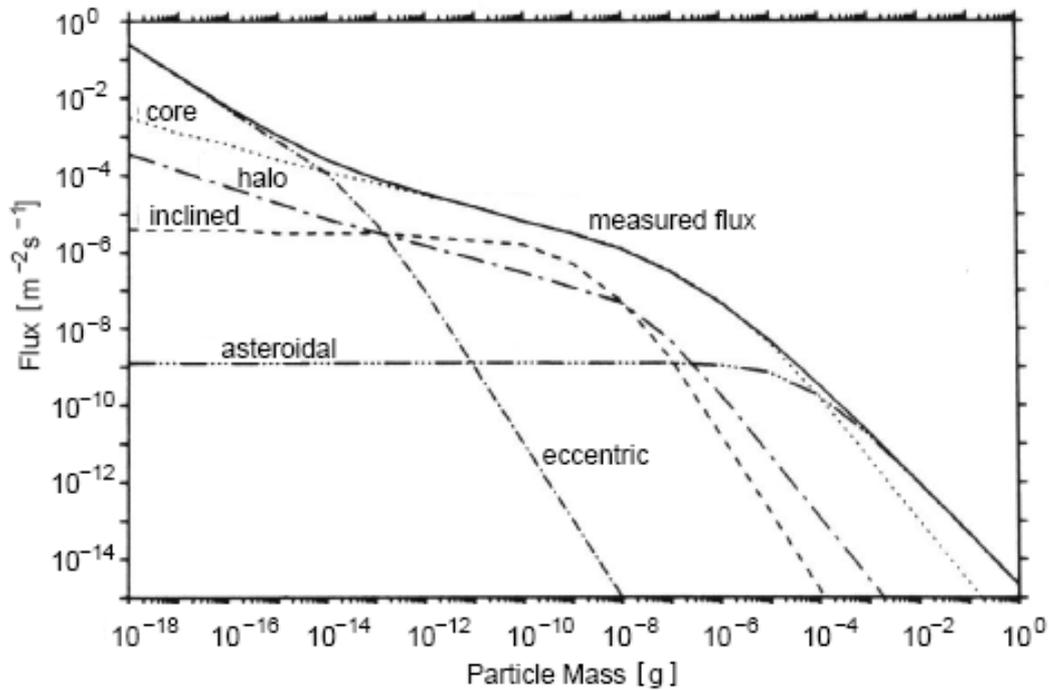


Figure 1: Predicted flux vs. meteoroid mass in a heliocentric system at 1 AU according to the Divine model.

Additional information:

Each population has its own specific directional and velocity distribution. The resulting directional distribution is not isotropic.

Different numerical implementations of the Divine model are available.

3.3. Divine-Staubach model

Applicable regime:

- Between 0.1 and 20 AU from the sun
- Mass range: 10^{-18} – 1 g

Basic features:

The model is a follow-up of the Divine model and has the same basic structure. It consists of 6 populations:

- A population (replaces inclined population of Divine model)
- B population (replaces eccentric population of Divine model)
- C population (replaces halo population of Divine model)
- Asteroidal population
- Core population
- Inter-Stellar Dust (ISD) population

The model is available as computer based tool.

Additional information:

Staubach updated the Divine model re-fitting the probability densities, taking into account data from dust detectors flown aboard the Ulysses and Galileo spacecraft. As a result of the broader data set, additional characteristics of the orbital distributions appeared. Accordingly, Staubach re-organized the minor populations (inclined, eccentric and halo) and their nomenclature. In addition, an interstellar contribution was added.

This directional distribution is not isotropic. Each population has its own specific directional and velocity distribution.

The modifications mainly concern masses smaller than 10^{-10} g. For larger masses results from the Divine and Divine-Staubach models are very similar or identical.

The Inter-Stellar Dust population is represented by a mono-directional stream of particles. Near 1 AU fluxes are calibrated to those from the Grün model.

3.4. IMEM/Dikarev model

Applicable regime:

- Between 0.1 and 10 AU from sun
- Mass range: 10^{-18} – 1 g

Basic features:

The model is made of 5 components which differ by their sources and dynamics:

- Asteroidal collisions
- Asteroidal Poynting-Robertson
- Comets collisions
- Comets Poynting-Robertson
- Interstellar dust (adopted from Divine-Staubach model, re-fitted with Ulysses data)

Dikarev used an improved and controlled data set and applied refined mathematical methods in order to describe three-dimensional distributions of orbital elements (instead of the mathematically separable distributions of Divine).

The model is available as computer based tool.

Additional information:

The model aims for a correct physical treatment of the sources and dynamics of the different components. Cometary sources clearly dominate (with > 95%) the population. This directional distribution is not isotropic. Each population has its own specific directional and velocity distribution.

Infrared measurements of the zodiacal cloud by the COBE/DIRBE instrument were adopted as new model reference.

Near 1 AU fluxes are calibrated to those from the Grün model. This fit was done differently than for the Divine and Divine/Staubach models. Those models fitted the particle size distribution to the Grün model, while the IMEM/Dikarev model was fitted to the underlying crater size distribution on the lunar rocks instead.

The Interstellar dust population was adopted from the Divine-Staubach model, however with a modified cumulative mass distribution and re-fitted again with Ulysses and Galileo data.

3.5. MEM model

Applicable regime:

- Between 0.2 and 2 AU from the sun
- Mass range: 10^{-6} – 10 g

Basic features:

Components of the model are:

- Comet disintegration from
 - a) Short period families (Jupiter and Halley)
 - b) Long period family
- (Asteroid collisions)

Near 1 AU fluxes are calibrated to those from the Grün model.

A constant mass density of 1.0 g/cm^3 is assumed.

The velocity distributions are independent from the particle sizes.

The model is available as computer based tool.

Additional Information:

The primary data source of the MEM model is the Canadian Meteor Orbit Radar (CMOR).

The model is based on 6 radar/photographic meteor sources (Helion, Anti-Helion, North Apex, South Apex, North Toroidal, South Toroidal).

The model assumes that most or all meteoroids are of cometary origin. Contributions from asteroid collisions can be considered or neglected.

4. Model predictions

4.1. Earth orbits

4.1.1. Fluxes

The different meteoroid models are first compared for Earth orbits. Results are here presented first for an ISS type orbit (circular at 400 km altitude and 51.6° inclination). Figure 2 shows predicted fluxes to one side of a Randomly Tumbling Plate (RTP) for a mass range of 10^{-15} to 1 g.

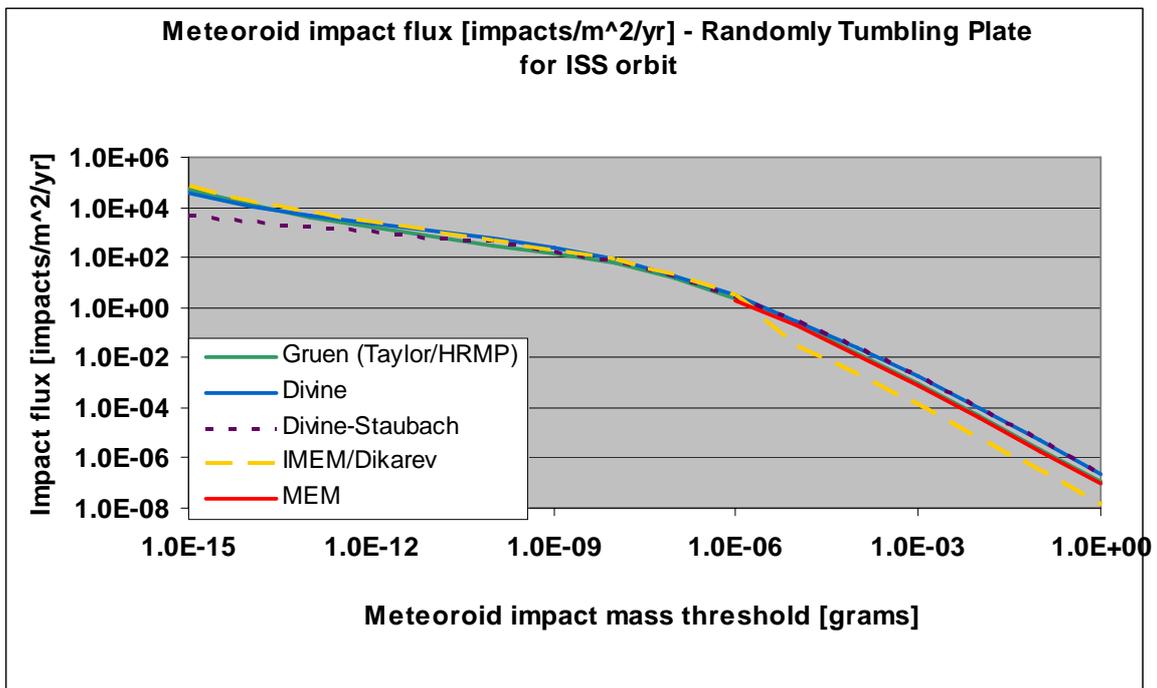


Figure 2: Predicted Impact flux for Randomly Tumbling Plate in ISS type orbit.

The calculated fluxes include the effects from Earth shielding and gravitational attraction. The model by Grün et al. has been combined with the Taylor/HRMP velocity distribution. For the Divine and Divine-Staubach models the IMEM implementation was used (in addition to the IMEM/Dikarev model, the IMEM framework allows to run also the Divine and Divine-Staubach models).

The flux predictions to a RTP agree quite well for all models. This is not really surprising as all the models analysed here have fitted the random plate flux near 1 AU to the interplanetary model by Grün et al. In the low mass regime ($< 10^{-12}$ g), the Divine-Staubach model is predicting lower fluxes compared to the other models.

The IMEM/Dikarev model predicts lower fluxes for meteoroid masses larger than 10^{-6} g. In the IMEM/Dikarev model, flux results are based on crater volume, which is

proportional to the kinetic energy of impacting particles. For the larger masses the IMEM/Dikarev model assumes impact velocities higher than the 20 km/s which were assumed by Grün et al. To be consistent with the crater data used by Grün et al, this leads to lower fluxes for a given fixed mass compared with the Grün model.

More detailed information is obtained by comparing the directional dependence of the models. For two mass thresholds, 10^{-6} and 10^{-3} g, the fluxes /m²/year from all models are predicted for oriented plates facing towards Ram, Starboard, Zenith and Wake. The results are given in Tables 1 and 2.

Table 1. Impact fluxes [/m²/yr] for oriented surfaces, an ISS type orbit (H=400km, I=51.6°) and masses > 10⁻⁶ g.

	Ram	Starboard	Zenith	Wake
Grün +HRMP	4.7E+0	2.2E+0	3.2E+0	6.6E-1
Divine	6.3E+0	3.3E+0	4.3E+0	7.1E-1
Divine-Staubach	6.3E+0	3.3E+0	4.3E+0	7.1E-1
IMEM/Dikarev	6.5E+0	3.3E+0	4.4E+0	4.9E-1
MEM	3.7E+0	2.0E+0	2.7E+0	7.2E-1

Table 2. Impact fluxes [/m²/yr] for oriented surfaces, an ISS type orbit (H=400km, I=51.6°) and masses > 10⁻³ g.

	Ram	Starboard	Zenith	Wake
Grün +HRMP	1.9E-3	8.9E-4	1.3E-3	2.7E-4
Divine	4.0E-3	2.1E-3	2.6E-3	2.7E-4
Divine-Staubach	4.0E-3	2.1E-3	2.6E-3	2.7E-4
IMEM/Dikarev	2.7E-4	3.2E-5	2.2E-4	6.4E-5
MEM	1.5E-3	8.3E-4	1.1E-3	3.0E-4

Directional effects result from model characteristics and from the orbital motion of the spacecraft. With the exception of the IMEM/Dikarev model for $m > 10^{-3}$ g, all models predict the highest flux for the ram facing surface and the lowest for the wake direction. Similar to the RTP analysis, the fluxes from the IMEM/Dikarev model differ from those predicted by the other models for $m > 10^{-3}$ g. For masses larger than 10^{-5} g predicted fluxes from IMEM/Dikarev are consistently lower compared to the other models. This is a known inherent feature of that model which predicts higher velocities and lower fluxes for all particle masses > 10^{-5} g. In addition, IMEM/Dikarev predicts the lowest fluxes for Starboard facing surfaces for $m > 10^{-5}$ g (see the example in Table 2 for $m > 10^{-3}$ g). This is a surprising finding which should be investigated further.

The Divine and Divine-Staubach models predict equal fluxes for $m > 10^{-6}$ g and $m > 10^{-3}$ g. The upgrade of the Divine model by Staubach should only influence the lower meteoroid mass regime.

4.1.2. Velocities

Figures 3 and 4 show the normalised velocity distributions for LEO (ISS orbit) and mass thresholds $m > 10^{-12}$ g and $m > 10^{-3}$ g. The IMEM/Dikarev, Divine and Divine-Staubach models have a build-in velocity distribution resulting from the source terms. The distributions denoted by SSP 30425 and Taylor/HRMP can be used with the isotropic distribution of the Grün model. The rather artificial SSP 30425 distribution was developed for engineering purposes of the Space Station Programme. It was one of the earliest developments of a velocity distribution and never aimed at scientific accuracy.

The lower threshold of $m > 10^{-12}$ g was here chosen to show the high velocity contributions of the interstellar source in the Divine-Staubach and IMEM/Dikarev models. According to these models interstellar particles only contribute for masses $< 10^{-9}$ g. The MEM model is only applicable for masses larger 10^{-6} g and therefore not included.

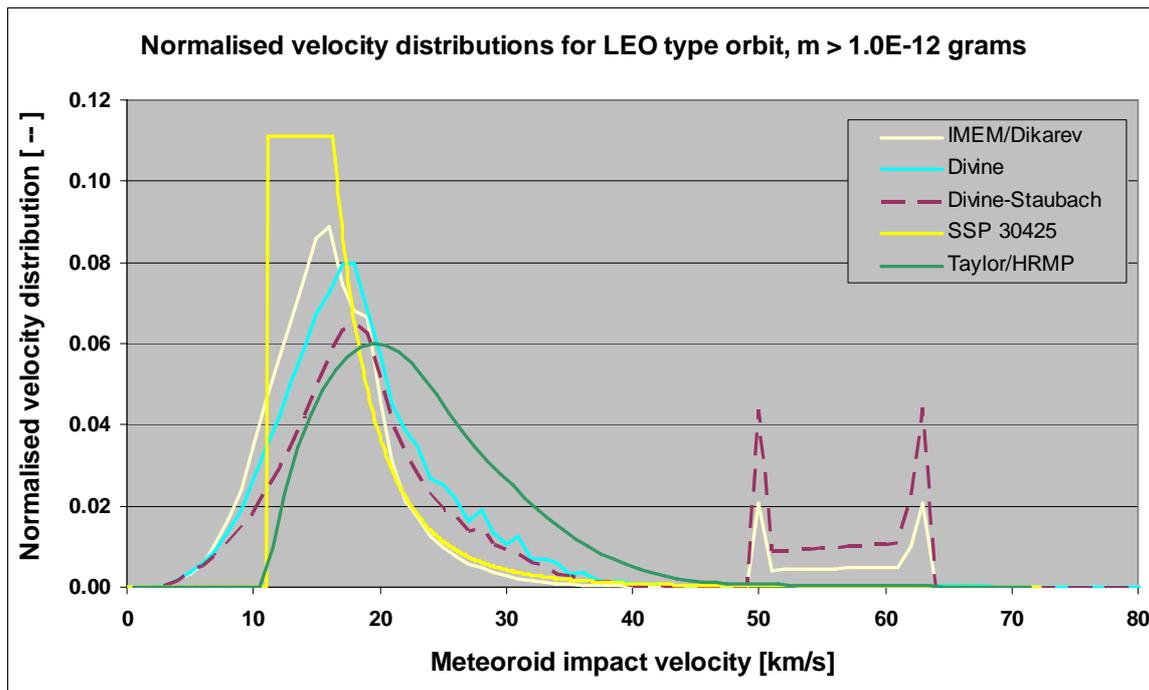


Figure 3. Normalized velocity distributions for ISS type orbit and $m > 10^{-12}$ g

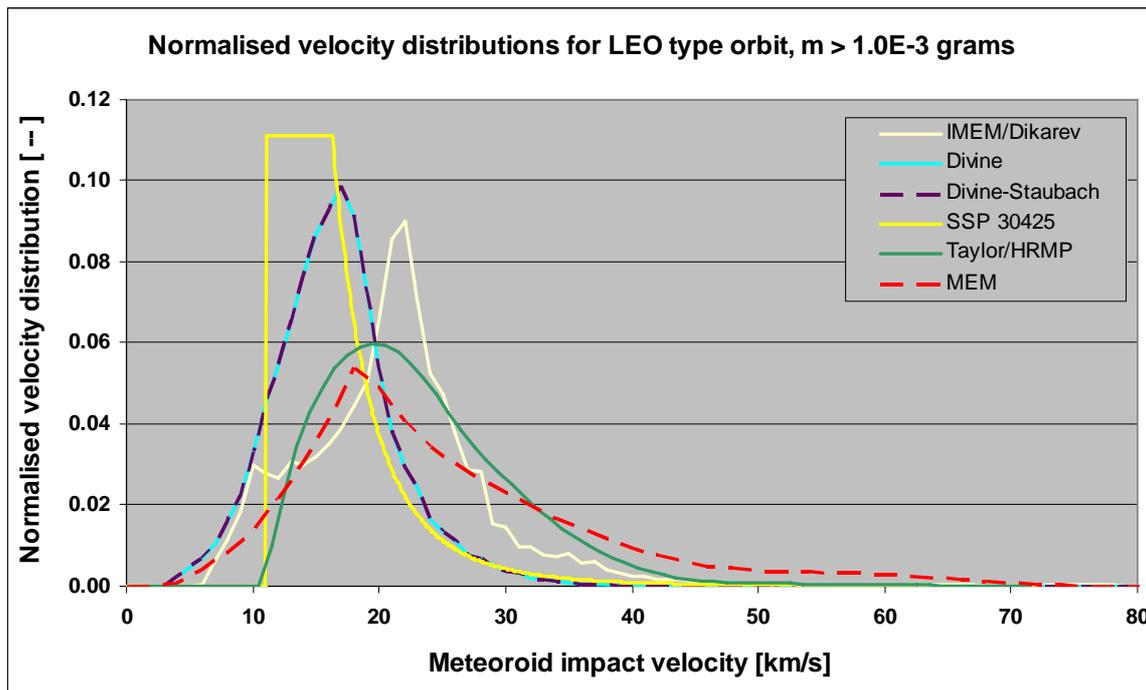


Figure 4. Normalized velocity distributions for ISS type orbit and $m > 10^{-3}$ g

The velocity distributions from the different models differ considerably. In the high mass regime ($> 10^{-3}$ g), the normalised velocity distribution graph for the IMEM/Dikarev model indeed peaks at higher impact velocities compared to the other models.

The normalised velocity distributions for GEO are presented in Figures 5 and 6 for $m > 10^{-12}$ g and $m > 10^{-3}$ g, respectively. Compared to LEO, the GEO distributions are shifted towards lower impact velocities. This is a direct result of the reduced gravitational attraction from Earth and lower spacecraft velocity in GEO. Velocity distributions for other mass thresholds show a similar behaviour when compared for LEO and GEO.

For the lower mass threshold, the velocity distributions of the Divine-Staubach and IMEM/Dikarev models have local maxima between 50 km/s and 65 km/s. These result from the ISD population which makes a noticeable contribution for smaller masses. The magnitude of this ISD contribution and the impact velocity depends on the season of the year. The models for the ISD populations assume a fixed velocity of 26 km/s relative to the sun and a fixed arrival direction in a sun-centered ecliptic reference system (77° longitude and -3° latitude for IMEM/Dikarev). The impact fluxes and velocities of ISD particles are then determined by the motion of the ISD particles and the Earth relative to the sun. The additional spacecraft motion introduces the double peaks between 48 km/s and 65 km/s in Figures 3 and 5. The results in Figures 3 and 5 are for 21 March when the ISD contribution and relative velocities are near maximum. The models also predict vanishing ISD fluxes for larger masses. This is evident in Figures 4 and 6 from the absence of this population for $m > 10^{-3}$ g.

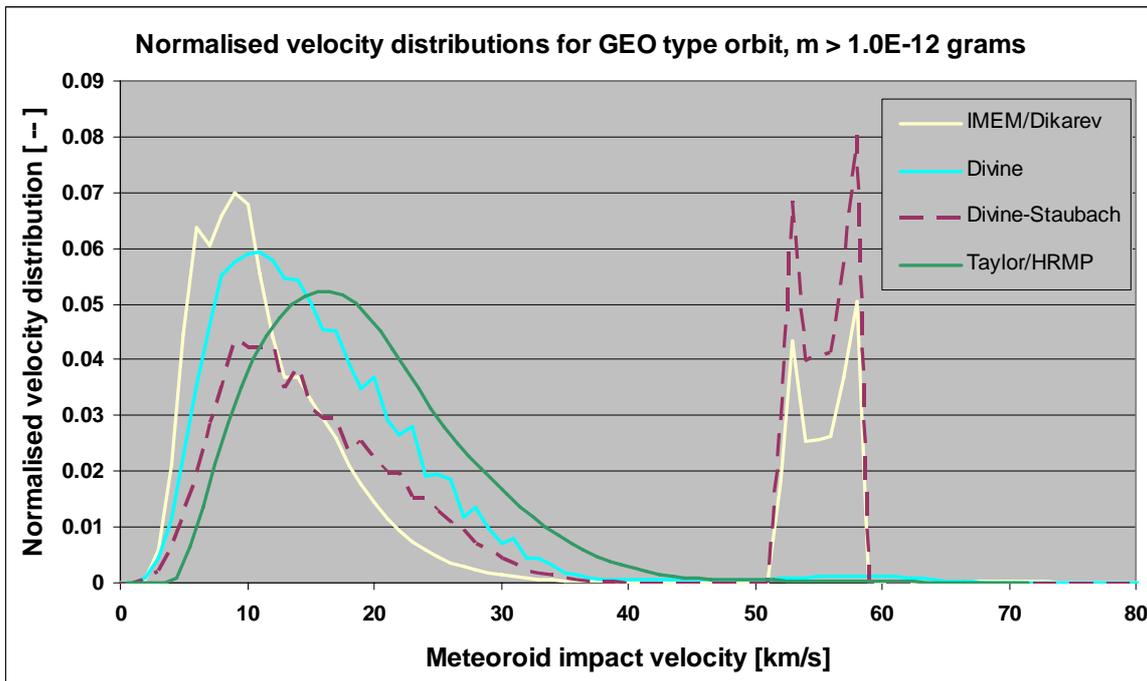


Figure 5. Normalized velocity distributions for GEO and $m > 10^{-12}$ g

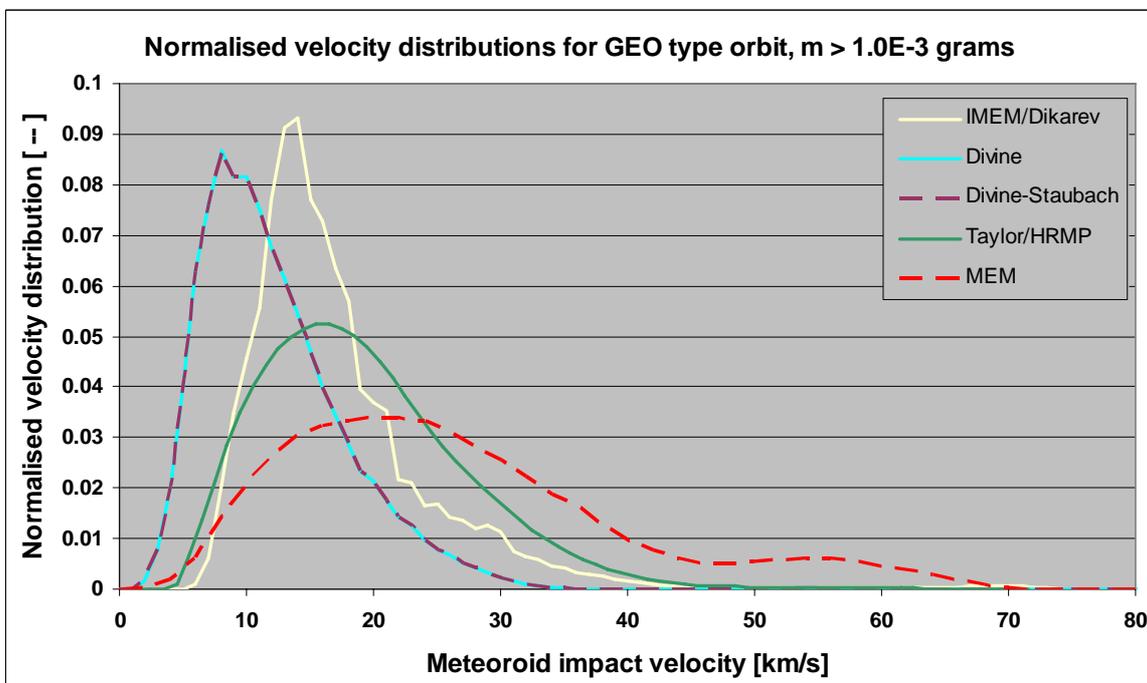


Figure 6. Normalized velocity distributions for GEO and $m > 10^{-3}$ g

Tables 3 and 4 give the average impact velocities to surfaces facing in ram, starboard, zenith and wake direction for $m > 10^{-6}$ g (Table 3) and $m > 10^{-3}$ g (Table 4).

Table 3: Impact velocity for oriented surfaces [km/s], ISS orbit, $m > 10^{-6}$ g

	Ram	Starboard	Zenith	Wake
Grün +HRMP	21.1	18.9	18.8	15.3
Divine	20.1	17.5	17.3	13.2
Divine-Staubach	20.3	17.8	17.6	13.2
IMEM/Dikarev	18.3	16.0	15.8	12.0
MEM	23.1	23.2	23.1	23.6

Table 4: Impact velocity for oriented surfaces [km/s], ISS orbit, $m > 10^{-3}$ g.

	Ram	Starboard	Zenith	Wake
Grün +HRMP	21.1	18.9	18.8	15.3
Divine	18.5	16.7	15.9	11.3
Divine-Staubach	18.1	16.4	15.6	11.2
IMEM/Dikarev	24.6	26.7	20.6	14.9
MEM	23.1	23.2	23.1	23.6

The impact velocities predicted by the Grün + HRMP and the MEM models are independent of the particle mass for the complete range of their applicability. This explains the identical values from those models in Tables 3 and 4. The velocity predictions from the Divine and Divine-Staubach models differ slightly. These models should mainly differ for masses smaller than the 10^{-6} g threshold in Table 3. As the corresponding predicted fluxes to oriented surfaces are essentially identical, the differences in Tables 3 and 4 might well be an artefact resulting from different numerical implementations of these models.

Most models predict highest average impact velocities for the ram facing surfaces and lowest for the wake direction. The MEM model usually predicts the highest impact fluxes. Average impact velocities from this model change only slightly for different orientations and the highest velocities are even predicted for the wake facing surfaces. For $m > 10^{-3}$ g IMEM/Dikarev predicts the absolute highest values from all models for the ram and starboard direction. This is a known feature of that model and goes together with lower fluxes at these masses (see Figure 1 and Table 2).

4.2. Interplanetary distances

4.2.1. Fluxes

In this chapter fluxes predicted by the various models at interplanetary distances are compared. The calculated fluxes are for targets in circular orbits around the sun at distances of 0.4 AU, 0.7 AU, 1.0 AU and 1.5AU, representing roughly the orbital radii of Mercury, Venus, Earth and Mars, respectively. Effects from the planets themselves (gravitational attraction and shielding) are excluded. All fluxes given are per m² per year and to one side of a randomly tumbling plate.

Table 5 gives flux predictions for $m > 10^{-6}$ g and Table 6 for $m > 10^{-3}$ g. The Grün model is only applicable for sun-distances near 1 AU. The small differences between the Divine and Divine-Staubach models might again be the result of different numerical implementations.

Table 5: Orientation averaged impact flux (RTP) [/m²/yr] at interplanetary distances for $m > 10^{-6}$ g.

	Mercury	Venus	Earth	Mars
Grün +HRMP	---	---	1.5E+0	---
Divine	9.0E+0	3.3E+0	1.8E+0	9.7E-1
Divine-Staubach	8.9E+0	3.3E+0	1.8E+0	9.6E-1
IMEM/Dikarev	5.4E+0	2.4E+0	1.4E+0	6.9E-1
MEM	5.8E+0	2.7E+0	1.4E+0	7.0E-1

Table 6: Orientation averaged impact flux (RTP) [/m²/yr] at interplanetary distances for $m > 10^{-3}$ g.

	Mercury	Venus	Earth	Mars
Grün +HRMP	---	---	6.0E-4	---
Divine	7.7E-4	5.1E-4	8.9E-4	1.9E-3
Divine-Staubach	7.7E-4	5.1E-4	8.9E-4	1.9E-3
IMEM/Dikarev	5.5E-5	6.9E-5	1.3E-4	3.6E-4
MEM	2.4E-3	1.1E-3	6.0E-4	2.9E-4

For $m > 10^{-6}$ g all models predict lower fluxes with increasing distances from the sun. For $m > 10^{-3}$ g the situation is quite different. The MEM model still predicts continuously decreasing fluxes from Mercury to Mars. On the contrary, IMEM/Dikarev predicts continuously increasing fluxes when the sun-distance is increased from Mercury to Mars. The Divine and Divine-Staubach models predict lowest fluxes at the Venus distance which increase from there towards Mercury and towards larger distances (Earth and Mars). This qualitative difference is a clear sign of the inherent differences of the models when fluxes near Earth are extrapolated (or calculated by numerical integration) for other sun-

distances. For $m > 10^{-3}$ g predicted absolute flux levels differ by up to a factor 43 at Mercury and a factor 6.5 at Mars. The 2 most recent models, IMEM/Dikarev and MEM even show the largest differences.

4.2.2. Velocities

Tables 7 and 8 give the orientation averaged impact velocities at interplanetary distances for $m > 10^{-6}$ g (Table 7) and $m > 10^{-3}$ g (Table 8). The calculated velocities correspond to the fluxes in Tables 5 and 6. They are for targets in circular orbits around the sun at distances of 0.4 AU, 0.7 AU, 1.0 AU and 1.5AU, representing roughly the orbital radii of Mercury, Venus, Earth and Mars, respectively. Effects from the planets themselves (gravitational attraction) are excluded.

As for Earth orbits, velocities from MEM are independent of particles mass and the differences between the Divine and Divine-Staubach models could be numerical artefacts.

All models predict continuously decreasing velocities from Mercury to Mars. Inside 1 AU (i.e. at Mercury and Venus) the IMEM/Dikarev model predicts the lowest velocities of all models for 10^{-6} g while it predicts the highest (with a peak value of 36.8 km/s at Mercury) velocities for $m > 10^{-3}$ g. Around 1 AU (near Earth) MEM predicts the highest velocities. This is consistent with the velocity distribution for high Earth orbits (GEO) presented in Figure 6.

Table 7: Orientation averaged impact velocities [km/s] at interplanetary distances for $m > 10^{-6}$ g.

	Mercury	Venus	Earth	Mars
Grün +HRMP	---	---	18.2	---
Divine	22.6	17.2	14.4	11.7
Divine-Staubach	22.9	17.3	14.5	11.6
IMEM/Dikarev	16.8	13.9	12.4	12.1
MEM	28.3	24.3	21.1	17.7

Table 8: Orientation averaged impact velocities [km/s] at interplanetary distances for $m > 10^{-3}$ g.

	Mercury	Venus	Earth	Mars
Grün +HRMP	---	---	18.2	---
Divine	22.3	15.7	12.3	10.0
Divine-Staubach	22.7	15.7	12.1	9.8
IMEM/Dikarev	36.8	24.8	17.1	10.9
MEM	28.3	24.3	21.1	17.7

The full orientation averaged velocity distributions at interplanetary distances for $m > 10^{-3}$ g are shown in Figures 7-10 for Mercury, Venus, Earth and Mars distances. The MEM, Divine-Staubach and IMEM/Dikarev models are compared. For the Earth distance the HRMP velocity distribution, used together with the Grün model, is included as well. The velocity distribution of the Divine model is not included, as it should be identical to the Divine-Staubach model (up to differences in the numerical implementation).

The 'oscillations' in the Divine-Staubach and even more in the IMEM/Dikarev model result from the different individual sources considered in these models together with a limited resolution of the binning and numerical treatment.

The velocity distributions of the Divine-Staubach and IMEM/Dikarev model are noticeable shifted towards lower velocities when the sun-distance is increased. The MEM distribution is little changed for all distances considered.

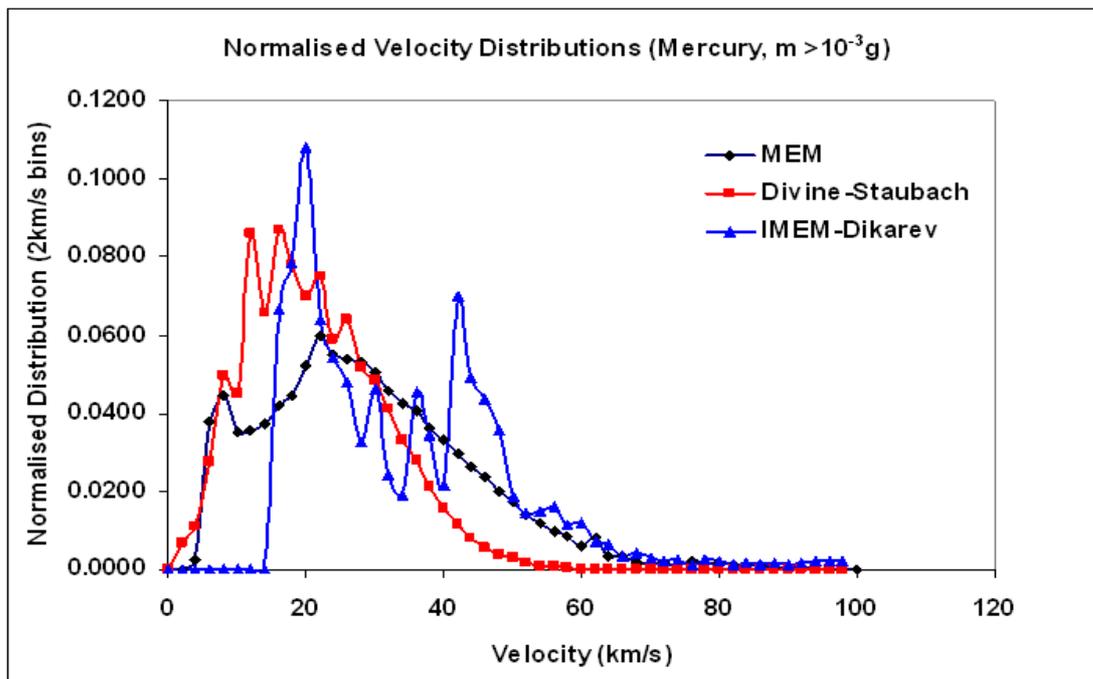


Figure 7: Orientation averaged velocity distribution at 0.4 AU (approx. Mercury distance) for $m > 10^{-3}$ g.

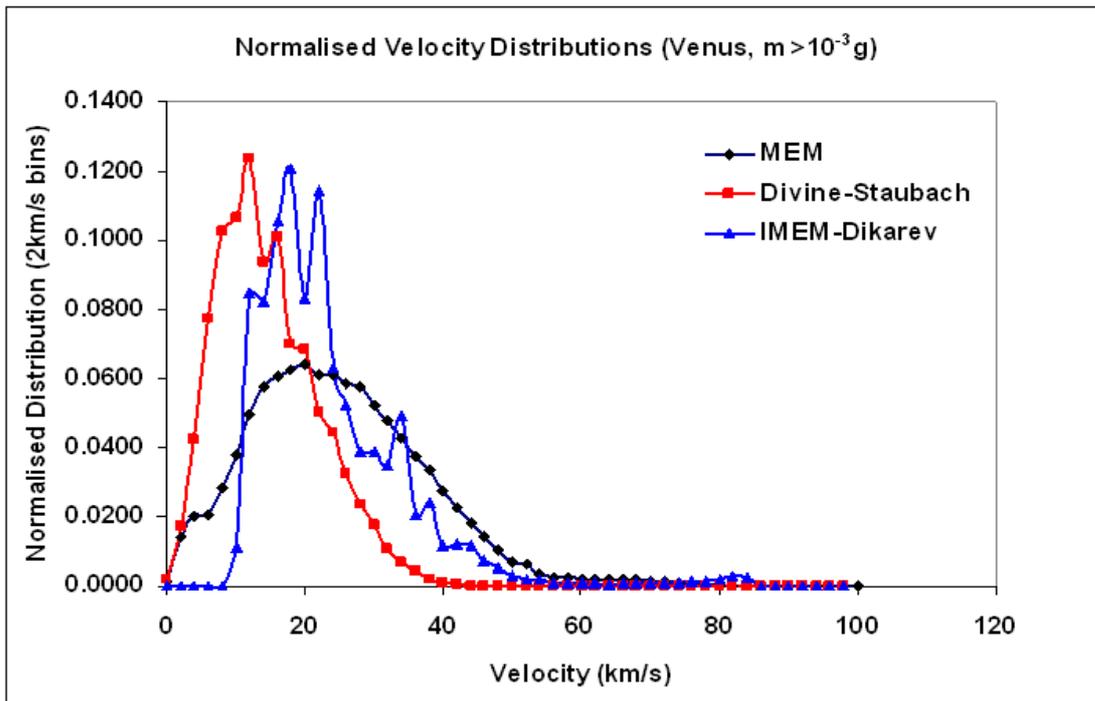


Figure 8: Orientation averaged velocity distribution at 0.7 AU (approx. Venus distance) for $m > 10^{-3}$ g.

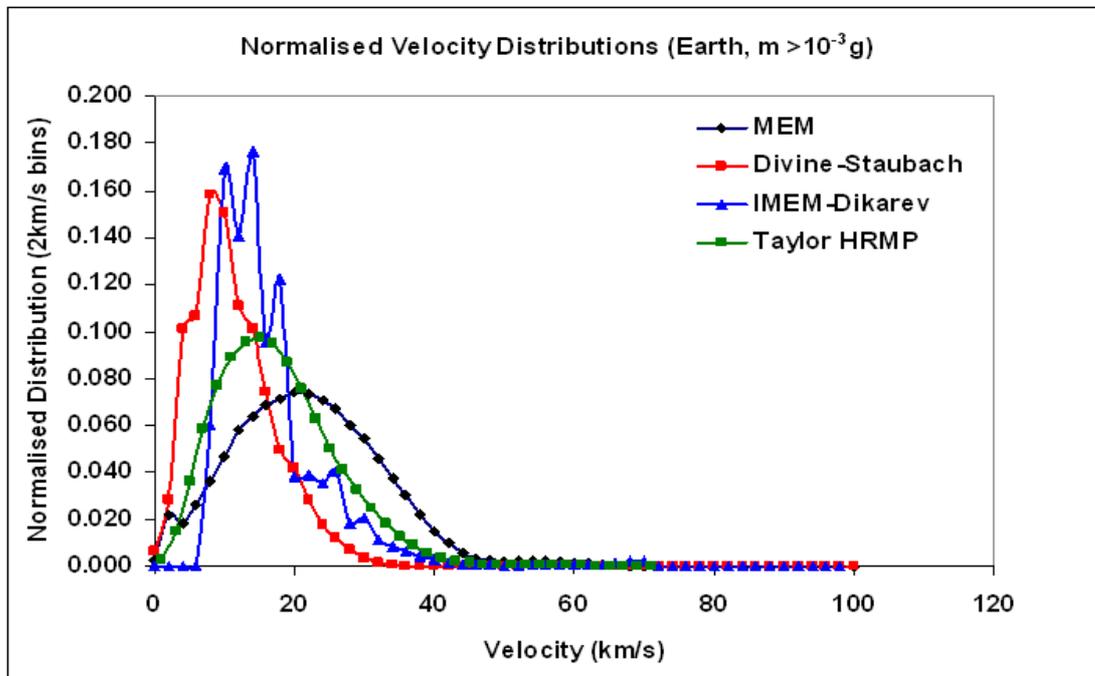


Figure 9: Orientation averaged velocity distribution at 1.0 AU (Earth distance) for $m > 10^{-3}$ g.

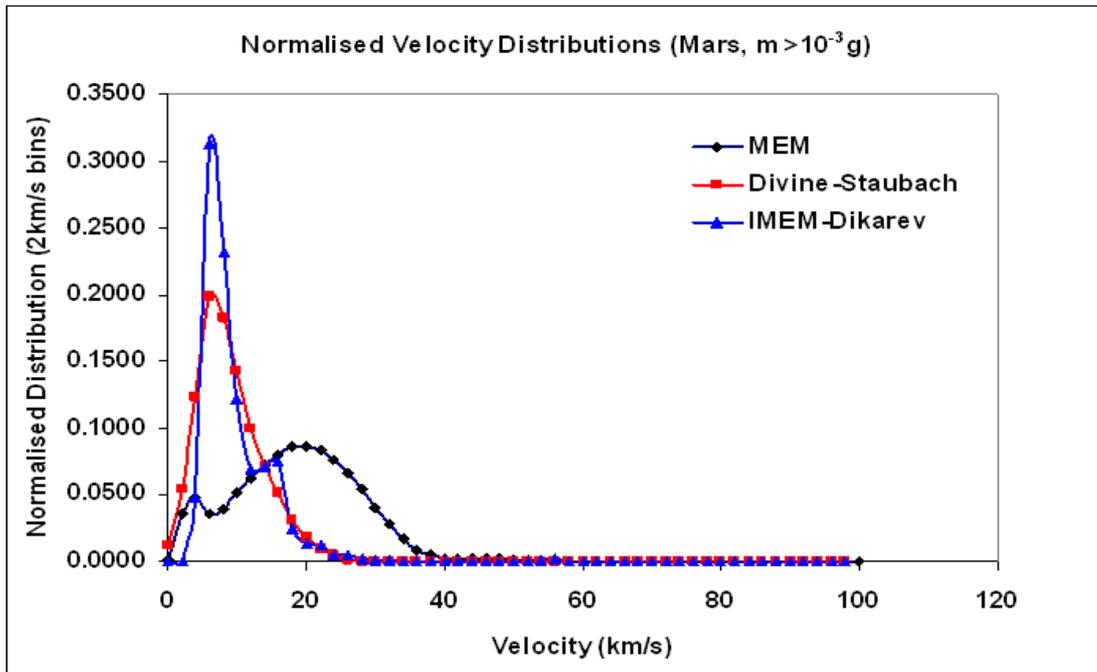


Figure 10: Orientation averaged velocity distribution at 1.5 AU (approx. Mars distance) for $m > 10^{-3}$ g.

5. Conclusions

For Earth orbits and in the vicinity of Earth, the meteoroid fluxes predicted for randomly oriented plates agree well for all models. That is not surprising as for all recent models the measurement data from the vicinity of the Earth has been refitted. Since these data, to a large degree, overlapped with the data already used by Grün et al., the flux levels are very similar for near Earth space. Some differences were found in the lowest and highest analysed meteoroid mass regimes. The IMEM/Dikarev model predicts lower meteoroid fluxes for the higher mass regime ($m > 10^{-5}$ g) compared to the other models, which is a direct consequence of the higher velocities, assumed by this model.

Even for Earth orbits, directional and velocity distributions of the various models show larger differences, indicating persistent uncertainties.

For sun-distances away from 1 AU differences in the model predictions are much larger. For the parameter sets analysed, differences between the models were up to a factor 43 for fluxes (for $m > 10^{-3}$ g at Mercury) and up to a factor 1.8 for velocities (for $m > 10^{-3}$ g at Mars). Near Earth meteoroid flux predictions are validated to some extent by data sets from ground observations and in-flight measurements. At other interplanetary distances,

these data sets become scarce and model developers had to rely on extrapolations and numerical simulations.

The present comparison was limited to the distances between 0.4 and 1.5 AU from the sun. At larger distances, model uncertainties and differences will be even larger (if the models are applicable at all).

For sun-distances near 1 AU all models have been fitted to the Grün model from 1985. Usually, the fluxes have been fitted. But the IMEM/Dikarev model re-fitted the effects (e.g. lunar crater measurements). For masses of 10^{-5} g or larger this model predicts higher average velocities than the other models. To be consistent with the Grün model this resulted in smaller fluxes at a given mass.

The various models are based on rather different assumptions on the meteoroid sources. The Divine and Divine-Staubach models assume a mixture of cometary and asteroidal sources, with the larger masses being dominated by asteroidal sources (see Figure 1). The most recent models, IMEM/Dikarev and MEM, both assume that the large majority of meteoroids is of cometary origin. However, besides this agreement the model assumptions differ widely. MEM is almost exclusively based on data from the Canadian radar CMOR. The spatial and velocity distribution measured by this radar is empirically fitted and extrapolated. The CMOR data are strictly valid for Earth only. It is certainly not straightforward to extrapolate a fit to these data to other sun-distances. The weak dependence of the MEM velocity distributions with sun-distance indicates a difficulty of such a model to correctly account for the orbital dynamics of interplanetary meteoroids.

The IMEM/Dikarev model, on the other hand, completely discarded measurements of the Australian AMOR radar, as these data could not be brought into agreement with data from the DIRBE (Diffuse Infrared Background Explorer) experiment on COBE (Cosmic Background Explorer), which were seen as more reliable than the radar data. IMEM/Dikarev assumed certain meteoroid sources (mainly cometary) and sinks and then followed the orbital evolution of the dust particles to a steady state situation. The resulting fluxes were then fitted to available observations. While this approach is physically correct in principle, it soon faced numerical limitations. The sudden jump between the collision and Poynting-Robertson mass regimes is evidence for this shortcoming. In addition, the selection of the source comet populations required some ad hoc assumptions.

It should be emphasized that even the Grün model, which forms the Earth anchor point for all models, has considerable inherent uncertainties. The model was derived assuming a fixed velocity of 20 km/s and a material density of 2.5 g/cm^3 . The Grün model is considered well validated by e.g. Lunar crater data and the impact crater analysis of retrieved hardware (e.g. LDEF, EURECA, solar arrays of Hubble Space Telescope). However, in each case the validation was via the impact effects, rather than by direct measurement of particle parameters. For different velocities or material densities of the impacting meteoroids the fluxes could be different and still fit all the available data. Accounting for the underlying assumptions, the flux uncertainty at a given mass is certainly a factor 0.33 to 3 of the nominal flux.

In addition, the Grün model does not attempt to model the directional dependence of meteoroids. It assumes an isotropic distribution w.r.t. to the Earth surface. While this is sufficient for long term measurements and effects near Earth, the lack of detail on the incident meteoroids and sources prevents extrapolation to other interplanetary distances (which probably was never intended when the model was developed).

From the model comparison presented in this report it can be concluded that our knowledge on the interplanetary meteoroid environment is still rather limited. All existing models have known shortcomings and/or large uncertainties resulting from the need to make ad hoc assumptions due to lack of good data. It might be surprising to many, but the meteoroid population appears to be one of the most uncertain space environment components.

Even near Earth meteoroid population models have large uncertainties. Present optical and radar measurements of meteors are strongly dominated by the high velocity tail of the meteoroid population. In-situ measurements are limited to very small dust particles and so far no detector could accurately measure the full trajectory of particles.

Increased efforts should be made to measure the full meteoroid population near Earth, including the complete range of velocities and the trajectory of the particles. Such detailed measurements should be made by both, ground based optical and radar instruments, and in-situ detectors. The trajectories are needed to determine the orbits and sources of the meteoroids. Once these are known, fluxes can be extrapolated to distances away from Earth with more confidence.

6. References

1. Grün E, Zook HA, Fechtig H, Giese RH (1985) Collisional Balance of the Meteoritic Complex. *Icarus* 62:244–272
2. Divine N (1993) Five Populations of Interplanetary Meteoroids. *J. Geophysical Research* 98:17029–17048
3. Staubach P, Grün E, Jehn R (1997) The Meteoroid Environment near Earth. *Advances in Space Research* 19:301–308
4. Dikarev V, Grün E, Baggaley J, Galligan D, Landgraf M, Jehn R (2005) The New ESA Meteoroid Model. *Advances in Space Research* 35:1282–1289
5. Jones J (2004) Meteoroid Engineering Model – Final Report. NASA/MSFC internal report SEE/CR-2004-400. Updates were made in 2007.
6. Kessler DJ, Reynolds RC, Anz-Meador PD (1994) Space Station Program Natural Environment Definition for Design, International Space Station Alpha. NASA SSP 30425, Revision B, National Aeronautics and Space Administration Space Station Program Office, Houston, TX, USA
7. Taylor AD (1995) The Harvard Radio Meteor Project Meteor Velocity Distribution Reappraised. *Icarus* 116:154–158