The Interplanetary Meteoroid Environment for eXploration – (IMEX) project

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The 'Interplanetary Meteoroid Environment for eXploration' (IMEX) project, funded by the European Space Agency (ESA), aims to characterize dust trails and streams produced by comets in the inner solar system. We are therefore developing a meteoroid stream model that consists of a large database of cometary streams from all known comets in the inner solar system. This model will be able to predict meteor showers from most known comets, that can be observed anywhere in the inner solar system, at any time 1980-2080. This is relevant for investigating meteor showers on the Earth, on other planets, or at spacecraft locations. Such assessment of the dust impact hazard to spacecraft is particularly important in the context of human exploration of the solar system.

1 Introduction

As they approach the Sun, comets heat up and release dust grains that were previously trapped in surface ices. The heavier dust particles considered here (sizes >100μm) are not strongly affected by radiation pressure or solar wind. Therefore, instead of being blown away by the Sun, they remain near the comet's orbit forming a dust trail. Eventually, however, various effects act to disperse all particles released by comets: planetary perturbations; Poynting-Robertson and solar wind drag; collisions. Eventually these particles lose their dynamical information about their parent bodies and can no longer be associated with individual comets. In this way, comets (and asteroids) populate the interplanetary background dust cloud that we observe from Earth as the zodiacal light, and which is responsible for sporadic meteors that are not associated with any meteor shower.

These cometary trails and meteoroid streams therefore form temporary structures in the solar system, superimposed on top of the interplanetary dust cloud. Cometary trails, visible in infrared images, are more recent structures that are thought to cause meteor storms or outbursts on the Earth; older dust in wider meteoroid streams causes annual meteor showers (Kresak, 1993). Significant modeling work exists for individual streams. In particular, there exists a large body of research on modeling the dust trail of comet 67P/Churyumov-Gerasimenko as a result of ESA's Rosetta mission (Agarwal et al., 2007 , 2010; Kelley et al., 2008; Fulle et al., 2010). Current meteoroid stream modeling is capable of predicting meteor storms (for example, Vaubaillon et al., 2005a,b).

Our approach is to attempt to build a model of meteoroid streams throughout the inner solar system. There are several reasons for building such a model: it can be used to study meteor showers on Earth and on other planets; to develop a map of cometary trails in the sky, which can be used to launch a search for these trails; and to study the timescales on which streams are dispersed by planetary perturbations and other effects.

Our initial motivation for this model, however, is the impact hazard to spacecraft. An understanding of the interplanetary environment, including the dust environment, is crucial for the planning of spacecraft missions in the inner solar system. Particles striking a spacecraft with high velocities can cause damage leading to the impairment or even failure of the spacecraft or its subsystems. Depending on the impactor's size the effects range from degradation of functional surfaces, such as optical systems or solar arrays, to cratering and structural penetration. Additionally, secondary effects such as electromagnetic pulses generated by the plasma release from impacts can interfere or even destroy sensitive electronics. For instance, it is thought that a Perseid meteoroid caused such an event on the Olympus 1 satellite in 1993, which resulted in the loss of the spacecraft (Caswell et al., 1995). Manned space activities are especially vulnerable to any damage caused by meteoroid impacts because of their much lower tolerance level, large cross sections and long exposure times.

ESA and NASA both have meteoroid engineering models to describe the interplanetary meteoroid background, such as ESA's Interplanetary Meteoroid Environment Model (IMEM) (Dikarev et al., 2005). However, no model exists to assess the risk to spacecraft of cometary meteoroid streams. The Interplanetary Meteoroid Environment for eXploration (IMEX) project attempts to address this problem by asking: can we predict the impact of meteoroid streams at any point in space or time? This extends the application of meteoroid stream modeling at the Earth to ask whether we can determine ‘meteor showers’ that occur at spacecraft locations. Such a model is also highly valuable as a database of meteor showers at all planets and other locations in the solar system, and can be used to investigate the creation and development of individual trails. The goal is to create a database of dust trails from more than 400 short-period comets in the inner solar system, which can be used for a variety of impact hazard and scientific purposes. Here we introduce our current model, and demonstrate how we use the Leonid meteor shower as a test case to verify the model.

2 The model

The aim of the model is to create a database of meteoroid streams from short period comets. This requires (1) emitting particles from a selection of comets, and (2) following their motion with time by integrating their trajectories. We save their positions and velocities to the database several times per orbit between 1980 and 2080.

We find 422 short-period comets from the JPL Small Body Database (SBDB) that have sufficient information and that have a perihelion within 3AU of the Sun. We emit particles between 1700 and 2080 for Halley-type comets, and between 1850 and 2080 for other comets. For each comet apparition, we emit particles randomly on the sunlight hemisphere of the comet, at 251 locations while the comet is within 3 AU of the Sun. Hundreds of thousands of particles are ejected for each comet: ~28000 per comet apparition for Halley-type comets; and ~14000 for other comets. Particles have 8 different masses logarithmically distributed, with radii between 100μm and 1cm, and bulk density 1000kgm^{-3}. We use the velocity model developed by Crifo and Rodionov (1997) and the mass distribution from Agarwal et al. (2010). Dust production is estimated using cometary total magnitudes (and total magnitude slopes) as given by the JPL (SBDB), using the result of Jorda et al. (2008). A dust to gas ratio of 1 is assumed. For a small number of major comets we use JPL HORIZONS orbits; for all other comets the orbits have been computed using the MODUST code (Rodmann, 2006), which uses a Hermite individual timestep scheme. This includes all important forces except the non-gravitational cometary forces, which are not well known for most comets.

The orbital integrations for the released particles are performed using a Runge-Kutta-Nyström 7(6) integrator with variable step size (Dormand and Prince, 1978). The emitted particles are individually integrated from their creation time up until 2080. Included are gravity of the Sun and eight planets, as well as radiation pressure and Poynting-Robertson drag (including a factor for solar wind drag). Particle positions and velocities are saved several times per orbit, and more often near perihelion and close planetary encounters. This creates a database from which the full trajectories of each particle from each comet can be reconstructed between 1980 and 2080.

The simulation of dust for many comets is a computationally intensive task, which usually would require the use of a supercomputer. However, supercomputing facilities are expensive and difficult to access, and so instead we share the work with many individual computers, connected through the internet. This approach is called distributed computing. The work (here, our group of dust particles) is split into many work units, which are distributed among participating computers. Once processed, the results are returned and can be stored and analyzed. The distribution and processing of the work units is managed by the BOINC system (Berkeley Open Infrastructure for Network Computing) developed at the University of Berkeley. It was originally designed to enable distributed computing for the SETI@home project, which tries to track down narrow-band signals, potentially sent by extraterrestrial civilizations, by data-mining telescope readouts. Since then, many more scientific projects have added to the BOINC platform. Computers participating in projects are owned by private users who donate their machines' idle computing power.

We utilize the Constellation BOINC platform to perform these meteoroid stream calculations, under the project 'CometTrails' (aerospaceresearch.net). Constellation aims to provide distributed computing capability to aerospace related science and engineering projects. Currently, ~13000 users are donating the idle time on ~70000 PCs. This form of citizen science provides the required computing performance for simulating millions of particles ejected by each of the 422 comets, while developing the relationship between scientists and the general public.

3 Test case: 55P/Tempel-Tuttle and Leonid meteor storms

We verify our model by determining how well it can describe past meteor storms. Here we compare our model for the trail of 55P/Tempel-Tuttle with observations of the 2001 Leonid meteor storm with a peak date of 18 November 18^{h}16^{m} UTC. We emit particles from the comet between 1690 and 2001, and integrate their trajectories until 2001. Only a subsection of the modeled particles will contribute to the stream at Earth: therefore, we select only those particles that cross the ecliptic plane within 5 days of the date of interest. The locations at which they cross the ecliptic plane (orbital nodes) are plotted in Figure 1. The path of the Earth is also plotted, so that we can see that the Earth crosses the meteoroids emitted during the comet apparitions with perihelia in 1766, 1866 and 1700. This plot agrees with a similar diagram using the model of McNaught and Asher (1999).

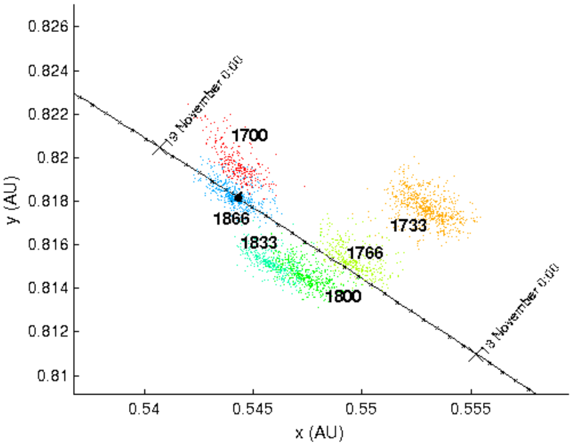

Figure 1 – Node distribution at the Earth of particles released from comet 55P/Tempel-Tuttle between 1690 and 1866, as seen on November 18 2001. Colors represent meteoroids emitted by the comet during different apparitions: the perihelion year of the comet apparition is superimposed. The black line indicates the path of the Earth. The Earth's position is indicated on the 18th and 19th of November and at every full hour.

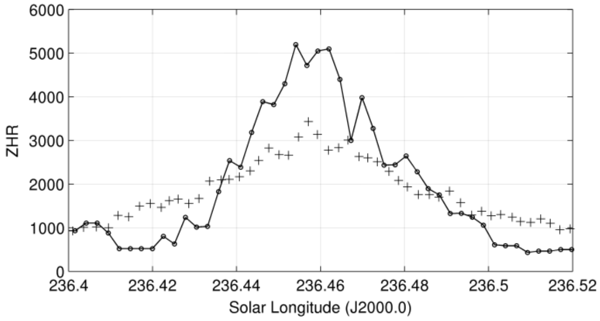

Figure 2 – Modeled (line) and observed (crosses) ZHR profile as a function of solar longitude, for a meteor storm on November 18 18h16m 2001. Observations are taken from Arlt et al. (2001).

We calculate a zenith hourly rate (ZHR) profile by determining a number density near the Earth as a function of time and estimating the ZHR by calculating a probability of observation based on the meteor magnitude, which is in turn derived from the meteoroid velocity and mass (Figure 2). We use methods described in Koschack and Rendtel (1990). We can see that the peak of both the observed ZHR profile and the modeled profile occurs at similar times: our modeled peak occurs 9 minutes before the observed peak. The width of our modeled profile is slightly too low, which is supposed to be related to differences in ejection mechanisms. The peak ZHR from our model is about 50% higher than the observed peak. This is the most uncertain part of our model, and is related to highly uncertain parameters including the cometary dust production rate and mass distribution. In general, however, the model is able to determine accurately the time at which a meteor shower occurs and to estimate the flux rate to an order of magnitude.

Summary

We have developed a model for meteoroid streams in the inner solar system, and demonstrated that it can describe meteor storms at the Earth, as illustrated using the 2001 Leonid storm. We are currently investigating other meteor storms and outburst events. We shortly embark on integrations of emitted particles from all 422 comets using the Constellation distributed computing system. This will provide a database of the trajectories of dust particles that can be accessed to determine meteor storms occurring at any point in the Solar System inwards of Jupiter.

There are several uncertainties in our model that will limit our ability to model the durations and fluxes of these events. Improvement of these requires cometary observations to understand properties and ejection mechanisms for individual comets, including ejection velocities, mass distributions, dust production rates, and the times and comet surface locations at which ejection occurs. It is hoped that the ESA Rosetta mission to 67P/Churyumov-Gerasimenko will dramatically improve our knowledge of comets and of the dust they emit[1].

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[1] We have also generated a video of the meteoroid stream of comet 67P/Churyumov-Gerasimenko between 1960 and 2100, see: https://www.youtube.com/watch?v=FY0vjbBp4eg

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