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Interplanetary Meteoroid Environment Model Update

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The effects of the sporadic meteoroid environment on interplanetary spacecraft have an important impact on mission design. A reformulation is described of the Divine interplanetary meteoroid model, called the meteoroid engineering model (METEM), that is capable of estimating many of those effects. METEM and the original Divine model it is based on made use of the new meteoroid data obtained since the 1970s, when the original NASA meteoroid models were developed, to provide a comprehensive phase space description of the environment. METEM allows detailed estimates of the meteoroids' directionality and variation with distance from the sun. It incorporates several different meteoroid populations, each population being described in terms of a distribution function in velocity phase space. These distribution functions are integrated along a spacecraft trajectory to give the meteoroid fluence as a function of velocity and angle relative to a specified surface. METEM predictions of mission meteoroid fluences are explicitly compared with those of the standard NASA models for three representative trajectories (an inner solar system, Helios-like mission; a mission at 1 AU; and a Cassini-like, outer solar system mission). In addition, the METEM model is used to estimate the angular variations in the meteoroid fluence expected along these trajectories, a unique feature of this new class of models that provides additional insights into how a spacecraft can be designed to protect it from meteoroids.

Nomenclature

A'	= equivalent sensitive area
C_0	= constant for shield material, 0.54 (for Al)
e	= eccentricity
F_a, f_a	= NASA model asteroidal fluence, particles/m^2, and flux, particles/m^{2}s
F_c, f_c	= NASA model cometary fluence, particles/m^2, and flux, particles/m^{2}s
f	= asteroid population heliocentric variation in number density
f_p	= penetrating meteoroid flux as function of time
G	= asteroid population heliocentric variation for the longitude function
H_m, H_M	= mass differential and cumulative distribution functions
h	= asteroid population latitudinal variation
i	= inclination
m	= meteor mass, g
N_1	= radial distribution, depends only on r_1
p_e	= eccentricity distribution, depends only on e
p_i	= inclination distribution, depends only on i
R	= heliocentric distance, AU
r_1	= perihelion distance
T	= time (mission duration)
t	= small time interval
t_c	= critical thickness of shield for which perforation will occur for particles equal to or greater than the critical size, cm
V_m	= impact speed, km/s
$\langle V_c \rangle$, $\langle V_a \rangle$	= NASA model cometary and asteroidal relative impact velocities, km/s
v_D	= speed with respect to detector
β	= heliocentric latitude
δ	= delta factor
η_D	= weighting factor for detector effects
λ	= heliocentric longitude
ρ_c, ρ_a	= cometary and asteroidal spatial density, particles/m^3
ρ_m	= density of projectile, g/cm^3

Introduction

COLLISIONS with meteoroids have been a concern for spacecraft designers since the early days of the space program. The sources of these particulates are believed to be the debris from asteroids and comets or the ejecta from collisions of meteoroids with large bodies such as the Earth or the moon. Given the pervasive nature of meteoroids, the effects of the macroscopic particulate environment must be quantified over the lifetime of a space system to project the life expectancy of exposed mechanical and electrical systems. For the last two and a half decades, the primary tools for modeling the meteoroid environment have been the models described in Refs. 1 and 2. New data, primarily from Helios, Voyager, and Earth-based radar, have become available since these models were formulated. In addition, the older models do not readily lend themselves to the determination of impact as a function of angle relative to a surface normal (the models basically assume all impacts are at normal incidence), nor to a determination of an accurate distribution of impact velocities with direction and mass. (Note that the older models do allow for an approximation to a distribution of velocities through the so-called delta function.) The need to incorporate the latest meteoroid data and to model the angular variations

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in the meteoroid fluence for interplanetary missions led to the development of a more detailed model by Divine[3] in the early 1990s. Since then, that model has seen wide acceptance in the international community. Unfortunately, the model has proven difficult for general use and requires intimate knowledge of the code to modify it and incorporate new results or features. This paper will describe tests of a reformulation of the Divine meteoroid code called the Meteoroid engineering model (METEM) recently developed to address these issues. The results of that code will be compared with the older NASA models,[1,2] and the new angular and velocity distribution features will be exploited to illustrate the practical value of the model.

Meteoroid Models: General Considerations

In practice, methods for modeling the meteoroid environment fall into three groups.

1) The first models single-particle dynamics, where the trajectories of individual particles are followed. This resembles the plasma physics particle in box approach and is used where, in the case of asteroids, there are a few well-defined particles.

2) The second models organized streams (meteor streams), rings (Saturn's rings), or shells (Earth space debris that have been randomized at a fixed orbital altitude).

3) The third uses algorithmic fits to the background, random environment. This is primarily the so-called sporadic meteors or the zodiacal light.

In principle, the single-particle physics applicable to the asteroids can be used to model any meteoroid environment. Unfortunately, models of the sporadic meteoroids or even the rings of Saturn would involve the tracking of millions of particles to adequately describe the actual environments, thus the need for some form of simplification. The algorithmic models on the other hand tend to only permit calculations of the specific quantities to which they have been fit. Here, after a brief review of the algorithmic fits characteristic of the NASA models,[1,2] the new, phase space density approach developed by Divine[3] will be presented. The phase space density description, while allowing simplification of the overall problem, also permits the derivation of many if not all the quantities necessary for studying the effects of the meteoroid environment on spacecraft.

In the following development, one problem in particular should be kept in mind, that of the penetration speed or, less accurately, impact velocity. The precise definition of impact velocity has proven to be difficult as the actual particulate environment is characterized by a velocity distribution rather than a single impact velocity assumed in the earlier models. Based primarily on how the impact velocities should be weighted when taking a mean or average, variations in estimates of the effects of impacts are possible. The problem results because the minimum mass capable of causing failure varies with velocity, typically decreasing with increasing velocity. In practical terms, the average velocity will often differ from a weighted velocity required for impact probability calculations. A second issue arises because the average impact velocity and meteoroid fluence both vary in time (or position) during the spacecraft mission so that the probability does not increase linearly in time but in a complex fashion. The actual value of the impact velocity to be used will depend on the orbital position of the spacecraft and its instantaneous velocity vector. The precise treatment of this velocity and the velocity distribution function pose an uncertainty in the following calculations. The NASA[1,2] and Divine[3] models treat this issue in different fashions as will become apparent.

NASA Interplanetary Meteoroid Models

The current NASA meteoroid models do not attempt to treat individual particles, but, like the algorithms or numeric expressions that define the neutral atmosphere, are fits to observations. They, therefore, are a very compact, though physically limited, representation of the meteoroid environment; specifically, the models provide a number density as a function of mass and a characteristic velocity or speed from which flux and fluence can be derived. To date, the NASA models are the accepted engineering meteoroid environment tool. The principle documents describing these models are Refs. 1 and 2.

The first document[1] defines the meteoroid environment between the Earth's surface and the moon in terms of simple numeric expressions. It provides working definitions of the three principle quantities needed to define the meteoroid environment: their mass vs number density, their velocity distribution, and their density (composition). Included in the document are listings of interplanetary meteor streams (the predictable component) and the Earth-based meteor observations on which the sporadic (here the background flux of meteoroids that are basically random) models are based. The second document[2] presents an extrapolation of the Earth-based observations to interplanetary space for sporadic meteoroids of different origins, cometary and asteroidal. These models of the sporadic meteors have served well for almost 25 years, and only as new data on the interplanetary meteoroid environment have become available were changes in these models proposed.[3,4] As these NASA meteoroid environment models are currently still the basis for most engineering studies of the effects of the meteoroid environment, they will be briefly described.

Meteoroids, as defined by the NASA documents, are solid particles orbiting in space that are either of cometary or asteroidal origin. The spatial volume of interest ranges from 0.1 to 30.0 AU. The mass range is from 10^{-12} to 10^{2} g. Knowledge of these particles is based primarily on Earth-based observations of meteors, comets, asteroids, the zodiacal light, and in-situ rocket and spacecraft measurements. The flux vs mass of the particles, the basic quantity required to model the meteoroid environment, is not directly measured but must be inferred, e.g., from light intensity, crater distributions, etc. The ground-based measurements consist principally of photographic and radar observations. The sporadic meteoroid component is divided into those of cometary origin and those of asteroidal origin. The distinction between these two groups will become clear in the following.

Cometary Meteors

In terms of the NASA models, cometary meteoroids in the mass range of interest (<100 g) are believed to be the solid remains of large water–ice comets that have long since evaporated or broken up due to collisions or that simply fragmented/dispersed from comet surfaces without destroying the comet. The remaining silicate or chondritic material is of very low density (0.16–4 g/cm^3) with an assumed value of 0.5 g/cm^3 for the NASA models. The primary flux inside 1.5 AU is made up of these cometary meteoroids. Reference 2 describes the integral cometary meteor number density ρ_c for a mass m or larger by

$$\log_{10}(\rho_c) = -18.173 - 1.213\log_{10}(m) - 1.5\log_{10}(R) - 0.869\,|\sin(\beta)| \tag{1}$$

The average impact velocity to the surface, as a function of spacecraft orbital parameters consisting of the ratio of the heliocentric spacecraft speed to the speed of a circular orbit at the same distance from the sun, σ; the angle between spacecraft velocity vector and circular orbit in same plane, θ; a cometary velocity function described in Ref. 2, U_c; and distance from sun, in AU, R, is given by

$$\langle V_c(\sigma,\theta,R)\rangle = R^{-\frac{1}{2}}U_c(\sigma,\theta) \tag{2}$$

This velocity is assumed to be normal to a surface for the NASA models when calculating impact effects.

Once a number density is determined and the impact velocity is computed, the cometary flux to a randomly tumbling plate can be estimated by the following simple formula:

$$f_c = \tfrac{1}{4}\rho_c\langle V_c\rangle\delta^{-1} \tag{3}$$

The total fluence F_c is the integral of f_c over time. The delta factor is a small correction factor (on the order of 1, typically) included to account for there being a distribution of velocities. It is given as a function of σ and θ in Ref. 2.

Asteroidal Meteors

As for the cometary meteoroids, the basic computation of the asteroidal flux follows three steps: determine the penetrating mass based on the particle density and impact velocity, determine the number density at the given mass, and compute the asteroidal flux f_a from $\frac{1}{4}\rho_a\langle V_a\rangle$. Unlike the cometary population of meteoroids, however, which is assumed to be fairly uniform in its characteristics with heliocentric distance, the asteroidal component shows a marked heliocentric variation in number density. Visual observations down to masses on the order of $10^{19}-10^{20}$ g demonstrate the existence of the well-known asteroid belts between roughly 1.5 and 3.5 AU. It was assumed from the comparative (with respect to the cometary meteoroids) rarity of asteroidal meteoroid falls at the Earth that the lower mass component of the asteroidal meteoroids is similarly confined to the 1.5–3.5 AU range. From laboratory studies of presumed asteroidal meteorites, the density of these particles averages about 3.5 g/cm^3, substantially denser than the cometary meteoroids. (Note that observations[4] on Pioneer 10 and 11 imply that this population does not exist at masses below 10^{-9} g, see subsequent blue ribbon panel recommendations, and, by extrapolation, may not exist in the mass range of interest to impact studies.)

In parallel with the cometary meteoroid model, Ref. 2 provides functional relationships for the variation of the asteroidal meteoroids with relative impact velocity, heliocentric longitude, and heliocentric latitude. U_a and $\langle V_a\rangle$ are the asteroidal versions of U_c and $\langle V_c\rangle$. U_a and $\langle V_a\rangle$ are related by

$$\langle V_a\rangle = R^{-\frac{1}{2}}U_a \tag{4}$$

Unlike U_c, asteroidal function U_a and its relationship to σ and θ vary with R. Reference 2 lists three different variations for U_a corresponding to $R = 1.7$, 2.5, and 4.0 AU. As a final component of the asteroidal model, δ is also introduced, but as this is so close to 1 (the asteroidal meteoroids have a very sharply peaked velocity distribution function), it is ignored in the NASA model. Again, all variations are assumed to be essentially independent of each other so that the flux is the product of all of the components. For the mass range of interest, the resulting equation is

$$\log_{10}(\rho_a) = -15.79 - 0.84\log_{10}(m) + f(R) + G(R)\cos(\lambda) + h(\beta) \tag{5}$$

As before,

$$f_a = \tfrac{1}{4}\rho_a\langle V_a\rangle \tag{6}$$

Galileo Meteoroid Model

An important revision to the NASA models was a version developed for the Galileo mission. To reflect Pioneer in situ meteoroid observations,[4] the NASA models were modified by a blue ribbon panel convened by NASA between 1978 and 1980 to incorporate the latest Pioneer 10/11 meteoroid data for the Galileo mission. The major recommendations of the panel were as follows:

1) Based on the Pioneer results, which indicated the absence of an asteroidal component at masses below about 10^{-9} g, the panel recommended that only the cometary component be considered.

2) The NASA cometary meteoroid model spatial density has a $R^{-1.5}$ dependence. As a conservative assumption, the panel recommended assuming a constant density twice that of the NASA cometary model at 1 AU between 1 and 5 AU. (It has since been tacitly assumed that the factor of two and constant density also be applied within 1 AU.)

3) As in the case of the NASA cometary meteoroid model, the flux was assumed to be isotropic.

4) The so-called δ factor, which takes into account the cometary relative velocity distribution, is assumed to be $\delta = 1$.

Of the assumptions, the elimination of the δ factor, used to correct for the velocity distribution, has caused the most concern. The consequences of this effect were found to be minimal, however, in direct comparisons with the results of the original NASA cometary model that included the factor and this Galileo model that did not.

Divine Model

Whereas the NASA models are empirical fits to the mass distribution and average impact velocity, the model developed by Divine[3] takes as a starting point the particle phase space density. To make this clear, consider the fundamental physical concepts associated with meteoroids. The physics of macroscopic particles, in principle, resemble that of a charged plasma environment as gravity, the principle controlling force (light pressure and electrostatic forces are ignored in this paper but they can be very important for the smaller or low-density particles), varies as the inverse of the distance between interacting objects just as in the case of electrostatic forces. It is common practice in defining the characteristics of a plasma to define a phase space distribution function. In particular, a particle in space has a mass m, a position vector $\boldsymbol{r}$ (with components x, y, z), and a velocity vector $\boldsymbol{v} = \mathrm{d}\boldsymbol{r}/\mathrm{d}t$ (components v_x, v_y, v_z). A particle population can be represented by a continuous distribution defined by

$$\mathrm{d}N = [H_m\,\mathrm{d}m][g_0(\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z)(\mathrm{d}v_x\,\mathrm{d}v_y\,\mathrm{d}v_z)] \tag{7}$$

where $\mathrm{d}N$ is the mean number of particles with mass, position, and velocity in the intervals $(m, m+\mathrm{d}m)$, $(x, x+\mathrm{d}x)$, $\ldots, (v_z, v_z+\mathrm{d}v_z)$. The components (x, y, z, v_x, v_y, v_z) are in heliocentric coordinates.

In the Divine[3] model, the dependence on mass m is assumed to reside exclusively in the function H_m (independent of $\boldsymbol{r}$ and $\boldsymbol{v}$). It is related to the cumulative mass distribution H_M by

$$H_M = \int_m^\infty H_m\,\mathrm{d}m \tag{8}$$

and g_0 is a density in position-velocity space like that for a gas or plasma and is independent of m and t. For meteoroids, g_0 can be taken as a function of the constants of motion in a gravity field, e.g., the six Keplerian orbital elements. In particular, it can be shown that g_0 can be described for the interplanetary meteoroids as

$$g_0 = (1/2\pi e)(r_1/GM_0)^{\frac{3}{2}}N_1 p_e p_i \tag{9}$$

Given the distributions for the inclination distribution function p_i, the eccentricity distribution function p_e, and the radial distribution function N_1, Divine[3] demonstrated that one can derive particle concentrations, fluxes (as functions of angle), fluences, and impact velocities (as functions of angle) along an orbit. The concentration, for example, is given by

$$N_M = H_M\sum_{l=1}^{4}\int \mathrm{d}r_1 \int \mathrm{d}e \int \mathrm{d}i\cdot g_0\frac{\partial(v_x, v_y, v_z)}{\partial(r_1, e, i)} \tag{10}$$

where $l = 1$–4 represents four possible particle directions. The flux is given by

$$J_M = \sum_{l=1}^{4}\int \mathrm{d}r_1 \int \mathrm{d}e \int \mathrm{d}i\cdot g_0\frac{\partial(v_x, v_y, v_z)}{\partial(r_1, e, i)}\cdot\left(\eta_D v_D\right)_l \tag{11}$$

For all impacts that contribute to the flux, the mean velocity (impact velocity here) is given by dividing the integral of the flux times the velocity by the flux[3] [Eq. (11)]

$$\langle v_D\rangle = \frac{1}{4\pi J_M}\sum_{l=1}^{4}\int \mathrm{d}r_1 \int \mathrm{d}e \int \mathrm{d}i\cdot g_0\frac{\partial(v_x, v_y, v_z)}{\partial(r_1, e, i)}\cdot\left(\eta_D v_D^2\right)_l \tag{12}$$

Data Inputs to Divine Model

The Divine meteoroid model is a much more comprehensive representation of the environment than the earlier NASA models. It can be used to describe a complex number of variations and populations

Table 1 Sources and ranges of input data for the Divine meteoroid model[3]

Data source	Heliocentric distance, AU	Mass, g
IF model[5]	0.98–1.02	10^{-18}–10^{0}
Pioneer 10[6]	1–18	$>3\times10^{-10}$
Pioneer 11[6]	1–9	$>10^{-9}$
Helios[7]		
Fluxes	0.31–0.98	$>10^{-10}$
Events	0.31–0.98	$>10^{-14}$
Galileo dust det.[8]	0.88–1.45	$>10^{-13}$
Ulysses dust exp.[8]	1.0-4.0	$>10^{-13}$
Radar meteors[9]	0.98–1.02	$>10^{-4}$
Zodiacal light[10]	0.3–1.0	10^{-8}–10^{-5}
Ref. 11	1	10^{-8}–10^{-5}
Ref. 12	3	10^{-8}–10^{-5}

simultaneously. Indeed, based on the preceding concepts, Divine[3] was able to fit almost all of the existing meteoroid data. These data sets included: the interplanetary flux (IF)[5] model, the Pioneer 10/11 data set,[6] the Helios fluxes/events measurements,[7] the Galileo dust detector,[8] data from the Ulysses dust experiment,[8] radar meteor observations,[9] and estimates of the distribution of the zodiacal light population.[10–12] The data sets, their sources, and distance and mass ranges are listed in Table 1 (Refs. 5–12).

Divine[3] found that five distinct populations were necessary to fit the data. In particular, the core population is the best single population fit to the data and reproduces the Galileo data. The inclined population is fit to portions of the Helios data not described by the core population. The eccentric population fits the variations in the Helios data not fit by the other two populations. The halo population fits the Pioneer and Ulysses data sets. The asteroidal population fits the Grün et al.[5] IF model at large masses and the nonzodiacal light component of the meteor data. The appropriate distributions corresponding to these populations are presented in Figs. 1–4. The densities assumed for these populations are 0.25 g/cm^3 for the eccentric population (note that this population contributes very little to any of the fluence calculations and can be ignored in general) and 2.5 g/cm^3 for all of the others. Figures 1–4 define the distribution curves for each population. These curves and the definition of density compromise the basis of Divine's meteoroid model. Flux, fluence, impact speed, etc., are all computed using these curves and Eqs. (7–12).

METEM Model

Despite its many advantages, the Divine model as originally formulated and coded has proven difficult to utilize and manipulate. There has been growing interest, however, in its use and further development. In particular, Matney and Kessler[13] showed that Divine's original formulation of p_i, p_e, and N_1 do not correspond to textbook definitions of the particle distribution functions; Divine's $p_i\,\mathrm{d}i$ is not, for example, the number of objects with inclinations between i and $i+\mathrm{d}i$. They find that the proper normalizations should be[13]

$$N_1' = r_1^2\cdot N_1,\qquad p_i' = \sin i\cdot p_i,\qquad p_e' = p_e/(1-e)^{\frac{3}{2}}\tag{13}$$

where the primed quantities correspond to the textbook definitions.

In addition to these suggested changes in normalization, Taylor[14] and colleagues have suggested that the original analysis of Sekanina and Southworth[9] of the radar meteors may have been flawed. It is suggested that an error in the bias-corrected values of the encounter velocities has been identified. This error is traced to an apparent typographical error in a formula, where a value of 1.86 should have been 1.36. To date, it is not clear whether or not the error is real. The data do, however, form an important part of the Divine model database, and when this issue is settled it may be necessary to update Divine's original distributions.

To address these two issues and to make the Divine model more accessible, the present authors have developed a new formulation of the Divine model. The new model, called METEM, directly addresses the concerns of Matney and Kessler.[13] Starting with the original distributions of Divine,[3] the METEM model converts them

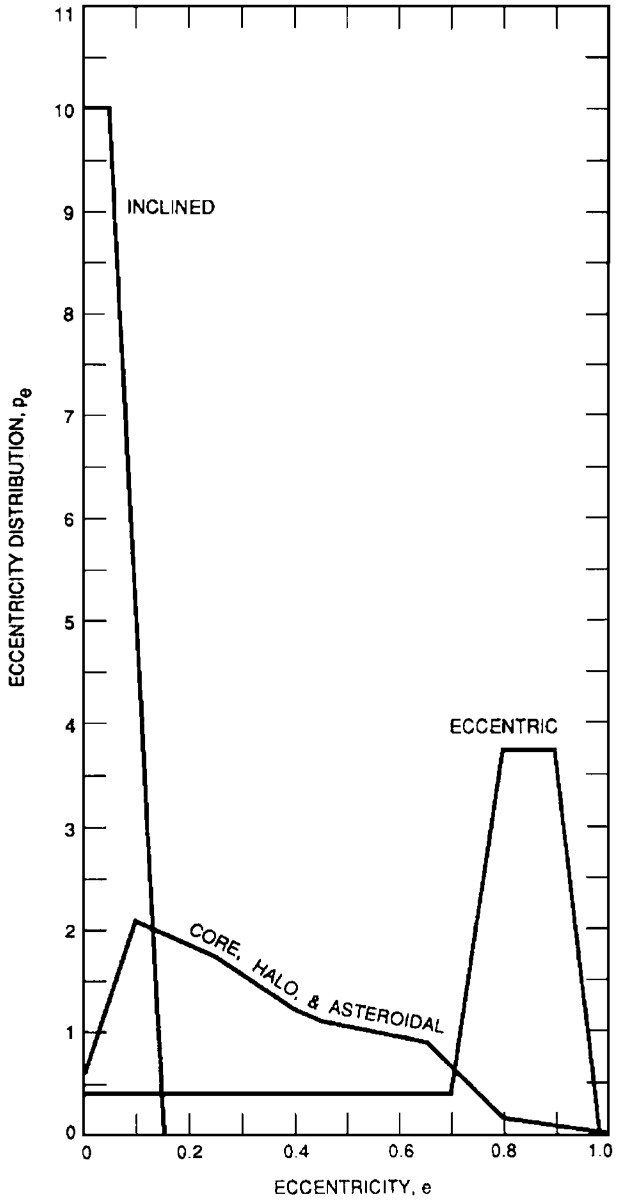

Fig. 1 Divine[3] model eccentricity distribution p_e, one of the functions used in Eq. (9) to define g_0.

internally into the normalizations of Eq. (13), which are then used in all subsequent computations; a user, thus, can input either the original distributions or those in Eq. (13). In addition, numerous ambiguities, singularities, and issues of precision have been corrected. A special version of METEM has also been developed that can be used to vary the Sekanina and Southworth[9] data inputs to test the effects of Taylor's[14] proposed correction. This version will be used to develop corrected versions of the distributions functions, Divine's or Matney and Kessler's versions, when a consensus is reached on the correct interpretation of that data. Finally, a user-friendly front end in Visual Basic® (vb) has been developed for METEM that makes input and output straightforward. The METEM formulation and its user-friendly METEMvb version have been carefully tested against the original Divine model and yield similar results over the same range of inputs.

METEM is not the only ongoing effort to revise and upgrade the original Divine model. Indeed, Staubach et al.[15] (see also Ref. 16) have investigated the effects of solar radiation pressure on the distributions for masses less than 10^{-10} g and have produced revisions to the original Divine model that take these effects into account. They are not included in METEM as the impact of the particles in this range typically have little or no effect on spacecraft performance, the primary use of the NASA and METEM models.

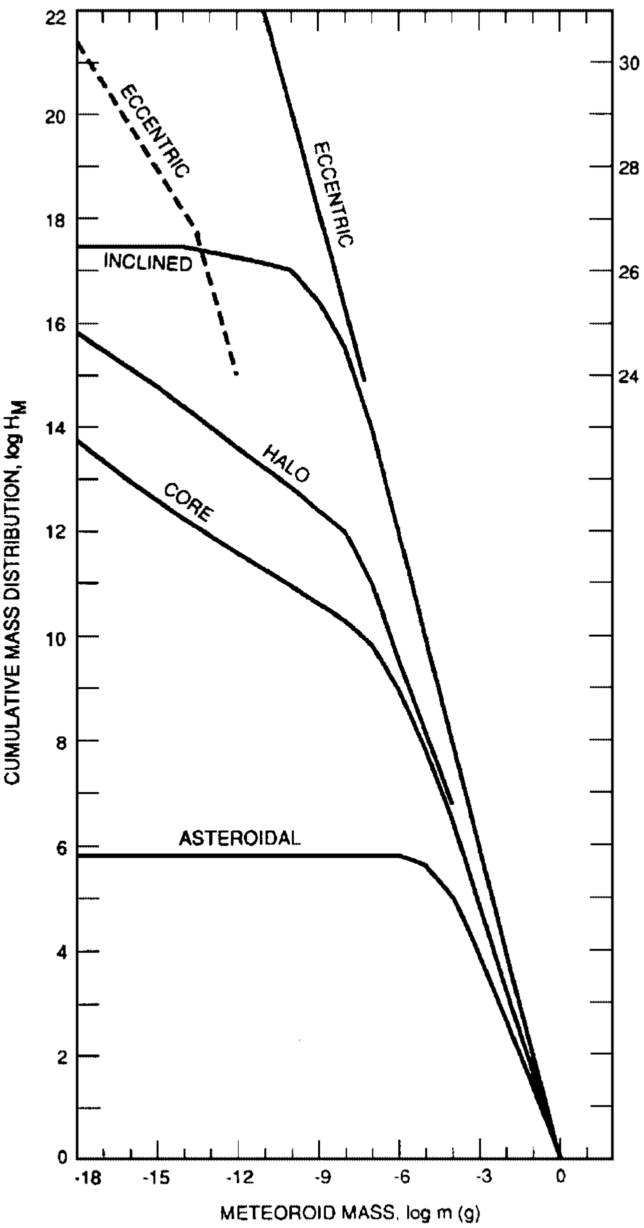

Fig. 2 Divine[3] model mass cumulative distribution H_M; see Eq. (8).

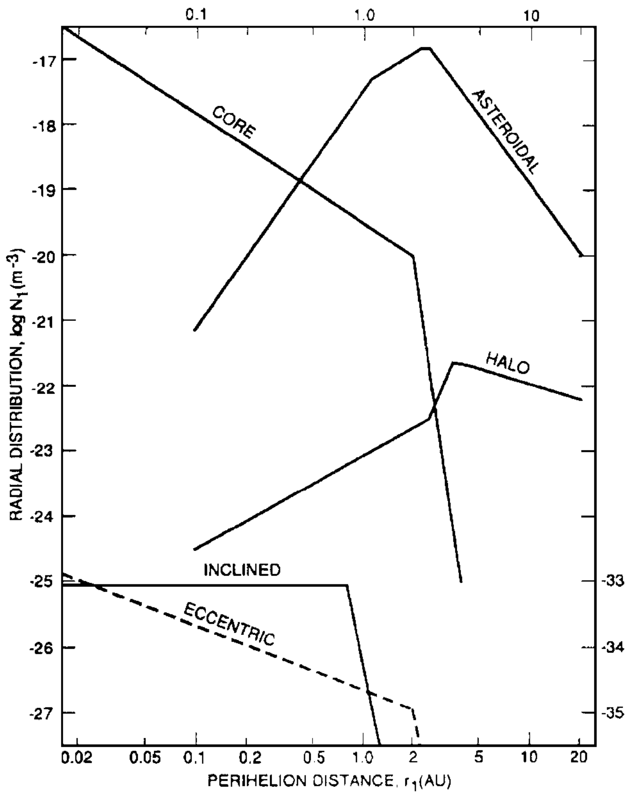

Fig. 3 Divine[3] model radial distribution N_1, one of the variables used in Eq. (9) to define g_0.

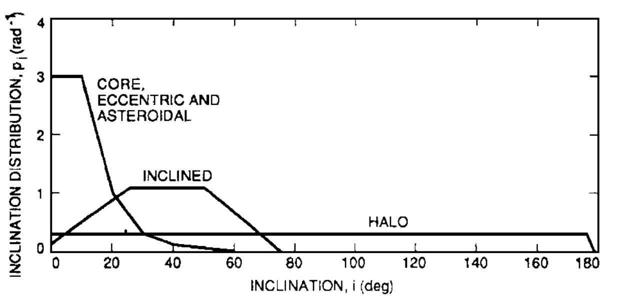

Fig. 4 Divine[3] model inclination distribution p_i, one of the variables used in Eq. (9) to define g_0.

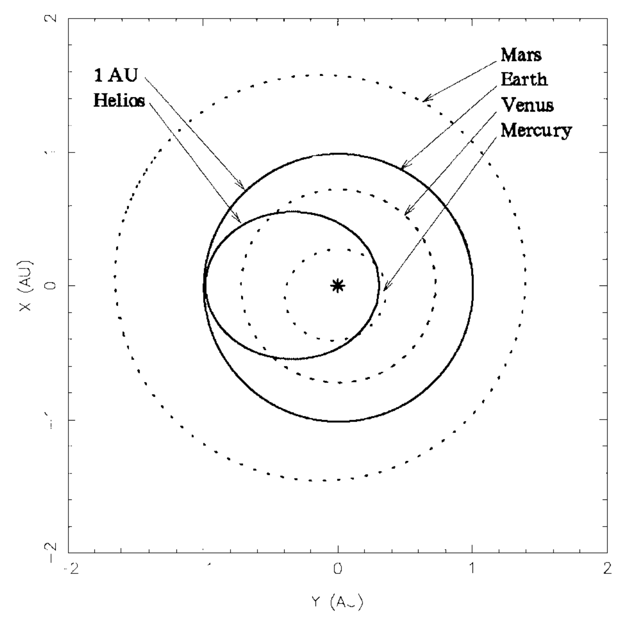

Fig. 5 Trajectories assumed for the Helios and 1-AU mission scenarios.

NASA–METEM Comparisons

The NASA models have been the baseline meteoroid models for over 25 years. As such, it is of real value to potential users to compare the predictions of these models with those of the newer Divine model as represented by METEM. Given the different formulations and data sources, it is only to be expected, however, that there will be observable differences between the models. To compare the models on an equal basis, three representative mission scenarios were selected: 1) a spacecraft in Earth orbit (in the absence of the Earth), 2) a representative Cassini trajectory to Saturn, and 3) an inner solar system mission, Helios. These orbit scenarios are shown in Figs. 5 and 6.

A primary use of meteoroid models is to predict the integral fluence for a given mass threshold or to estimate the probability of a system failing due to meteoroid impact. The former requires calculating the fluence of particles with a mass m or higher onto a (typically) randomly tumbling plate. As an adjunct, the average impact speed is usually desired. In the latter case, one requires a definition of a failure criteria. Typically, this is a surface penetration formula that describes the relationship between the mass and velocity of a meteoroid that just fails a tank, battery, solar cell, etc. Here the well-known single-surface penetration formula for thin plates[17] for particles from 50 μm to $\sim$1 cm diameter impacting aluminum will be assumed. The thin-plate formula is based on empirical fits

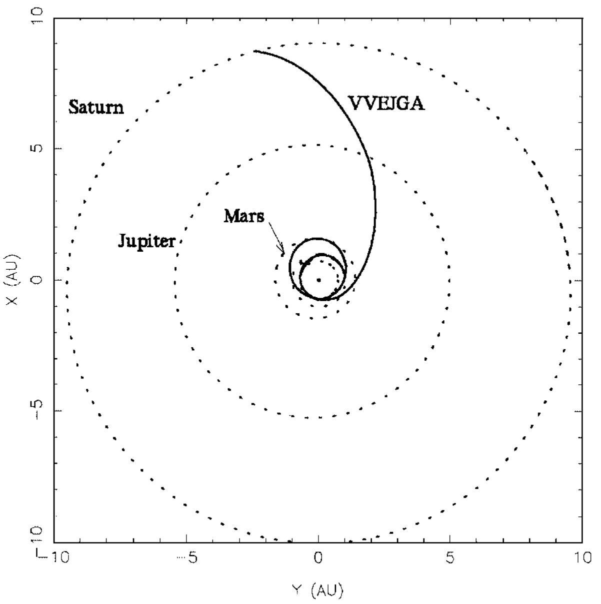

Fig. 6 Trajectory assumed for a representative Cassini mission to Saturn; this is a Venus–Venus–Earth–Jupiter gravity assist trajectory.

to data and gives the minimum thickness necessary to prevent perforation for a given mass/velocity combination,

$$t_c = C_0 \rho_m^{\frac{1}{6}} m^{0.352} V_m^{0.875} \tag{14}$$

V_m is assumed to be the average impact velocity for the NASA models as given by Eqs. (2) and (4) (it is defined by these models to be normal to the surface). For METEM, V_m is assumed to be the absolute magnitude of the velocity vector relative to the surface. METEM gives the actual impact velocity vector relative to the surface, but this definition was selected so as to give a worst case. To illustrate the calculation of a mission failure probability, it will be assumed that t_c is the thickness of an aluminum shield that would just be perforated by a 1-g particle of 2.5-g/cm^3 density and impact speed of 20 km/s. All other densities, masses, and velocities of impacting particles will be scaled according to Eq. (14) using this thickness to determine whether they would cause failure (that is, any particle mass/velocity combinations requiring a smaller thickness than t_c will be assumed to not cause failure).

Once a failure criterion is established, the total fluence at each trajectory position to a randomly tumbling plate is estimated over the entire range of velocities and masses that cause surface penetration. The probability of failure is then computed from an estimate of the appropriate sensitive area multiplied by this critical fluence. In statistical terms, the probability of X impacts on a spacecraft is given by

$$P(X, t) = \frac{(f_p A' t)^X e^{-f_p A' t}}{X!} \tag{15}$$

Here, rather then compute the probability of failure, the fluence for the critical mass m_c (impacts per unit area for the mass/velocity combinations that will just perforate a surface of thickness t_c) will be estimated as a function of mission duration for each model.

Figures 7 and 8 compare the mission fluences for METEM and the three NASA models: the asteroid component (APROB), the cometary component (NASA), and the Galileo cometary model (GAL) for the three missions. Figure 7 is the fluence of all particles with a mass of 1 g or higher, whereas Fig. 8 is the fluence for all penetrating particles meeting the thin-plate, single-surface penetration formula [Eq. (14)] criteria for a randomly tumbling surface.

The final mission fluences for Figs. 7 and 8 are given in Table 2. The main points to note for these results are as follows. The NASA asteroidal component typically dominates if the spacecraft passes through the asteroid belt between 1.5 and 3.5 AU. The Divine[3] model estimates, which are the sums of five different populations,

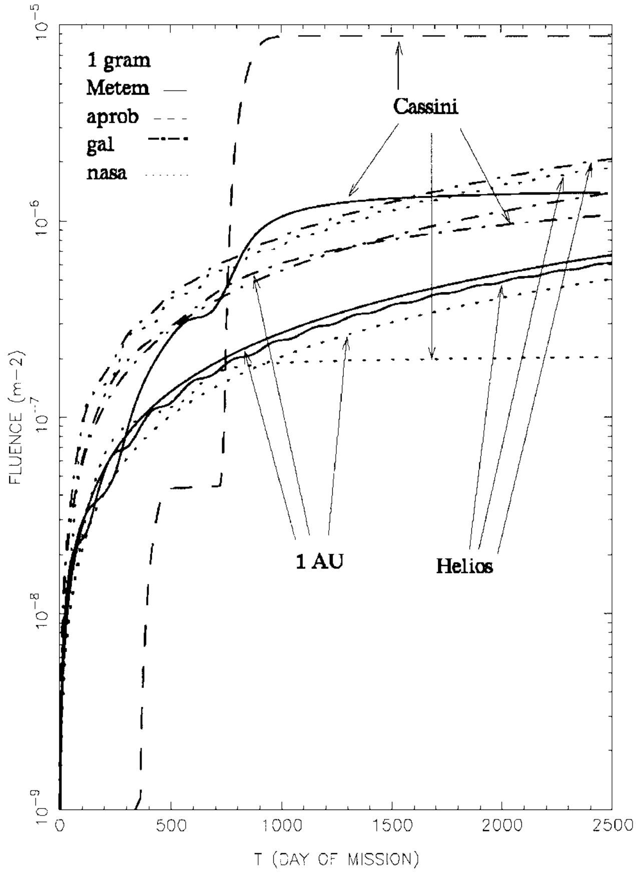

Fig. 7 Fluence as a function of mission elapsed time for the Helios, 1-AU, and Cassini mission scenarios at a fixed mass threshold of 1 g.

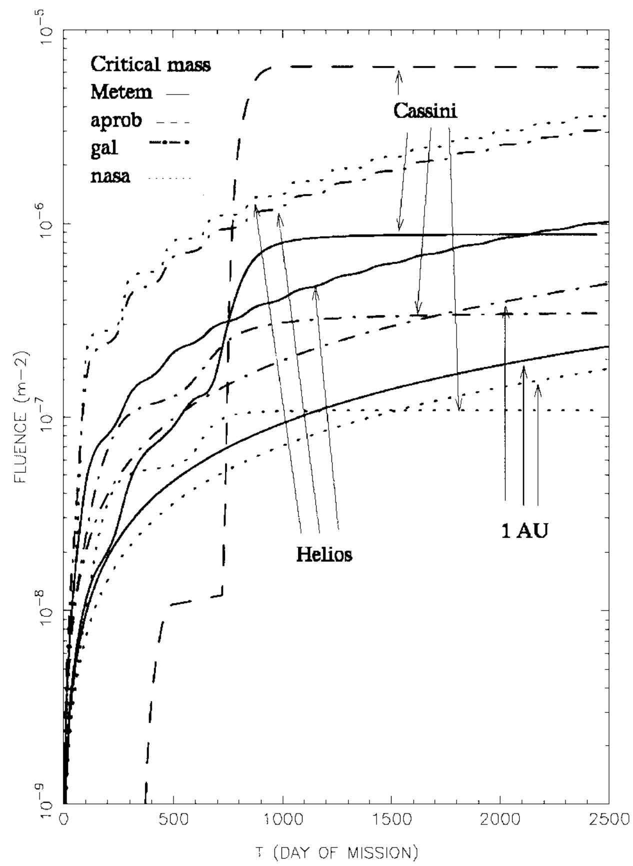

Fig. 8 Total fluence capable of perforating a fixed aluminum shield thickness as a function of mission elapsed time for the Helios, 1-AU, and Cassini mission scenarios; shield selected to have a thickness sufficient to protect against a 1-g particle of 2.5-g/cm^3 density at an impact velocity of 20 km/s [see Eq. (14)].

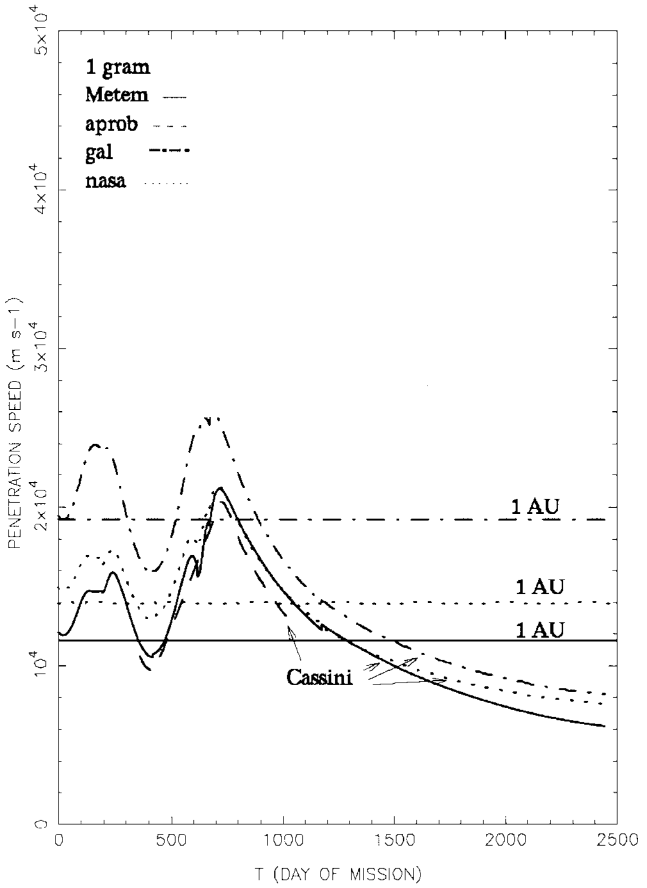

Fig. 9 Impact speed as a function of mission elapsed time for a fixed mass threshold of 1 g for the Cassini and 1-AU trajectories.

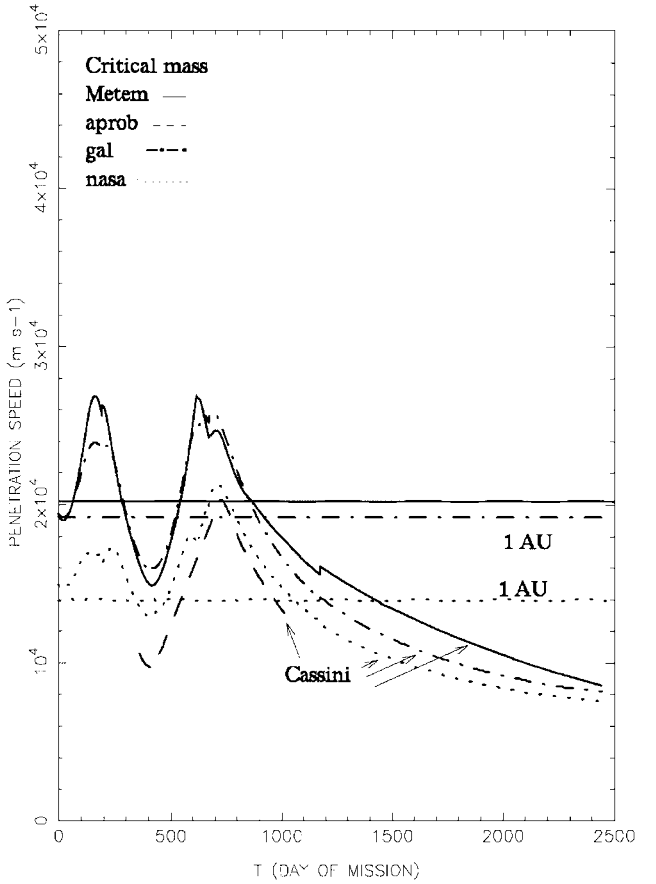

Fig. 11 Impact speed for a fixed shield thickness for the Cassini and 1-AU trajectories (see Fig. 8 caption).

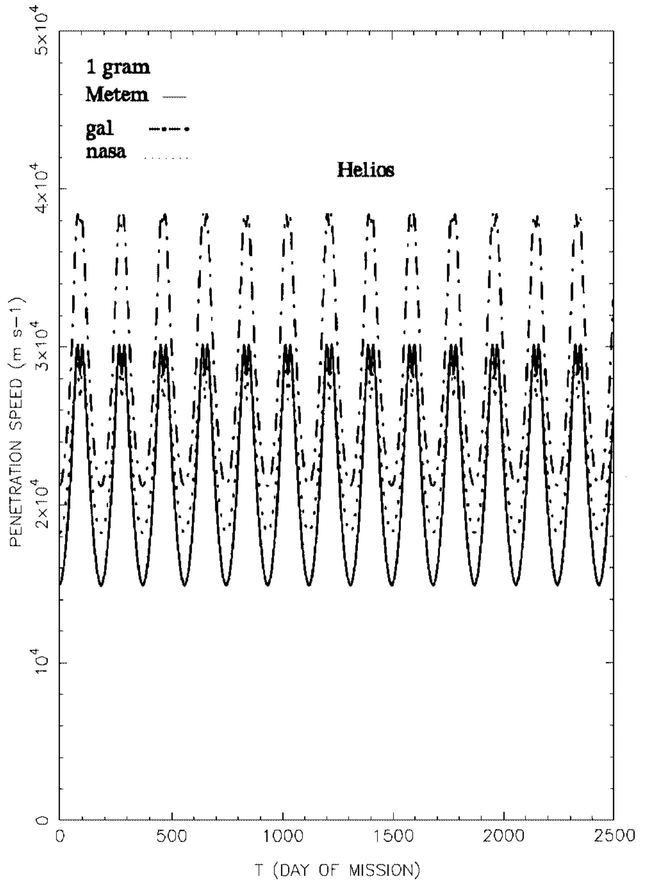

Fig. 10 Impact speed as a function of mission elapsed time for a fixed mass threshold of 1 g for the Helios trajectory.

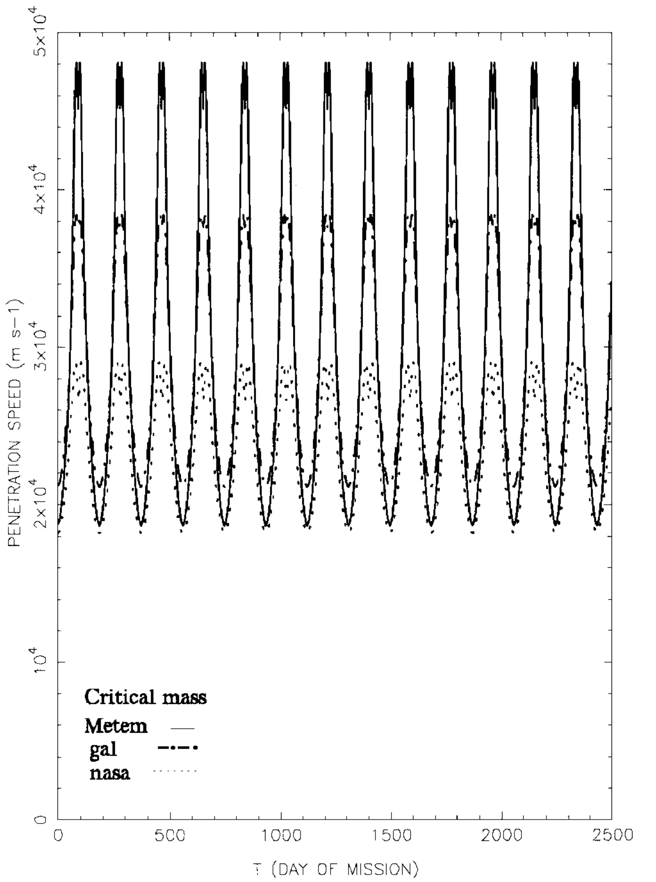

Fig. 12 Impact speed for a fixed shield thickness for the Helios trajectory (see Fig. 8 caption).

Table 2 Total mission fluences for the Helios, 1 AU, and Cassini missions

Model	Helios, 187.3 days	1 AU, 365.6 days	Cassini, 2447 days
	Fluence $(m > 1\ g)\ m^{-2}$		
METEM	4.48E-8	9.79E-8	1.40E-6
APROB	0.0	0.0	8.73E-6
GAL	1.55E-7	2.03E-7	1.06E-6
NASA	1.41E-7	7.38E-8	2.01E-7
	Fluence $(m_c)\ m^{-2}$		
METEM	7.75E-8	3.39E-8	8.80E-7
APROB	0.0	0.0	6.45E-6
GAL	2.34E-7	7.13E-8	3.43E-7
NASA	2.76E-7	2.59E-8	1.08E-7

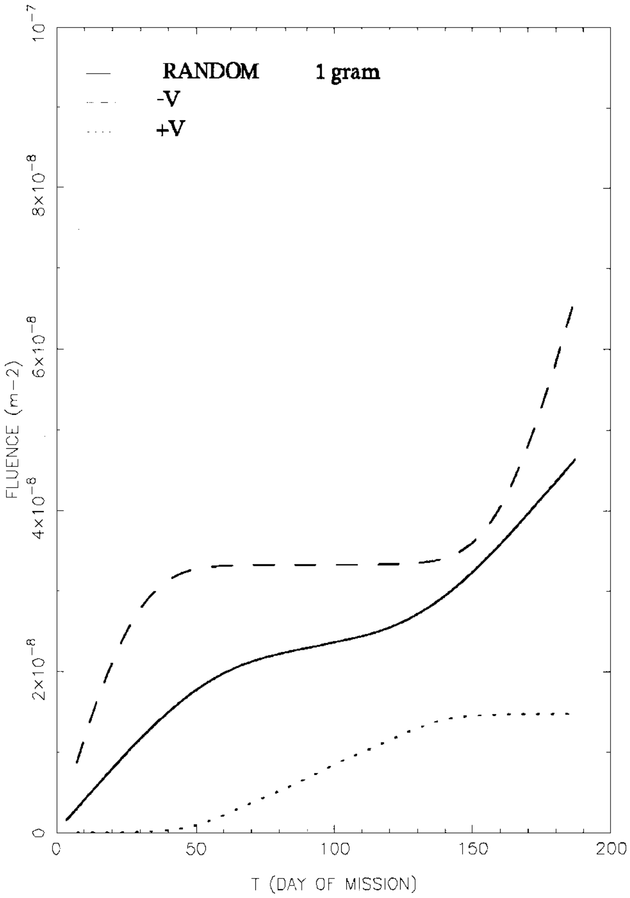

Fig. 13 Fluence for a fixed threshold of 1 g for the Helios mission trajectory onto a randomly tumbling plate; fluence is compared for a surface oriented in the direction of the spacecraft velocity vector (+*V*), for a surface oriented opposite to that direction (− *V*), and for a randomly tumbling plate.

are one-third of the NASA cometary fluences for Helios, roughly equal for 1 AU, and higher (2–7 times) for Cassini for the 1-g mass threshold. Similar results hold for the penetration formula. Qualitatively, however, the Divine fluences follow the same patterns as the cometary model fluences as a function of mission elapsed time. The NASA asteroidal component exceeds the Divine model fluences by a factor of ~8 and follows a very different pattern.

Although not unanticipated (the models are based on different data and distribution assumptions), the reasons for these differences between the models are of interest. Aside from the density differences (0.5 g/cm^3 for the cometary models, 2.5 g/cm^3 for 4 of the 5 Divine[3] populations), the other important property is the average impact velocity. To study its behavior, the mean impact speed [estimated by Eqs. (2) and (4) for the NASA models and by the ratio of the integral of the product of the fluence and velocity divided by the integral of the fluence for the Divine model; see Eq. (12)] has also been computed as a function of mission elapsed time. These values are plotted in Figs. 9–12.

The major contribution to the differences between the models in these estimates is that the impact speed for METEM is averaged over five populations. The individual populations for METEM have average impact speeds that cover a wide range of values, e.g., at 1 AU for a 1-g particle threshold, the speeds are total: 11.6 km/s, core: 13.9 km/s, inclined: 22.1 km/s, eccentric: 23.6 km/s, halo: 48.9 km/s, and asteroid: 11.5 km/s. Figures 9 and 10 reflect this averaging. In the NASA models, the velocity of the asteroidal component is significantly lower than that of the cometary components (the Galileo model has a different velocity than the NASA cometary model because of the δ factor). The NASA cometary component has a velocity close to the average impact speed for the Divine model for the 1-g threshold fluences. However, when a penetration relation is considered, the GAL and METEM velocities more closely agree. This agreement is most likely due to the increased weighting in the Divine model of the lower mass/higher velocity particle populations that dominate in the latter case because of their higher fluxes.

Fluence onto an Oriented Plate

The final property to be presented is the variation in fluence as a function of orientation. Unlike the NASA models, the Divine model can explicitly estimate the fluence to a surface oriented in a fixed direction in space as opposed to the randomly tumbling plate. The ability to estimate the fluence to a surface is a valuable improvement as a spacecraft can be deliberately flown in a specific orientation to limit the impacts on a particular surface (a rocket nozzle or tank surface, for example). Figures 13–15 present estimates of the meteoroid fluence to a randomly tumbling surface, a surface oriented in the spacecraft velocity direction, and in a direction opposite to the velocity vector. (Note that the Divine model can calculate the actual impact velocity vector to a surface as a function of angle normal to the surface. We again assume a worst-case estimate of the fluence in

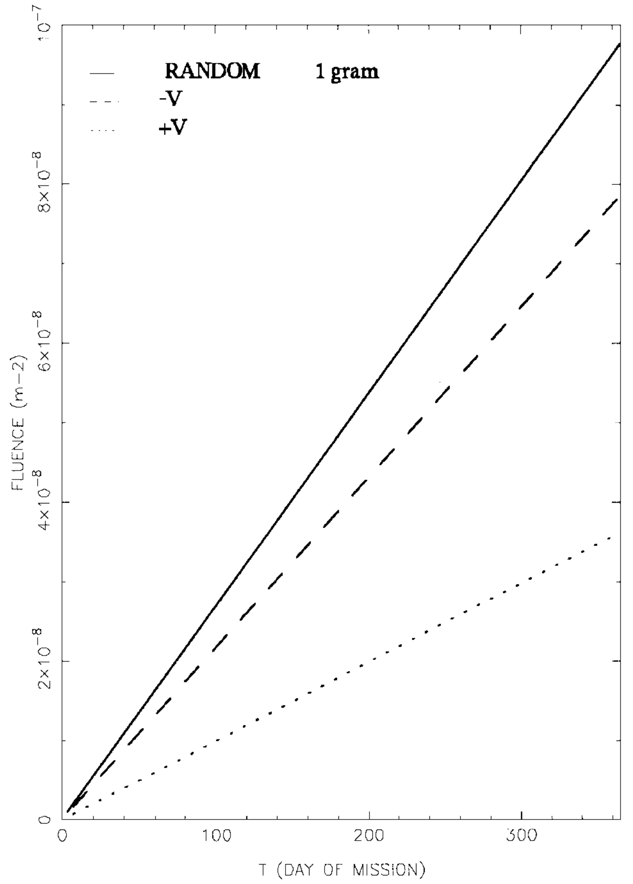

Fig. 14 Fluence (for a spacecraft at 1 AU) for a fixed threshold of 1 g onto a randomly tumbling plate compared to a surface oriented in the direction of the spacecraft velocity vector (+*V*) and opposite to that direction (− *V*).

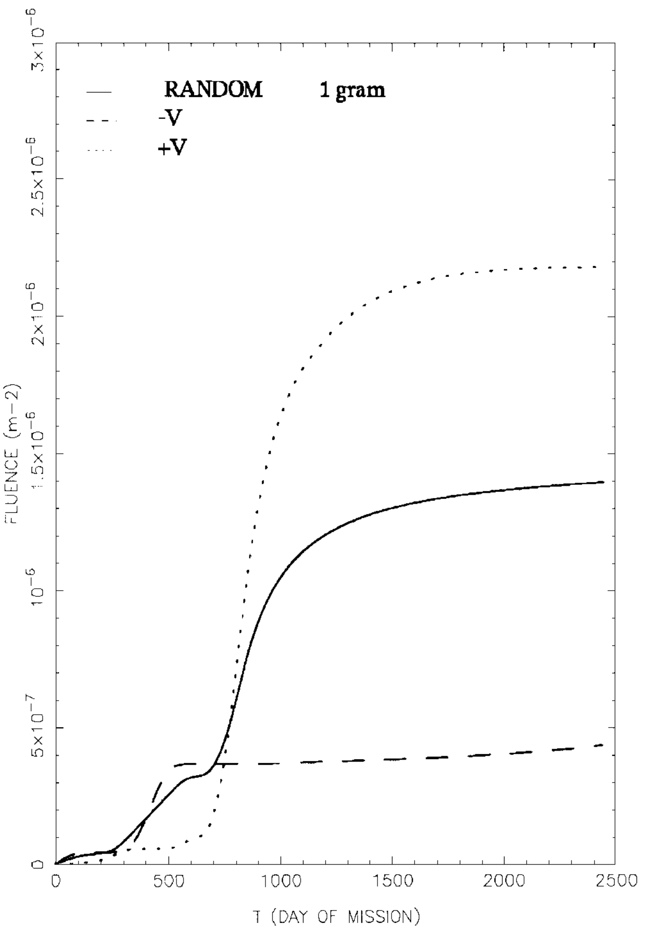

Fig. 15 Fluence (for the Cassini trajectory) for a fixed threshold of 1 g onto a randomly tumbling plate compared to a surface oriented in the direction of the spacecraft velocity vector (+*V*) and opposite to that direction (− *V*).

terms of the total impact speed into the oriented surface as opposed to just the normal component.)

The differences in fluence to the forward and tailward surfaces of a spacecraft are striking. For the Helios mission, when the spacecraft is moving slower than the circular orbit speed at aphelion, the spacecraft sees more fluence in the direction opposite the velocity vector and on its sides (as approximated by the randomly tumbling surface) than from the forward direction; the meteoroid flux is overtaking the spacecraft. For Fig. 14, at 1 AU, the flux to the sides (the randomly tumbling results) dominates; few particles are catching up from behind and fewer still are being overtaken. Finally, for the outer solar system missions, when the spacecraft is moving faster than the circular orbit velocity, the flux in the direction of the velocity vector dominates; the spacecraft overtakes the meteoroids. Note, in particular, the switch over in behavior around day 700 for the Cassini trajectory.

Conclusions

The new Divine model (in the form of the METEM code) produces results that at least subjectively resemble the older NASA meteoroid models. The differences in assumed populations, however, make a quantitative comparison difficult. Even so, this paper provides a link between the older models and the newer one that should prove useful for those seeking to compare their predictions. As a secondary objective, the paper has demonstrated the capabilities of the new model, in particular, its capability to estimate fluences to oriented surfaces. The Divine model is now available to the general community as the compiled METEM code that can be run on a wide range of personal computers and main frame computers or with a Visual Basic® front end (METEMvb) for use on Windows-based personal computers.

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