The Sporadic Meteoroid Complex and Spacecraft Risk

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Abstract

The meteoroid population in near-Earth space is typically broken down into two components: shower meteoroids which orbit in collimated streams, and the older sporadic meteoroids which have been dispersed into a much broader uncollimated distribution of orbits. The sporadic meteors dominate the meteoroid flux at Earth in the size range of those particles of the most of the risk to spacecraft (approximately 100 microns to 1cm). We describe the results of numerical simulations of the sporadic meteoroid complex by full physical modeling of meteoroids from ejection from their parent body through their perturbation by planets and radiation forces though the end of their lives through collision or ejection from the solar system. This model together with comparison with optical and radar measurements of meteoroid fluxes in near Earth space will allow improved assessment of the risk to spacecraft in near-Earth space from the sporadic complex.

1 Introduction

Spacecraft can be hit by meteoroids. When this happens, damage to the spacecraft and/or injury to personnel may result. For this reasons, the properties of the meteoroid flux in near-Earth space are of great interest.

The meteoroid population is classified in two components. The first, “shower meteors”, follow orbits that are strongly collimated. These orbits are also often closely correlated with that of the parent body which released the particles. This stream of meteoroids may move over time to a different orbit or even split into several separate streams due to perturbations by the planets, radiation effects, *etc.* Eventually the meteoroid stream disperses at which point the original close orbital relationship between individual meteoroids becomes difficult to determine. The particles have then become part of the second component of the meteoroid population, the “sporadic meteors”, which are more widely dispersed. We also note that the lifetime of meteoroids is much shorter than the 4.5 billion year age of the Solar System. Thus the meteoroid population must be constantly replenished and is inextricably linked to the population of parent bodies, comets and asteroids, which release them.

Once released from their parent body, most meteoroids continue to orbit the Sun but are subject to a variety of influences which change their orbits over time. These effects include the gravity of the planets, Poynting-Robertson drag, and collisions.

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Under these influences, meteoroids gradually migrate throughout the Solar System. Those that arrive at Earth do so primarily from three pairs of radiant directions whose positions remain relatively constant with respect to the moving Earth. These three pairs include the helion/anti-helion sources, the north and south apex sources and the north and south toroidal sources. The fidelity of any model of the sporadics, such as the one discussed here, can be judged partly by whether or not it can reproduce this observed meteoroid distribution.
A numerical model of the sporadics has some advantages over a purely observational model. Though a numerical model must certainly reproduce observations, it can go beyond them. A numerical model can say something about particles too large to be effectively monitored observationally (owing to their rare and random nature) as well as about meteoroids with slow (< 10 km/s) velocities, which are heavily biased against in both radar and visual meteor searches. Such a model can also indicate the meteoroid flux at other regions in the Solar System where measurements have yet to be made.

2 The Model

Our numerical model is constructed around a simulated Solar System which includes the Sun and all eight major planets, with masses, positions and velocities derived from the JPL DE405 ephemeris [1]. The behavior of meteoroids within this model solar system was simulated with one of two simulation codes. The first was a symplectic integrator based on the Wisdom-Holman algorithm [2] with close approaches handled by the hybridmethod [3], coded and used by PW(time step = 7 days unless otherwise noted). The second was a Radau integrator [4] coded and used by JV (time step = 1 day).

The process by which meteoroids are ejected is modeled here by the [5] ejection model for cometary parent bodies. Asteroidal meteoroids are assumed ejected by collisions in the main belt which provide them with 3 km/s ejection velocities independent of their size.

The meteoroids simulated ranged in radius R from 10 μm to 10 cm, distributed uniformly in the log of their radius (*i.e.* a histogram of number N binned over $\log_{10}(R)$ is flat). This size distribution was designed to produce sufficient number statistics at all sizes, and was re-weighted to properly reproduce the observed size distribution of meteoroids at the end.

Meteoroids are removed from the simulations if they fall into the Sun, move beyond 1000 AU or collide with a planet. They are also removed if their age exceeds the collisional lifetime determined for meteoroids in our Solar System. The lifetime used here is based on those of [6] and [7]. Shower meteors are also removed.

Once the simulations are complete, we have a dynamical model of meteoroids from four parent populations: Jupiter Family comets, Halley-family comets (prograde and retrograde) and the main asteroid belt. A mathematical weighting then applied to each meteoroid to account for its likelihood of impacting the Earth (time spent in near-Earth space, relative velocity, gravitational focusing, *etc.*) to connect the model to the observed sporadic meteor population. The relative strengths of the cometary populations were weighted according to the observed strengths of the helion/anti-helion, north/south apex and north/south toroidal sporadic meteor sources respectively. The contribution from the asteroid belt remains difficult to ascertain, as their low impact velocities with the Earth makes the measurement of their numbers in near-Earth space very uncertain.

3. Discussion

From our model, we ascertained that comet 2P/Encke is the dominant contributor to the helion and anti-helion sources by a factor of 10. The primary contributor to the apex source was 55P/Tempel- Tuttle. Comet 8P/Tuttle was the dominant contributor to the toroidal sources, however this source proved problematic and may be populated by meteoroids originating from a comet or comets which no longer exist.

Our model can explain the relative strengths of the apex, anti/helion and toroidal sources with the simple assumption that Halley-family comets produce roughly 100 times more dust than short-period comets. This could be accounted for if Halley-family comet nuclei are typically a factor of 10 larger than those of Jupiter-family comets (observations indicate a factor of 2-3 [8]), different dust-gas ratios or different active lifetimes.

Our model also reproduces the different strengths of the helion and anti-helion sources, though they have the same parent objects. The numerical model reproduces the observed sporadic complex at least in its broad outlines. Since the model also contains information on the sporadic complex that has not yet been measured (eg. low relative velocities, sizes not well-measured to date), once convinced the model can reproduce the known properties of the complex, we can examine it further to explore these as-yet-unmeasured properties.

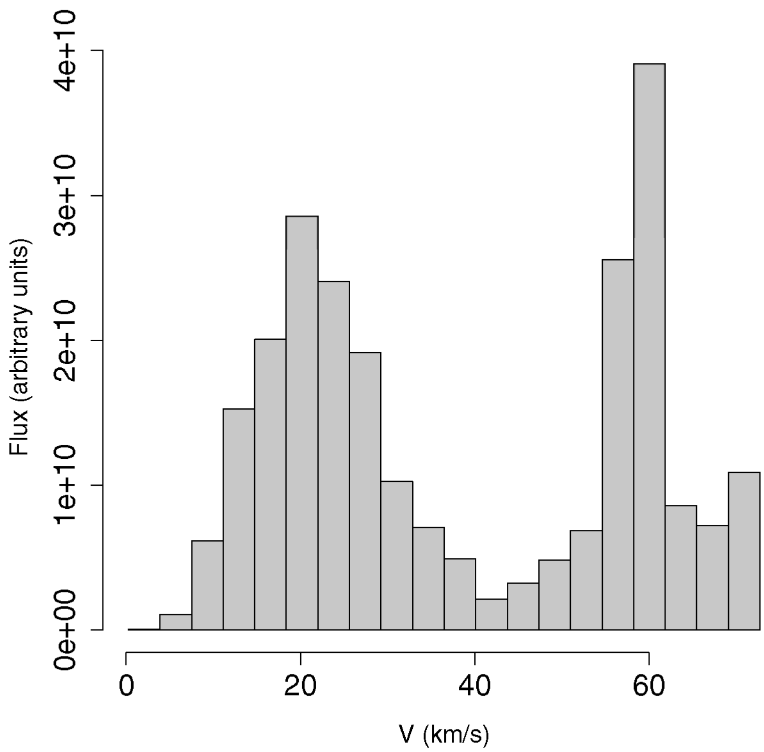

Figure 1: Model velocity distribution at Earth.

From the point of view of spacecraft safety, the model reveals a strong low-velocity of the cometary meteoroid component that is not seen by meteor patrol radars. [9] find only about 10% of observed meteors have heliocentric velocities below 20 km/s. Our model finds over 20% of the flux of sporadic meteors with cometary parents have speeds less than 20 km/s (Figure 1). This total does not include the asteroidal meteors, almost all of which arrive below this speed threshold, but whose absolute numbers are hard to determine because they are more difficult to observe either by radar or visually. Thus we conclude there is a substantial unmeasured component of the low-velocity meteoroid flux.

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