

Meteoroid environment modeling: the Meteoroid Engineering Model and shower forecasting

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I. INTRODUCTION

The meteoroid environment is often divided conceptually into meteor showers and the sporadic meteor background. It is commonly but incorrectly assumed that meteoroid impacts primarily occur during meteor showers; instead, the vast majority of hazardous meteoroids belong to the sporadic complex. Unlike meteor showers, which persist for a few hours to a few weeks, sporadic meteoroids impact the Earth's atmosphere and spacecraft throughout the year. The Meteoroid Environment Office (MEO) has produced two environment models to handle these cases: the Meteoroid Engineering Model (MEM) and an annual meteor shower forecast.

The sporadic complex, despite its year-round activity, is not isotropic in its directionality. Instead, their apparent points of origin, or radiants, are organized into groups called "sources". The speed, directionality, and size distribution of these sporadic sources are modeled by the Meteoroid Engineering Model (MEM), which is currently in its second major release version (MEMR2) [Moorhead et al., 2015]. MEM provides the meteoroid flux relative to a user-provided spacecraft trajectory; it provides the total flux as well as the flux per angular bin, speed interval, and on specific surfaces (ram, wake, etc.). Because the sporadic complex dominates the meteoroid flux, MEM is the most appropriate model to use in spacecraft design.

Although showers make up a small fraction of the meteoroid environment, they can produce significant short-term enhancements of the meteoroid flux. Thus, it can be valuable to consider showers when assessing risks associated with vehicle operations that are brief in duration. To assist with such assessments, the MEO issues an annual forecast that reports meteor shower fluxes as a function of time and compares showers with the time-averaged total meteoroid flux. This permits missions to do quick assessments of the increase in risk posed by meteor showers.

Section II describes MEM in more detail and describes our current efforts to improve its characteristics for a future release. Section III describes the annual shower forecast and highlights recent improvements made to its algorithm and inputs.

II. THE METEOROID ENGINEERING MODEL (MEM)

A. Description

MEM is a stand-alone piece of software that models the meteoroid environment [Jones, 2004; McNamara et al., 2004]. Although MEM does not explicitly model meteor showers, showers are included in the total flux reported by the software. MEM reports fluxes for meteoroids that are potentially hazardous to spacecraft, which are those ranging from 10^{-6} to 10 g in mass. For MEM's assumed meteoroid bulk density of 1 g/cm^3 , this corresponds to meteoroid diameters ranging from

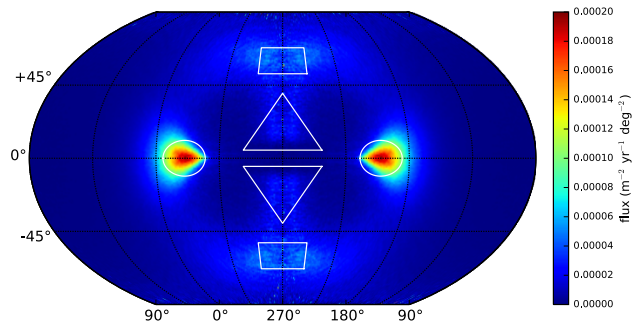


Figure 1. Interplanetary meteoroid flux at 1 au, broken down by radiant (direction relative to the Earth) and weighted to a constant limiting kinetic energy. The horizontal and vertical axes correspond to Sun-centered ecliptic longitude and latitude, respectively; these angles belong to a non-inertial coordinate system in which a longitude of 0° always corresponds to the apparent position of the Sun and a longitude of 270° always corresponds to the Earth's ram direction. Circles mark the helion and anti-helion sporadic sources, triangles mark the north and south apex sources, and trapezoids mark the north and south toroidal sources.

124 μm to 2.7 cm. Larger objects would of course also damage a spacecraft, but their flux is vanishingly low. MEM calculates the flux, speed, and directionality of the meteoroid environment relative to a user-supplied spacecraft trajectory, taking the spacecraft's motion into account.

Although earlier models treated meteoroid directionality as being isotropic [Smith et al., 1994], MEM reproduces the observed directionality of the meteoroid environment. Sporadic meteors are organized into three pairs of sources: the helion and antihelion sources, which appear to originate from the sunward and anti-sunward directions; the north and south apex sources, whose meteors impact the Earth head-on and at high speeds; and the toroidal sources, which are significantly inclined (see Fig. 1). This directionality is needed to correctly assess the flux on spacecraft components that maintain special orientations. For instance, a component that constantly faces the Sun, and is thus maximally exposed to the helion source, can encounter almost twice the flux as a component that does not maintain any fixed orientation.

MEM also reports meteoroid velocities. Because meteoroid directionality and velocity are interlinked, MEM reports both the overall velocity distribution as well as the flux within a three-dimensional grid (two angular dimensions and one speed dimension). All velocities are reported relative to the spacecraft's position and velocity.

MEM is valid in the inner solar system (0.2 to 2 au) and offers interplanetary, near-Earth, and cis-lunar sub-models. The interplanetary sub-model describes the meteoroid flux at locations that are far removed from planets and moons. The near-Earth and cis-lunar sub-models calculate the effect of the Earth and Moon, respectively, on the meteoroid flux due to gravitational focusing and planetary shielding.

MEM is an engineering model, by which we mean that it is designed to support spacecraft risk assessments; any scientific value is incidental. As a result, MEM models only hazardous meteoroids, and does not contain a dust model. Users occasionally ask if MEM can be extended to smaller masses, but we advise against this. Particles smaller than MEM’s lower limit of $1 \mu\text{g}$ will be subject to radiation pressure and Poynting-Robertson drag and thus will likely have different speeds and radiant distributions than larger meteoroids. Dynamical simulations suggest that this is in fact the case [Wiegert et al., 2009].

B. Revised environment for MEMR3

The “pillars” of MEM are: [1] the total flux as a function of limiting mass, [2] its breakdown by speed and directionality, and [3] meteoroid bulk density. Each of these quantities typically factors into ballistic limit equations and affects the depth and breadth of an impact crater. The MEO is currently revisiting each of these pillars in pursuit of an improved future model.

We have revised the meteoroid velocity and directionality distributions using radar meteor observations from the Canadian Meteor Orbit Radar (CMOR), which detects meteoroids as small as $\sim 10^{-5}$ g (at high speeds). Our revised distribution was de-biased using modern treatments of the ionization efficiency, which produces a steeper speed distribution than previous efforts [Moorhead et al., 2017a]. More recently, we devised a method to “sharpen” the speed distribution, removing the blurring effect of uncertainty in our velocity measurements. The sharpened distribution naturally lacks meteoroids with speeds above the heliocentric escape velocity and below 14 km/s (see Fig. 2). The resulting distribution has a top-of-atmosphere rms speed of 20 km/s. A full exploration of the associated uncertainties is on-going.

All versions of MEM to date assume a constant meteoroid bulk density of 1 g/cm^3 . This density, when combined with MEM’s meteoroid flux and speed distribution, produces a cratering rate that is nearly identical to the [Grün et al., 1985] cratering rate. Although a delta function is not a realistic density distribution, the lack of good meteoroid density measurements meant that a more complex distribution was not justified. However, recent improvements in meteor ablation modeling now allow for density estimates. One survey by [Kikwaya et al., 2011] indicates that meteoroid density may be closely tied to dynamical type, where meteoroids originating from comets and asteroids with shorter, less inclined orbits have higher densities and those originating from comets with long or highly inclined orbits have lower densities (see Fig. 3). Based on this work, we assign high densities to helion and antihelion meteoroids and low densities to all other sporadic meteoroids.

[Grün et al. 1985] derived the interplanetary dust and meteoroid flux, as a function of mass, from a variety of sources. The meteoroid portion of the Grün flux is primarily tied to crater counts from several in situ measurements, most notably Pegasus. As mentioned previously, crater size and depth is not a function of impactor mass alone, but is also influenced by the angle of impact and the impactor’s speed and

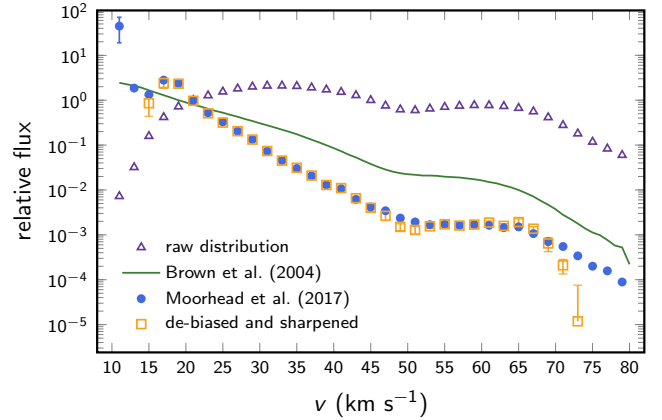


Figure 2. Raw, de-biased [Moorhead et al., 2017a], and sharpened velocity distributions of meteors at the top of the atmosphere as observed by CMOR. We include the distribution of [Brown et al., 2004] for comparison; our revised speed distribution is steeper but lacks meteoroids at speeds below 14 km/s.

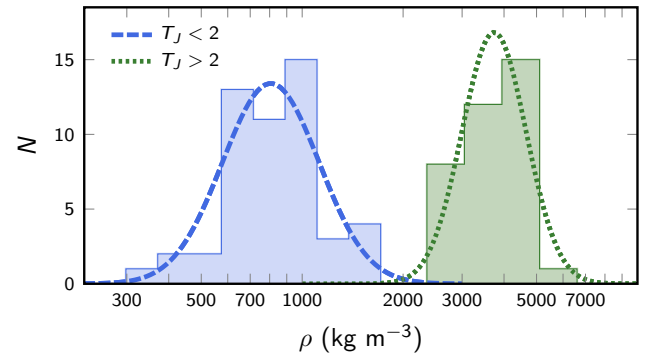


Figure 3. Density distribution for two groups of meteoroids modeled by [Kikwaya et al., 2011]. Meteoroids with comparatively short, circular, low-inclination orbits (those with Tisserand parameter, $T_J > 2$) have higher densities, while meteoroids not in this group have lower densities. The histograms reflect the data, while the dashed and dotted lines represent a log-normal fit to each group.

density. Thus, as we revise the velocity, directionality, and density, we may also need to revise our expression for the mass-limited flux in order to maintain agreement with in situ data. The MEO plans to reassess the mass-limited flux, and characterize its associated uncertainty, in the near future.

III. METEOR SHOWER FORECASTING

The MEO generates an annual meteor shower forecast that complements time-invariant meteoroid models such as MEM. The forecast is designed to support quick assessments of the additional risk posed by showers, and therefore differs from MEM in several key ways. While MEM takes the form of a standalone piece of software that can be run by the user to generate a custom environment, the forecast is a “pre-packaged” product that consists of a report and data tables. The forecast does not describe the environment to the same level of detail as MEM does, but instead reports shower fluxes for a “worst-case” scenario in which a spacecraft surface faces and is fully exposed to the shower radiant. If the risk in this

scenario exceeds tolerances, a more detailed analysis would be needed.

A. Description

The annual forecast is based on zenithal hourly rates (ZHRs), which describe the rate at which visual meteors occur when a shower radiant is directly overhead. ZHR is a fundamental observable in visual meteor astronomy and thus measurements of ZHR are much more common than direct flux measurements. We convert ZHR to flux using the algorithm of [Koschack and Rendtel, 1990]. The activity profile, or $ZHR(t)$, for each shower is assumed to follow a double exponential function (see Fig. 4). Its shape is governed by four parameters: peak ZHR (ZHR_0), time of peak activity (λ_0 , expressed in terms of solar longitude), and two exponents (B_p and B_m). In some cases where there is a pronounced central peak (such as the Perseids and Leonids), a shower may be composed of two sets of parameters.

The forecast is built from a list of shower parameters that include the four shape parameters (ZHR_0 , λ_0 , B_+ , and B_-) as well as a term describing the steepness of the meteor magnitude distribution (the population index, r) and the shower's velocity at the top of the atmosphere (v). Using these terms, we calculate the meteoroid flux at the International Space Station's typical altitude of 400 km. We do not, however, take the spacecraft's motion into account; velocities are reported relative to the Earth, and radiants are unaberrated.

We report fluxes to four limiting particle kinetic energies (see Fig. 5). Kinetic energy is used rather than mass due to the fact that ballistic limit equations are nearly proportional to kinetic energy (see, for example, [Hayashida and Robinson, 1991]). However, we do equate these energies to particle size at a reference velocity of 20 km/s. This allows users to select the kinetic energy limit that is closest to their damage threshold.

The shower forecast not only reports shower fluxes, but compares these fluxes to the baseline meteoroid flux. The forecast quotes "enhancement factors" that represent the percent increase in flux over the baseline caused by active meteor showers. When no showers are active, it is possible to have a negative enhancement factors, reflecting the fact that total meteor activity is slightly below average.

We generate the forecast from a list of standard shower characteristics, plus any predictions of shower variability. This variability is predicted using dynamical simulations of meteor streams [Moser and Cooke, 2004; Moser and Cooke, 2008]. These simulations model the ejection of particles from comets and the subsequent evolution of a meteoroid stream under the influence of gravity and radiative forces. The modeled particles are monitored for close encounters with the Earth; an unusually high number of such close encounters can indicate a shower outburst. For instance, heightened Perseid activity was predicted in 2016 and included in that year's forecast. Observations of the 2016 Perseids largely validated these predictions.

In addition to the annual forecast, the MEO also generates custom forecasts. For extravehicular activities (EVAs), the MEO generates shorter-duration forecasts with higher time

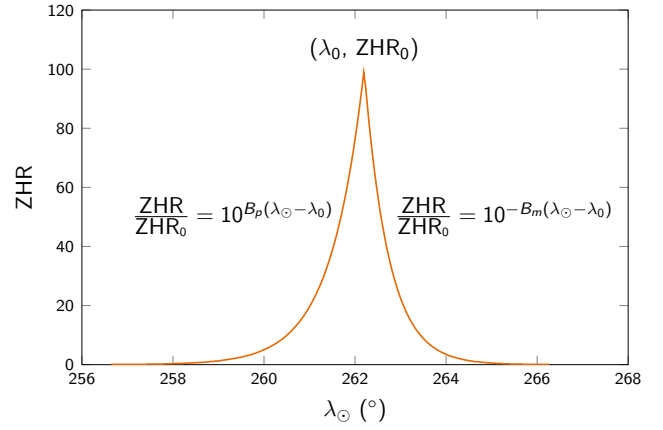


Figure 4. Zenithal hourly rate (ZHR) as a function of time (expressed in terms of solar longitude) for an idealized meteor shower. ZHR reaches a maximum at λ_0 , and a double exponential function describes the shape of the activity profile. Note that this profile can be symmetric if $B_m \neq B_p$.

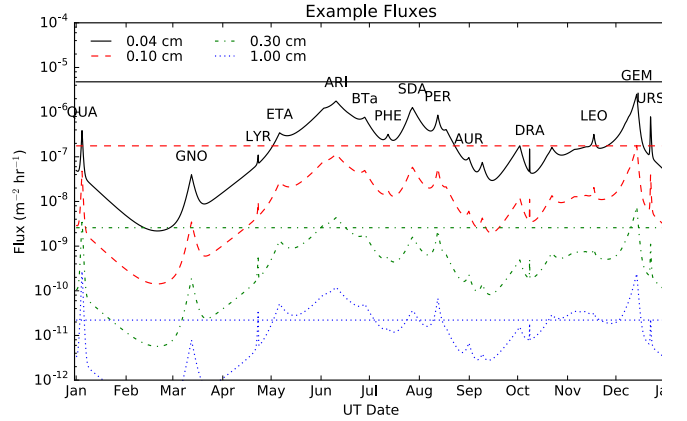


Figure 5. MEO annual meteor shower forecast sample output. This plot shows the total particle flux due to meteor showers over the course of one year for four particle energies. Peaks corresponding to major meteor showers are labeled with the shower code. The total flux (sporadic and shower combined) corresponding to each particle energy is also shown as a horizontal line. Note that for small particle sizes, meteor showers do not exceed the average flux, while at large sizes, many showers exceed the average.

resolution. We have also recently generated lunar shower forecasts to support investigations of meteor shower activity near the lunar surface.

B. Recent revisions

We have recently revised both our forecasting algorithm and our standard list of meteor shower characteristics. Changes to our algorithm consist of:

- the removal of a flux multiplier that was based on a magnitude-mass relation that is inconsistent with [Koschack and Rendtel, 1990],
- including the slight decrease in flux and speed at 400 km relative to that at the top of the atmosphere due to gravitational focusing,
- removing planetary shielding from shower fluxes in order to better describe a "worst-case" scenario in which the spacecraft is fully exposed to the shower,

- substituting correct gravitational focusing and shielding factors [Kessler, 1972] for incorrect factors [Smith et al., 1994] in the baseline flux calculation, and
- correcting the calculation of the percentage of the baseline flux that is due to meteor showers.

Additional details are available in [Moorhead et al., 2017b].

We revised our shower list in two ways. First, we removed twenty-four meteor showers that are minor, are not detected by our systems, and have few corroborating publications in meteor literature. For the remaining showers, we updated their names and three-letter codes to match the International Astronomical Union’s list of meteor showers. Second, we used 14 years of meteor shower fluxes measured by CMOR to newly characterize meteor shower activity profiles. We were able to improve activity profiles for 11 major meteor showers, often significantly. Daytime meteor showers in particular benefited from a radar-based activity profile characterization (see Fig. 6) for an example.

IV. SUMMARY

The MEO has developed two unique tools to assist risk assessments corresponding to the sporadic meteoroid environment and meteor showers. The MEM software allows users to generate the meteoroid environment relative to a specific spacecraft trajectory, and provides a detailed breakdown by direction, speed, and mass. MEM is best used during the design stage of a vehicle.

The annual forecast takes the form of a report and data tables and is designed to enable quick risk assessments relating to meteor showers. The forecast reports fluxes and relates these fluxes to the baseline flux. Thus, if a user has assessed the typical meteoroid impact risk with a tool such as MEM, the forecast can be used to quantify the increase in risk due to showers relative to this existing assessment. Spacecraft operators may use this information to decide whether to engage in short-term mitigation procedures in the case of significantly increased risk.

Both MEM and the shower forecast have undergone or are undergoing revisions. The MEO is currently engaged in an in-depth revision of the velocity, directionality, and density distributions used by MEM. These revised distributions will also be used to re-assess the mass-limited meteoroid flux and its associated uncertainties. The shower forecast’s algorithms and shower list have both been recently revised [Moorhead et al., 2017b] to produce a more accurate description of meteor shower activity patterns.

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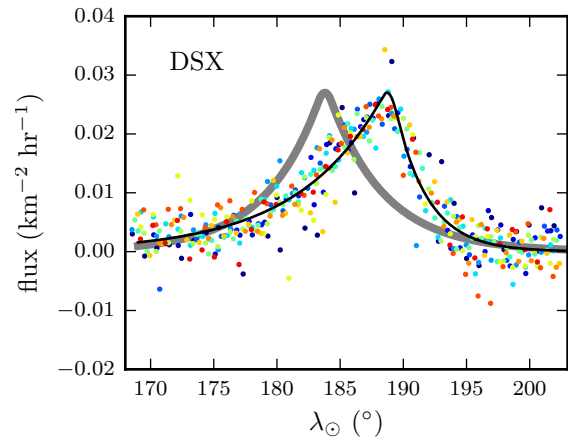


Figure 6. A double exponential activity profile (black line) fit to detrended fluxes (points) corresponding to the Daytime Sextantid (DSX) radiant as measured by CMOR. The amplitude has been permitted to vary by year; in this plot, each year’s data has been renormalized to match the average flux amplitude. The activity profile used in previous meteor shower forecasts (thick gray line) is included for the sake of comparison.

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