Earth, Moon, and Planets (2004) 95:123–139
DOI 10.1007/s11038-004-9044-8

METEOROID ENGINEERING MODEL (MEM): A METEOROID MODEL FOR THE INNER SOLAR SYSTEM

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(Received 15 October 2004; Accepted 30 June 2005)

Abstract. In an attempt to overcome some of the deficiencies of existing meteoroid models, NASA's Space Environments and Effects (SEE) Program sponsored a 3 year research effort at the University of Western Ontario. The resulting understanding of the sporadic meteoroid environment – particularly the nature and distribution of the sporadic sources – were then incorporated into a new Meteoroid Engineering Model (MEM) by members of the Space Environments Team at NASA's Marshall Space Flight Center. This paper discusses some of the revolutionary aspects of MEM which include (a) identification of the sporadic radiants with real sources of meteoroids, such as comets, (b) a physics-based approach which yields accurate fluxes and directionality for interplanetary spacecraft anywhere from 0.2 to 2.0 astronomical units (AU), and (c) velocity distributions obtained from theory and validated against observation. Use of the model, which gives penetrating fluxes and average impact speeds on the surfaces of a cube-like structure, is also described along with its current limitations and plans for future improvements.

Keywords: Engineering model, interplanetary, sporadic meteoroids

1. Background

The sporadic environment consists of a diffuse background of meteoroids of cometary or asteroidal origin. They represent a continuous risk to spacecraft throughout the year, unlike meteor showers or storms, which occur when Earth passes very near the nodal crossings of comets, or, in some instances, asteroids. Although the risk to spacecraft is high during showers and storms, the sporadic meteoroid environment still poses a greater risk, as the integrated number is much greater than that of shower meteoroids, which are only present for a relatively short period of time. Mitigating the meteoroid risks from such events can be accomplished by operational procedures, such as reorienting a vehicle to point sensitive equipment away from the radiant, or slewing solar panels edge on to minimize cross sectional area and closing shutters to protect sensitive optics. However, the constant threat presented by the sporadic meteoroid background must be reduced in the design of the vehicle, which can lead to significant engineering challenges. Often operators and designers choose to shield their spacecraft against the hypervelocity impacts. But, in the never-ending search for ways to reduce vehicle mass, questions inevitably arise… How much shielding is necessary and what parts of the spacecraft are most exposed?

To answer those questions, spacecraft designers need to have access to an engineering tool that accurately models the locations of the sporadic meteoroid radiants, with their relative strengths and proper velocity distributions. But there are several different methods for modeling these desired parameters. Some models rely on empirical fits to *in-situ* dust measurements from space probes, zodiacal light observations, lunar micro-crater counts, and ground based radar observations. Such fits, however, are limited by the quality of the data used in the fit, and must be used cautiously when designing vehicles destined for locations or particle sizes not covered by the observations. Another approach involves modeling the meteoroid orbital evolution from the distributions of the sporadic sources, relying only on observations to calibrate the model. This paper briefly addresses some of the shortcomings of empirical models of the past, and advocates the more physical alternative approach. We hope to address some of the issues that are of concern to spacecraft designers and mission analysts, specifically the flux of meteoroids of a certain mass or range of masses, the distribution of impacting speeds, and the directions from which those meteoroids are coming.

2. Other NASA Models

The models of the past were mathematical models, simple or complex numerical expressions fit to observations from a variety of data sources patchworked together. These expressions, though physically limited, defined the interplanetary meteoroid environment in terms of mass flux, velocity distribution, and meteoroid density. Most models also assumed that the sporadic background was omni-directional, an assumption that is known to be invalid.

The most popular NASA models are based on the "Interplanetary Dust Model" of Grün (Grün et al., 1985), a simple, easy-to-use equation that accurately fits the measured dust fluxes near Earth's orbit, but does not contain directionality and requires a single average meteoroid speed, rather than a distribution of velocities. The flux component of this model is described in NASA Technical Memorandum (TM) 4527 (Anderson, 1994) and NASA Space Station Program SSP 30425. However, these documents also specify the use of a velocity distribution developed by Cour-Palais, based on photographic meteor velocity determinations, rather than the single speed advocated by Grün. The velocity distribution given in the NASA TM has an average speed of 17 km/s near Earth; for Earth orbiting spacecraft that number is 19 km/s, which is low compared to new information from radar observations. This older velocity distribution did not work well with the Grün flux because Grün's equation was meant to be used with a flux weighted average meteoroid speed of 20 km/s. That value was justified based on two reasons, the first of which being that cratering and destructive collisions depend on v^2; the average effect corresponding to a higher speed (over the average impact speeds on the moon from 13 to 18 km/s). Secondly, mutual collisions among meteoroids occur at higher speeds than impacts on the moon and on Earth because their eccentricity and inclination is generally larger than that of Earth, (Grün et al., 1985).

Older NASA meteoroid models, NASA SP-8013 (Cour-Palais, 1969) and SP-8038 (Kessler, 1970), define the sporadic meteoroid environment for mass ranges of 10^{-12} to 1 g. The mass density of meteoroids used in these models are 0.5 g/cm^3 with an average speed of 20 km/s, which was derived from photographic measurements (Dohnanyi, 1966), along with the assumption of the independence of mass and velocity. Again, these models are simple numerical equations that describe the flux of particles as a function of mass. The models also only deal with meteoroids of cometary origin, with the asteroidal contribution treated as negligible, a very highly disputed assumption. The flux equations were derived from measurements from meteoroid detectors of masses smaller than 10^{-6} g, and from Earth-based radar and photographic techniques for masses larger than 10^{-6} g.

Divine's (1993) "Five Populations of Interplanetary Meteoroids" model uses more complicated mathematics to obtain empirical fits for the orbital distributions of particles from a variety of data sources. In his paper, he describes his model as a numerical model, one which both supports the evaluation of concentration and flux. The original Divine meteoroid model was based heavily on the measurements and analysis of the dust populations, particles much less massive than the 10^{-6} g that most spacecraft designers consider to be the lower end of the threat regime. For the more massive particles, Divine relied on zodiacal light studies (Levasseur-Regourd and Dumont, 1980) and radar measurements to construct his model. Unfortunately, some biases and limitations associated with these data were not addressed. To be more specific, zodiacal light is mostly created by particles in the 10^{-8}–10^{-5} g range (Grün et al., 1985), with the dominant contribution to the light coming from the lower end of this mass range, which barely extends into the threat regime. For larger particles, Divine relied on radar measurements from Sekanina and Southworth's (1975) Harvard Radio Meteor Project (HRMP). Divine's speed distributions were based on this HRMP data, which provided the meteor orbital information. It was discovered by Taylor (1995) that a mistake had been made in the de-biasing of those speed distributions, which are now known to contain biases towards the lower speeds. The biases are due to an absent correction for the initial trail radius effect, which causes higher velocity meteors to be missed because of increased attenuation at increasing altitudes. Additionally, the Harvard dataset only applied to orbits that intersected the Earth's, leaving Divine to rely on interpolation methods for the un-sampled inner solar system. The valid distance for this radar data is 0.98–1.02 AU. Figure 1 shows the ranges in mass and distance from measurements collected for his model. It also shows the gaps in measurements and the limited amount of data on larger meteoroid particles of interest.

The current version of METEM, the model based on Divine's work, does not accurately model the sporadic directionality or velocity distributions. Figure 2 displays the discrepancy between METEM's directionality and what Earth-based radars believe it to be. The comparison is made for meteoroids with mass $m \geq 10^{-4}$ g encountering the Earth (Taylor and McBride, 1997). This discrepancy was discovered in private communications and analysis with M. Matney at Johnson Space Center (JSC). Additionally, METEM relies on a concentration dependence proportional to $r^{-1.3}$ (Leinert et al., 1983) which is

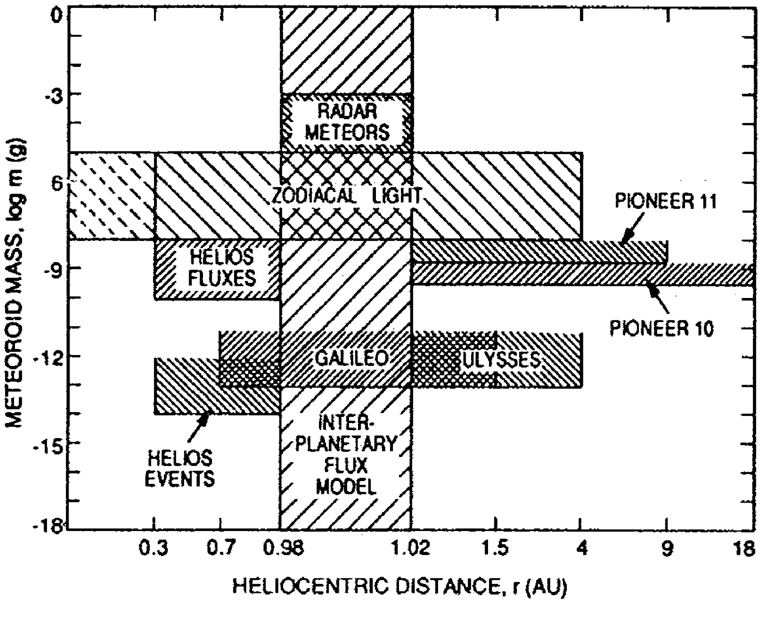

Figure 1. Coverage in mass and heliocentric distance for the data sets used in Divine (Divine, 1993).

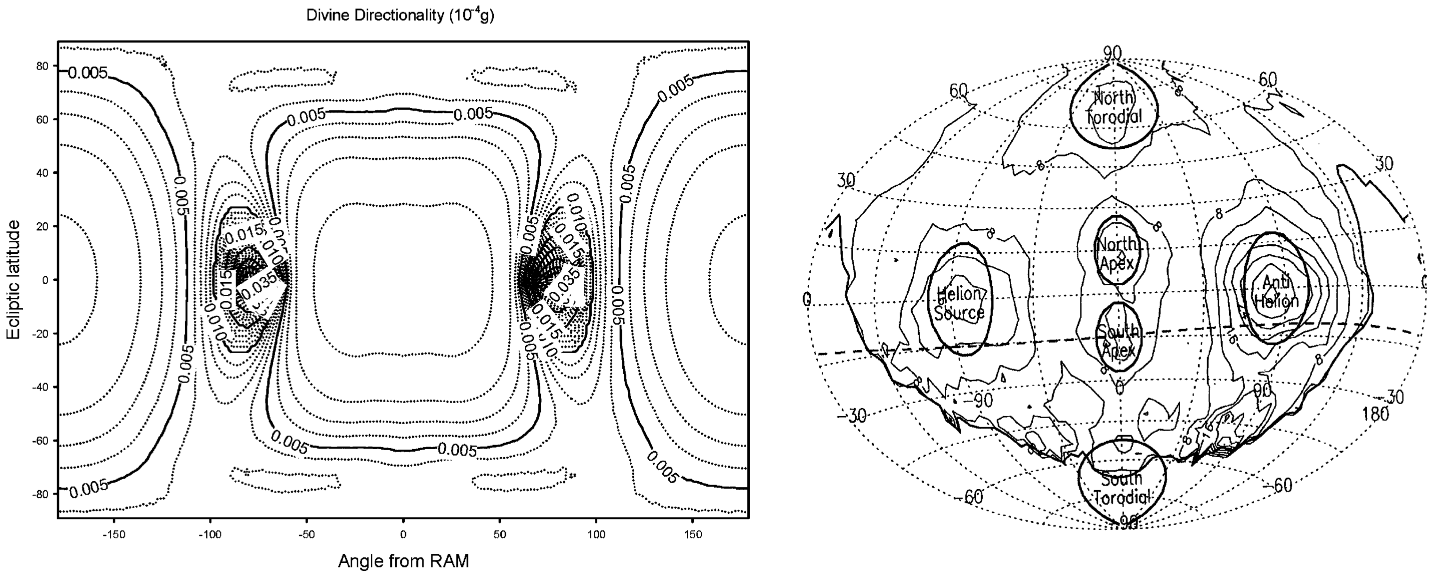

Figure 2. Comparison of METEM/Divine meteoroid directionality vs. Earth-based radar (Matney, 2004) (Taylor and McBride, 1997).

derived from zodiacal light concentrations and Helios data. Divine's model also adopts solar gravitational force as the only operative force acting on the particles in heliocentric orbits. The other forces such as planetary perturbations, non-gravitational forces (specifically radiation pressure), collisions etc. have been omitted from this model. The one population from METEM/Divine that most closely models the larger particles and best fits all the different measurement sources was the "core" population, the backbone of the model (Divine, 1993). The other populations were add-ons to cover special purposes. The average meteoroid density assumed for this core population is 2.5 g/cm^3, with an average speed of 13.8 km/s at Earth.

Recently, Divine's model has been updated by members of NASA's Jet Propulsion Laboratory (Garrett et al., 1999) and Jehn (2000) to correct for the velocity bias and incorporate new meteoroid data and an updated user interface. The previous versions of METEM were very difficult for the general user requiring knowledge of the code to edit and run it (Garrett et al., 1999). The most recent version of METEM is still quite complicated and seems geared more to those interested in designing new spacecraft dust detectors rather than protecting specific surfaces from penetration.

Despite the more complex formalism of the Divine model, the fact remains that it and all of the previous NASA models are fundamentally empirical fits to observations, mathematical constructs with interpolation schemes for the areas beyond the measurements. The limitations of this approach have been previously discussed, and so another technique must be employed to model the environment, especially for the larger particles damaging to spacecraft. This approach must also be capable of allowing confident extrapolation into areas where observations are lacking.

We feel that this can be accomplished by adopting a "physics-based" approach, defined here to mean that the sources of sporadic meteoroids are tied to actual comet families and asteroids and that the steady-state distribution of the orbits of meteoroids released from these sources can be modeled under various forces to produce radiants and velocity distributions as seen by ground based radar (Jones et al., 2001). Once validated by an observation point (e.g., the Earth), the model can be extended beyond this point to be used any place where the sources and the physics incorporated within the model are valid. Unlike the previously described numerical models, MEM follows this physics-based approach, opened by Leinert, (Leinert et al., 1983).

3. Meteroid Engineering Model (MEM)

Deficiencies in the current meteoroid models spurred a recent effort by the SEE program to develop a new meteoroid engineering model that incorporated a physics-based approach to modeling the sporadic environment, with validation against radar observations (Jones, 2003). The task was to construct a model that could predict the concentration and velocity distribution of meteoroids within the inner solar system from 0.2 to 2.0 AU, using observational measurements to constrain the physical model, rather than build one based on empirical fits. Because micrometeoroid detectors on board space probes and satellites have observed highly directional fluxes of interplanetary dust particles that vary in particle size (Grün et al., 1985) and NASA is planning large oriented spacecraft such as Solar Sails and James Webb Space Telescope, incorporating directionality was of great importance in this model.

Previous work done by Jones and Brown (1993) show that the sporadic meteoroid environment as observed from Earth can be described by four major sources in six radiants distributed symmetrically about the celestial sphere in sun-centered ecliptic coordinates. The primary sources of the Helion/Anti-Helion, North and South Apex, and North and South Toroidal radiants are Jupiter family comets, or JFC's, long period comets, and Halley family comets, respectively. The asteroid component, not very well understood, at least in terms of its strength relative to the cometary sources, is also modeled. Some specific details on the physics behind the model are described in following paragraphs.

First, MEM assumes that comets are a major source of sporadic meteoroids. The orbits of the comets are distributed symmetrically about the ecliptic pole (ascending nodes and arguments of perihelion are uniformly distributed), so that the important parameters are a, the semi-major axis, e, the eccentricity, and i, the inclination. Asteroids also contribute to the meteoroid population, and the model incorporates distributions in a, e, and i provided by J.C. Liou at NASA's Johnson Space Center. Here again, the assumption of axial symmetry about the ecliptic pole is made.

It was realized early on that incorporating the effects of planetary perturbations on the meteoroids increases the computational burden tremendously; therefore those effects were ignored. One justification for the neglect of this effect is that, over the long-term, the average gravitational perturbing force on those meteoroids that don't make a close encounter with a planet is azimuthally symmetric. In these cases, the meteoroid orbit is changed slightly since the planet's mass is small relative to the sun and the main perturbation is a precession of perihelion, which does not significantly change an azimuthally symmetric orbital distribution. The model does include the important dust producing mechanism of catastrophic collisions and the Poynting-Robertson (PR) effect in a parametric model that has been fitted to observations made with Canadian Meteor Orbit Radar (CMOR) system. Other effects not considered in this model are very close planetary encounters and mean motion resonances, which probably affect only a relatively small fraction of the meteoroid population.

Given all the forces and assumptions, one is then able to estimate the steady-state orbital distributions of the ejected meteoroids and convert these distributions into a flux of particles that would be observed from Earth or a spacecraft. The first step is to determine the concentration of meteoroids $S(r)$ as a function of heliocentric distance r, from the Sun. Where Q is the aphelia, and q is the perihelia distances. This can be done by invoking the standard expression given by Opik (1951), Kessler (1981) and Steel and Elford (1986):

$$S(r) \propto \frac{1}{r} \int \int \frac{N(Q,q)}{(Q+q)\sqrt{(r-q)(Q-r)}} \tag{3.1}$$

In developing distributions for the sporadic complex, comets can be organized initially by period and Tisserand parameter. The two main groups considered are the short-period and the long-period comets. The short period group has orbits which are closely aligned with the ecliptic and their periods are less than 200 years; the long-period comet orbits are essentially isotropically distributed with periods greater than 200 years. In addition, the short-period group can be further categorized into two main families: the Jupiter family of comets with periods less than 20 years and Tisserand parameters greater than 2.0 and the Halley family with periods greater than 20 years and Tisserand parameters less than 2.0.

With the main groups of comets now organized into the Jupiter family, Halley family and Long-period comets, meteoroid production rates can be assessed. It is important to note that the orbital distribution of the parent comets is not the same as the source production function since those comets that come close to the Sun will produce correspondingly more meteoroids than the comets with more distant perihelia. Several authors have shown that the threshold for the sublimation process to occur is around 2.3 AU (Delsemme, 1976; Jones, 1995). When the comet comes closer to the sun than 2.3 AU, sublimation predominates over radiation. To describe this relationship, the true anomaly θ_c at which the distance to the Sun is 2.3 AU is described by equating the sublimation rate per unit area to the solar flux, and applying appropriate averaging. Also, if the assumption is made that the composition of comets is uniform (the ratio of dust to ice is constant), then it follows that the amount of meteoric material released is proportional to the amount of ice sublimated as the comet passes close to the Sun. The average rate of production of meteoric material can then be given by

$$P_{\text{avg}} \propto \frac{\theta_c(1-e)^2}{q^2\sqrt{1-e^2}} \tag{3.2}$$

where e is the eccentricity, q the perihelion distance, and θ_c is the true anomaly. After applying this equation to the groups of comets named above, one finds that the Jupiter family accounts for 91% of the meteoric material, the Halley family 5% and the Long-period family 4%. Of the Jupiter family of comets, only a subset are meteoroid producing comets, those with Tisserand parameters close to 2.8. Applying these definitions and limitations described here to the Marsden Catalog of Cometary Orbits (Marsden, 1989), the following results are obtained.

Analyses of the zodiacal light observations by the Helios I and II space probes show strong evidence that the density of interplanetary dust varies with heliocentric distance according to $r^{-1.3}$ (Leinert et al., 1983). Recall that the particles responsible for the majority of the zodiacal light are smaller than typical penetrating meteoroids but not so small as to be removed by radiation pressure; therefore it is reasonable to assume the same dependence on heliocentric distance r for the larger particles (Grün et al., 1985). These same zodiacal light observations also imply that the orbital distributions of interplanetary particles have azimuthal symmetry. It is logical then to assume that the source distributions can be considered separable into a part, $N(Q,q)$ that depends only on the the aphelion distance Q, the perihelion distance q, and another part that depends only on the orbital inclination.

As our model follows the same observed $r^{-1.3}$ dependence of particle concentration on distance from Sun, a constraint is placed on the aphelion distribution of the helion/anti-helion source to be identical to that of their parent Jupiter family of comets. The perihelion distribution is unknown, due to observational biases and the unknown effects of the variation of sublimation efficiency with age. This being the case, the following has been chosen as the form for the distribution function of Jupiter family perihelia:

$$n(q) \propto \{1 - (q/2.3)^m\}^t (q/2.3)^{m-1} \tag{3.3}$$

The aphelia distribution can be described by a gaussian where $\overline{Q}$ is the mean aphelion distance and σ the associated standard deviation:

$$n(Q) \propto e^{-((Q-\bar{Q})/\sigma)^2} \tag{3.4}$$

In order to develop the distribution of inclinations for the Jupiter family group, it is necessary to assume that the orbital inclinations of those particles in the threat regime are not significantly changed when they are released from their parent comets. However, the distribution of inclinations for the entire set of particles associated with the Jupiter family comets is not necessarily what needs to be considered; rather, emphasis will be placed on those particles with orbital planes capable of intersecting that of the Earth. This distribution is different from the whole set of Jupiter family particles and can be described by:

$$n(i) \propto e^{-(i/15.9)^2} \tag{3.5}$$

An interesting aspect of function (3.3) is that not only does it go to zero beyond 2.3 AU (as it should), but it is also extremely flexible because of the parameters m and t. The Q and q distributions can be generated separately as they appear to be uncorrelated. With a given $\{m,t\}$ the particle concentration, $S(r)$, becomes

$$S(r) \propto \frac{1}{r} \sum_t \frac{1}{(Q_t + q_t)\sqrt{(r - q_t)(Q_t - r)}} \tag{3.6}$$

Other factors must be invoked to determine the values that best fit all the observations. The zodiacal light observations show that the particle concentration increases with decreasing heliocentric distance, which seems to imply some mechanism, such as the PR effect, that transports particles towards the Sun. An important factor in this effect is the length of time the particles are likely to survive. Consideration of the two processes active in reducing the particle population reveals that catastrophic collisions with other meteoroids are more important than the erosion resulting from collisions with much smaller particles, (Grün et al., 1985). As the majority of the short-period particles have low inclinations, one can assume that for those particles there is no dependence of the collisional lifetimes on orbital inclination. The rate of collisions with particles of similar size varies as $q/r^{1.3}a^{1.5}$. The relative collision speed, v_{rel} is determined mainly by collision geometry and can be described by:

$$v_{\text{rel}} \propto \frac{1}{\sqrt{r}} \tag{3.7}$$

The relative number of such particles depends on their mass distribution which is modeled as a power law (Grün et al., 1985):

$$dn \propto m^{-2.34} dm \tag{3.8}$$

where n is the particle number and m the meteoroid mass. These factors can be combined to produce a rough expression for the collision lifetime, t_{coll}:

$$t_{\text{coll}} \propto q^{1.64} a^{1.5} \tag{3.9}$$

The effect of PR aging on the orbital parameters of the particles has been calculated by Wyatt and Whipple (1950), who published equations for the rate of change of semi-major axis, a, and rate of change of eccentricity, e, as functions of a variable $\alpha = 3.55 \times 10^{-8}/s\rho$ AU/year, where s and ρ are the radius and density of the particle in c.g.s units. This simulation uses about 5×10^5 particles evolved over several thousand years; direct integration of the Wyatt and Whipple equations would take very long computation times. Consequently, their scheme has been modified by using numerical approximations for the time integrals, making the calculations of the evolved orbits very fast. It is now appropriate to introduce another quantity, $\tau_{\rm pr} = 1/4\alpha$, which is the time for a particle initially in a circular orbit at 1 AU to spiral into the Sun. For a 10^{-4} g particle with density 1.0 gram/cm^3, $\tau_{\rm pr} = 2 \times 10^5$ years. To avoid limiting collisional lifetime to particles of a specific mass, it is convenient to express that relationship in terms of $\tau_{\rm pr}$; in these generalized time units equation 3.9 may be rewritten as:

$$\tau_{\rm coll} = fq^{1.64}a^{1.5} \tag{3.10}$$

where f is the ratio of the collisional lifetime to the PR lifetime of a particle in a circular orbit at 1 AU. This approach is not ideal, as the probability of catastrophic collision changes during the orbit evolution. However, to avoid a detailed and computationally complex scheme, perhaps the details can be hidden in a proper choice of the parameter f. Therefore, the orbital distributions can be described by three parameters: m, t, and f, which can be determined through comparisons with observations, in particular those of zodiacal light and CMOR radar data. The CMOR data was used because its 3-frequency observations of meteors provided the material needed for Campbell-Brown and Jones (2003) to develop a model of meteor ablation that agrees well with the data. The 3-frequency setup also allowed for the estimation of the velocity bias due to the initial trail radius effect. The following table (Table I) compares the measured characteristics of the helion/anti-helion sources according to Brown (1994) and Jones and Brown (1993) to an analysis of radar meteor data from the IAUMDC (Lindblad, 1995). The CMOR data has had three corrections applied to it – the initial trail radius effect, deceleration of the particle in Earth's atmosphere (Baggaley et al., 1994), and the increase in speed due to Earth's gravity.

An initial comparison of this model's source concentrations and velocity distributions were made against the HRMP data by Jones et al. (2001). Even though the HRMP data had velocity biasing errors affecting the relative strengths of the sources, one can make a comparison to a given source to see

TABLE I
Rader determination of helion/anti-helion characteristics

	HRMP	CMOP (2003)
Helion long.	341–345 deg	338 deg
Antihelion long.	193–201 deg	202 deg
$<V_g>$	31.7 km/s	34.4 km/s

if the model's distributions accurately match the radar observations. Taylor (1995) has shown that the biases between fast and slow meteors doesn't change the velocity distribution of an individual source very much. The Harvard data was the only known published data set of radar meteors at the time this model was created and some basic comparisons can be made, provided the biases are understood. Jones et al. (2001) did show that the orbital distributions described in MEM do accurately match the radar speed distributions and source concentrations very well, which is a good indication that the model orbital distributions are reliable, at least to first order. Current versions of these distributions were successfully compared to the newer CMOR data because of the improved bias corrections and data quality.

The process of deriving the distributions for the particles ejected from the long period comets is complicated by the fact that little is known of the variation of their concentration with heliocentric distance. Previous studies have shown that the space density of the high speed meteors attributed to the long period source are a small fraction of that produced by short-period comets. It was realized that, because the orbits of the long-period comets are so extended, the distribution of the dust they produce is dominated in the inner Solar System by the distribution of their perihelia. Everhart (1967) studied the effects of observational bias on the orbital distribution of long-period comets and proposed a likely distribution, which has been modified to account for sublimation. The distribution for the inverse semi-major axis, $b = 1/a$, is described exponentially as:

$$n(b) \propto e^{-b/129} \tag{3.11}$$

Since the orbital poles are distributed isotropically for long-period comets, the distribution of inclinations are uniform between 0° and 180°.

Collisions are incorporated in a similar manner as for short-period comet particles, except that in the long-period case, the inclinations do matter. The majority of collisions will occur with the dust from the short-period comets because they reside close to the ecliptic. So the long-period particles with low inclination orbits will most likely collide with the short-period particles aligned with the ecliptic disc. Again, the collision lifetime are characterized by the parameter f, but an additional factor is now introduced to allow for the orbital inclination of particles in retrograde orbits. Those particles with retrograde orbits close to the ecliptic will have shorter lifetimes than those with prograde orbits because of the relative impact speeds. The collision lifetime for long-period particles is therefore:

$$\tau_{\mathrm{coll}} = f q^{1.64} a^{1.5} e^{\frac{1}{2}\left(\frac{i-180}{11.2}\right)^2} \tag{3.12}$$

Consideration of the inclination distribution of the toroidal source makes it clear that the distribution is not isotropic, as that would only add to the strength of the radiants in the direction of the apex. It is reasonable to conclude that the toroidal source of sporadics is not from long-period comets but are somehow related to the short-period comets or asteroids. Tentatively, they are assigned then to the Halley family of short-period comets with periods between 20 and 200 years. As the inclinations of the observed toroidal meteors are high, their orbits place them out of the ecliptic and therefore don't suffer much from collisions with ecliptic dust. The assumption was then made to ignore the effects of collisions for the toroidal source. Lacking information regarding the observational selection effects, the distribution of perihelia for this Halley family group is of the same form as the long-period perihelia distribution, Equation (3.3). The inverse semi-major axis distribution was taken to be uniformly distributed between about 0.029 and 0.136/AU, corresponding to the range of the Halley family group. The inclination distribution is assumed to be gaussian.

Orbital distributions for the asteroidal component were provided by J.C. Liou, based on infra-red observations of 25 μ asteroidal particles. Since asteroidal meteors are difficult to detect, there are no observational constraints from radar meteor observations, hence no adjustable parameters. No inter-particle collisions are modeled for this population; however, it is expected not to influence the final results since those orbits have low eccentricities and the included PR effect only circularizes them. Also, as the orbits of the asteroidal meteoroids are more circular, only orbits with semi-major axes close to 1 AU will be observable from Earth, and they should be the same whatever their age.

In the model, a Monte-Carlo method was used in the generation of semi-major axes for the asteroidal component, and then the normalized distribution function was approximated by a 5th order polynomial:

$$n(a) = \sum_{k=0}^{5} c_k a^k \tag{3.13}$$

The eccentricity distribution, ecc, is described well by a Weibull distribution:

$$n(\mathrm{ecc}) \propto e^{-(\mathrm{ecc}/0.158)^{2.24}} (\mathrm{ecc}/1.58)^{1.24} \tag{3.14}$$

The inclination distribution is characterized by a double gaussian as

$$n(i) \propto 8.57 e^{-(i/2.57)^2} + 2.57 e^{-(i/8.57)^2} \tag{3.15}$$

Several of the parameters describing the orbital distributions for the sources are educated guesses and rough fits. However, more time and observations will result in improved distributions. Amazingly, even with these simple assumptions, the source radiants constructed from the model distributions produce very agreeable results when compared to the radar meteor observations.

A brief summary of the engineering approach adopted by MEM can now be summarized. The fundamental core of the program, some precepts of which are outlined above, calculates integral meteoroid fluxes and impacting speeds relative to the spacecraft. In this core, meteoroid velocities and spatial densities are derived from distributions of cometary and asteroidal meteoroid orbits. From these relative velocities and spatial densities, a meteoroid flux is calculated at the spacecraft location, and then arranged in a directional grid form, each cell having the appropriate flux strengths and velocity weights. Inherent in the computations are the debiasing, mass-weighting, initial trail radius correction, and relative source strength corrections applied by Campbell-Brown and Jones (2003). These results are then used to construct the mass-limited or penetrating meteoroid flux onto the spacecraft by employing a ray tracing algorithm to integrate the flux from the sporadic radiants over various surfaces of the vehicle. The model is capable of computing the flux of mass ranges damaging to spacecraft, 10^{-6}–10 g. For hypervelocity impact shielding, two single-wall penetration equations, those of Fish-Summers and Cour-Palais, are implemented, under the assumption that the density of the meteoroids is 1.0 g/cm^3. These equations were chosen because they give adequate predictions of aluminum plate impact tests, with that of Fish-Summers being the more conservative. More information about these penetration equations can be found in Elfer (1996). Final results are presented as flux of particles greater than and including a specific mass with average impacting speeds on each surface of a cubical spacecraft, along with the normalized velocity distribution for the entire spacecraft.

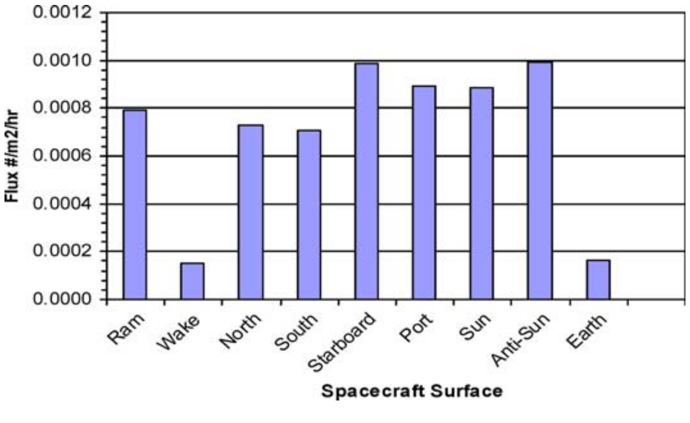

Figure 3. Flux on Spacecraft Surfaces 1 AU, 10^{-6} g mass.

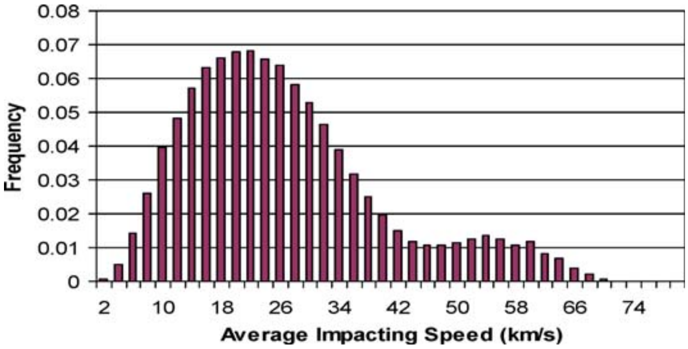

Figure 4. Total Speed Distribution.

4. Results from MEM

Below are some results from a test case from MEM Version 1.0. This scenario models a cubical spacecraft in a nearly circular heliocentric orbit of 1 AU. Penetrating fluxes are not calculated; the choice has been made to compute the flux of meteoroids greater than and including 10^{-6} g. Figure 3 is a graphical representation of flux on each surface of the vehicle. For zero eccentricities, the position vector and the velocity vector are perpendicular and therefore the starboard and port surfaces will be equivalent to the sun and anti-sun surfaces. If an elliptical heliocentric orbit is chosen, those surfaces will display different flux values. Figure 4 represents the distribution of particles at the spacecraft location and Table II describes the average impacting speed on each surface.

Note that MEM predicts an average flux weighted speed of meteoroids of 23.9 km/s at Earth, compared to the Grün value of 20 km/s. This new value agrees with the observations from the CMOR system.

5. Current Limitations and Future Plans

The current release of MEM, delivered to the SEE program in May 2004, does not contain gravitational focusing, so it is applicable only for spacecraft in

TABLE II
Average Impacting Speed (km/s) by Surface

Ram	Wake	North	South	Starboard	Port	Sun	Anti-Sun	Earth
26	21.6	24	24.1	24.2	24	24	24.2	21.4

interplanetary space within the inner Solar System. It is quite obvious that the relative strengths of the sources, especially that of the asteroidal component, and the biases in the observations (especially those from radar) used to calibrate the model are all areas that need further work. Consistency with other data, such as that from LDEF and photographic/electro-optical systems, must be investigated. However, the engineering focus of this model requires an accurate environment description only of particles of sufficient mass to damage spacecraft; we are quite aware that it may not adequately depict the "dust" environment, consisting of particles smaller than 10 μ in diameter. This is to be expected, as other forces, such as electromagnetic (Lorentzian), and other sources (interstellar) begin to come into play as we move down in the mass scale.

Future releases will incorporate gravitational focusing so that the program is applicable near planets, making it useful for lunar or Martian mission designs. Other updates will include additional surfaces pointed towards the sun/anti-sun and earth directions, spinning surfaces, different spacecraft orientations, velocity distributions on each surface, and additional penetration equations, perhaps even user defined ones. Updates to the physics model will be included as more data is analyzed, and we fully anticipate incorporating annual variation in the sporadic background, including distributions for meteor densities (already in work), and extending the model beyond Mars.

6. Summary

This recent research effort has produced a new tool that will help spacecraft designers mitigate the risks posed by sporadic meteoroids. The directionality effects, source strengths and velocities presented in this model are an improvement over past models and with future releases and updates in the penetration equations and spacecraft orientations, it is our hope that this will provide a more reliable meteoroid environment for the design of interplanetary spacecraft.

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