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A dynamical model of the sporadic meteoroid complex

Paul Wiegert[a,*], Jeremie Vaubaillon[b], Margaret Campbell-Brown[a]

[a] *Dept. of Physics and Astronomy, The University of Western Ontario, London, Canada*
[b] *Spitzer Space Center, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91125, USA*

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ABSTRACT

Sporadic meteoroids are the most abundant yet least understood component of the Earth's meteoroid complex. This paper aims to build a physics-based model of this complex calibrated with five years of radar observations. The model of the sporadic meteoroid complex presented here includes the effects of the Sun and all eight planets, radiation forces and collisions. The model uses the observed meteor patrol radar strengths of the sporadic meteors to solve for the dust production rates of the populations of comets modeled, as well as the mass index. The model can explain some of the differences between the meteor velocity distributions seen by transverse versus radial scatter radars. The different ionization limits of the two techniques result in their looking at different populations with different velocity distributions. Radial scatter radars see primarily meteors from 55P/Tempel–Tuttle (or an orbitally similar lost comet), while transverse scatter radars are dominated by larger meteoroids from the Jupiter-family comets. In fact, our results suggest that the sporadic complex is better understood as originating from a small number of comets which transfer material to near-Earth space quite efficiently, rather than as a product of the cometary population as a whole. The model also sheds light on variations in the mass index reported by different radars, revealing it to be a result of their sampling different portions of the meteoroid population. In addition, we find that a mass index of $s = 2.34$ as observed at Earth requires a shallower index ($s = 2.2$) at the time of meteoroid production because of size-dependent processes in the evolution of meteoroids. The model also reveals the origin of the 55° radius ring seen centered on the Earth's apex (a result of high-inclination meteoroids undergoing Kozai oscillation) and the central condensations seen in the apex sources, as well as providing insight into the strength asymmetry of the helion and anti-helion sources.

1. Introduction

The meteoroid population is traditionally broken down into two components. The first is the "stream meteoroids," which follow orbits around the Sun that are strongly correlated with each other. These orbits are also often closely correlated with that of the parent body which released the particles, since the ejection process produces changes to the velocity which are typically small compared to the orbital velocity. Over time, the stream of meteoroids produced by the parent may move to a markedly different orbit or split into several separate streams as differential perturbations due to the planets, radiation effects, etc. modify their orbits in various ways (Vaubaillon et al., 2006). Eventually, perturbations accumulate and disperse the meteoroid stream, the original close orbital relationship between individual meteoroids becoming difficult to determine.

At this point, the particles have become part of the second component of the meteoroid population, the "sporadic meteoroids," which form a more diffuse but far from isotropic background flux of particles. The division of streams and sporadics, though somewhat artificial, remains useful nonetheless. Since the time-integrated flux of visual meteors at Earth is dominated by about a factor of 10 by sporadics (Jones and Brown, 1993), models of the near-Earth environment are incomplete without serious consideration of the sporadic meteoroids.

Once released from their parent body, be it comet or asteroid, the smallest meteoritic particles ($\lesssim 0.1$ μm) will be ejected by radiation forces (the so-called β meteoroids). Larger ones continue to orbit the Sun. Unlike the planets whose substantial mass keeps them rather firmly on their orbits, meteoroids are subjected to a variety of influences which change their orbits over time. These effects include the gravity of the planets, Poynting–Robertson and solar wind drag, and collisions.

Here we present the results of a physics-based model of the sporadic complex which numerically integrates the orbits of meteoroids from their ejection from a parent body through to their eventual destruction or loss from the Solar System. Our work par-

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[*] Corresponding author. Fax: +1 519 661 2033.
E-mail address: pwiegert@uwo.ca (P. Wiegert).

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allels in some ways that of the ESA meteoroid model (Landgraf et al., 2001; Dikarev et al., 2002, 2004). In fact, the ESA meteoroid model incorporates more observational constraints than our own, including many obtained by spacecraft, while we rely only on Earth-bound radar measurements. Nevertheless, our simple model can answer a number of outstanding questions relating to the sporadic meteoroid complex.

The construction of our model presents many challenges. There are hundreds of known comets, each producing dust at variable (and largely unknown) rates, so dust production must be estimated. Meteoroids in the inner Solar System may persist for millions of years, so the current sporadic complex likely contains particles that originated from parents that are long dead or otherwise lost. The inhabitants of the sporadic complex are truly astronomical in number, a heterogeneous collection of cometary and asteroidal particles, too numerous to simulate in their entirety. Given the number of free parameters and their degeneracy, we have chosen to construct our model on the pillars of simplicity and physicality. In other words, we will keep the number of free parameters of the model to a minimum and link them clearly to physical processes. Thus our emphasis will be on the construction of a physically meaningful model and then examining how it does or does not reproduce observations rather than fine-tuning the model at the expense of understanding its inner workings.

The primary free parameters in our model are the relative dust contributions of the various parent objects of the sporadic complex, and we will fit these parameters to match meteoroid fluxes at Earth, a process we call “calibration” (Section 4.1). We allow five parameters, one for each of the five meteoroid parent populations we examine: the Jupiter-family comets (JFCs), the prograde and retrograde Halley-family comets (HFCs, which we examine separately but ultimately assign equal dust production coefficients), the asteroid belt and the near-Earth asteroids. Thus all the myriad details of the variability between parent objects of a particular type are encapsulated in a single free parameter. We also allow a single free parameter for the slope of the size distribution, also be fitted to observations. This brings the total number of tunable parameters in the model to six.

It is worth emphasizing the centrality of this procedure. Instead of assuming a dust production rate or size distribution, we instead use radar observations of the sporadic meteors to fit these parameters, replacing rather poorly known quantities with very well known ones.

In the construction of our model, our biggest assumptions are that

1. The five parent populations each produce dust at fixed rates which remain constant with time.
2. The current orbits of the parent objects simulated are representative of those of all parent orbits over the lifetime of a typical sporadic meteor (0.1–10 Myr).
3. No meteoroids are produced by sources other than the known comets and asteroids.
4. The properties of the dust are independent of the parent, and the size distribution produced is a fixed power-law.

Insofar as these assumptions hold, our model can be expected to reproduce the observed sporadic complex. We will see that in fact the broad strokes of the observed sporadic complex are reproduced by such a model, including the radiant, velocity and orbital element distributions. Section 2 outlines our simulation code and methods, Section 3 details the meteoroid source populations used here, Section 4 discusses how we calibrate the model, Section 5 presents our discussion of the results, and our conclusions are presented in Section 6.

2. Methods

Our simulated Solar System includes the Sun and all eight major planets with masses, positions and velocities derived from the JPL DE405 ephemeris (Standish, E.M., 1998. Planetary and lunar ephemerides DE405/LE405. Technical report, NASA Jet Propulsion Laboratory). The simulations of the meteoroids were performed with one of two simulation codes, with a few portions run on both codes and compared to ensure they were producing similar results. The first of these codes was a symplectic integrator based on the Wisdom–Holman algorithm (Wisdom and Holman, 1991) with close approaches handled by the hybrid method (Chambers, 1999), coded and used by PW (time step = 7 days unless otherwise noted). The second was a Radau integrator (Everhart, 1985) coded and used by JV (variable time step set initially to 1 day). Both these codes are mature and well-tested. The simulations include the effects of Poynting–Robertson drag, solar radiation pressure and collisions.

2.1. *Meteoroid modeling*

2.1.1. *Cometary meteoroids*

Cometary meteoroid ejection is modeled by the Crifo and Rodionov (1997) cometary ejection model. Comets are all assumed to have a Bond albedo of 0.04, a density of 1000 $\mathrm{kg\,m^{-3}}$, a radius of 1 km and an active fraction of 0.2. Ejection was usually begun at 3 AU, though in a few cases of comets with larger perihelion distances q (*i.e.* 74P and 31P) the ejection process was started further out at 4 AU.

The meteoroids simulated ranged in radius from 10 μm to 10 cm, distributed uniformly in the log of their radius (*i.e.* a histogram of number N binned over $\log(r)$ is flat). This size distribution was designed to produce sufficient number statistics at all sizes, and was re-weighted according to the observed size distribution of meteoroids at the end (see Section 2.2.2).

Each parent (of which there are 38, parent selection is described in Section 3.1) produces 4000 meteoroid particles released during a single perihelion passage. As a simulation progresses, these meteoroids represent older and older members of the overall population. Snapshots of the simulated meteoroids are recorded at intervals, and the ensemble of the meteoroid orbits recorded during the simulation provide us with the evolution of the meteoroid complex over time. Thus an effective number of 8×10^5 meteoroids of varying ages are produced per parent, or 38 parents × 4000 particles × 200 snapshots = 30.4 million meteoroids in total.

2.1.2. *Asteroidal meteoroids*

Asteroidal dust production is modeled in two ways. The dust production of near-Earth asteroids is handled the same as cometary dust (*i.e.* by the Crifo and Rodionov, 1997 model). However, dust from the main belt is generated differently. Instead of being ejected from a parent body, a suite of 4000 particles of sizes 10 μm to 10 cm is initially randomly distributed in the asteroid belt. These meteoroids have initial elements of $2 < a < 3.3$ AU, $0 < e < 0.3$ and $0^\circ < i < 30^\circ$, to which was added a random velocity kick of 3 km/s. These orbital elements were chosen to represent the debris of collisions between asteroids in the densest portion of the main belt, debris which may be a dominant source of meteoroids in near-Earth space (Dermott et al., 2002a). The velocity of 3 km/s was chosen as being typical of collision velocities in the main belt (Vedder, 1998). It is worth noting that collisions in the main belt are not violent enough to put much material directly onto Earth-crossing orbits. However, meteoroids from the main belt may eventually reach the Earth (if not destroyed in subsequent collisions) through the effects of P–R drag and orbital resonances, particularly with Jupiter and Saturn.