Interplanetary Meteoroid Environment for Exploration (IMEX):

Dust Streams in Space

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Abstract

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Abstract

Motivation

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 (of sizes > 100 μm) 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 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).

The approach of the 'Interplanetary Meteoroid Environment for eXploration' (IMEX) project is to build a model of meteoroid streams throughout the inner solar system. Our motivation for this model 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 impactors 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. 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. Such a model can also be used to study meteor showers on Earth and at 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.

The major space agencies (ESA and NASA) 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 streams. The IMEX project attempts to address this problem by providing a temporal and spatial model of meteoroid streams in the inner solar system, to be used to predict the impact of meteoroid streams at spacecraft locations.

The Meteoroid Stream 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 3 AU 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 100 μm and 1 cm, and bulk density 1000 kgm^{-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, with a total size of ~ 2.5 TB.

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.

Operation of the Model

The IMEX meteoroid stream model is accessed in using four MATLAB functions. It is operated by typing the following commands at the MATLAB command line:

1. **'RUN_ALL.m'**
   'RUN_ALL.m' takes a given point in space and time (such as a spacecraft location), finds the streams that intersect this location, and calculates the number densities and velocities of the particles within each stream. It is used to determine the streams that are a potential hazard at a spacecraft or planet location.

2. **'RUN_ALL_TRAJECTORY.m'**
   'RUN_ALL_TRAJECTORY.m' provides the same information as 'RUN_ALL.m', but at a set of timesteps along the trajectory of a spacecraft or other object. The timesteps are defined by user inputs, either evenly in distance or time. It is useful when it is important to consider the whole spacecraft trajectory.

3. **'RUN_STREAMPLOT.m'**
   'RUN_STREAMPLOT.m' allows the user to specify a time and a comet, and the model calculates

and displays the streams from this comet on the given date. It is useful when the stream of interest is known, and more detail is needed on the stream structure in space.

4. **'RUN_STREAM_SEGMENT.m'**
   'RUN_STREAM_SEGMENT.m' is a tool that examines the stream of one comet at a set of timesteps along a segment of the spacecraft trajectory. Number density and velocities are provided at each timestep. It is useful to understand the full encounter of the stream with the spacecraft.

Interstellar Dust Module

IMEX also contains a module for interstellar dust (ISD). This is a significant improvement on exisiting models due to the full modelling of radiation and Lorentz forces that contribute to spatial and temporal variations in the ISD, and improved spatial resolution. The model uses the same initial conditions used by the models of Landgraf (2000) and Sterken et al. (2012). The dynamics of particles in these simulations are determined by (solar) gravity, solar radiation pressure force and Lorentz forces.

Monte Carlo simulations of the modeled ISD trajectories were run, in which the initial location and time of the ISD grain were varied. The densities, velocity components and dispersion for each ISD grain mass are stored in a solar system 'simulation box' with a length of 20 AU length (from -10 AU to +10 AU). The spatial resolution is 0.25 AU, which is a factor of 6 better than the current simulation database from Sterken et al. (2012). This spatial resolution requires a temporal resolution of about 0.5 months, assuming an average ISD speed of 26 kms^{-1}. The expected memory needed per simulation output file is 22 GB, which can be reduced to 11 GB when the results are stored in single instead of double precision. The cluster in the Max Planck Institut für Sonnensystemforschung (MPS) was used for these computations.

Operation of the model

The ISD module of IMEX consists of a number of IDL functions to access data cubes containing the density and velocity information for all simulated ISD particles, and to use this information to calculate the flux rates along a given spacecraft trajectory. Inputs are the spacecraft trajectory and the time. Outputs are the density and velocity components of ISD dust at each point along the trajectory, along with the dust impact rate.

Tests of the Meteoroid Stream Model

Data on meteoroid streams is available as infrared images of cometary trails; and from observations of meteor showers, which occur when streams intersect Earth. We use these observations to test our model.

The Trail of 67P/Churyumov-Gerasimenko

Trail observations in the infrared can provide direct information on both the dimensions of the trail and the number density of particles in the trail. We reproduce the geometry of the 67P/Churyumov-Gerasimenko stream as observed by Kelley et al. (2008) and Agarwal et al. (2010), and compare the brightness and profiles of our model trail to the observed trail. The trail profiles match when a very low ejection velocity is used for the grains. When we use a dust to gas of 1, the maximum brightness of our modelled trail is about a factor $\sim$ 2–4 lower than the observed values. Our results would therefore be consistent with the observations if this comet has a higher dust to gas ratio of 3 or 4 - which is in agreement with other publications (Sykes and Walker, 1992; Weiler et al., 2004; Snodgrass et al., 2013). Our modeling of the trail of comet 67P/Churyumov-Gerasimenko demonstrates that the IMEX model can be used to fit observations of cometary trails, although refinement of some parameters may be required. Figure 1 demonstrates how the trail of this comet develops with time.

Meteor Storms at Earth

We also test whether the model can reproduce known meteor storms at the Earth. Because the model only releases dust particles over 200–400 year timescales, it is only capable of modelling the most compact meteoroid trails that cause meteor storms or outbursts: meteor showers are caused by streams that may have developed over thousands of years. In particular, we test storms of comet 55P/Tempel-Tuttle (Leonids) 1999-2002 and 1966, and storms of 21P/Giacobini-Zinner (October Draconids) in 2011 and 1946. For the Leonids, we find that we are able to match the timing of the storms to within about 30 minutes. In cases where the Earth passes through the centre of the stream, we can well reproduce the zenith hourly rate (ZHR) profile with time: the maximum rates of particles at Earth as within a factor of two. In cases where the Earth passes throught the edge of the stream (such as in 1999), the ZHR is less well modelled: it may be possible to use this to improve the initial emission parameters. The ZHR for the Draconid storm in 1946 is well modelled by the model. However, the model produces two peaks for the 8 October 2011 meteor outburst, when only one was observed. The first outburst, that was not observed, consisted of only large grains, while the observed outburst contained small particles. At the time, other modellers also found this double peak: IMEX is consistent with other models. Further information on dust emission parameters is required to improve models of meteor storms and outbursts.

Conclusion

The IMEX model provides a model of cometary trails and streams in the solar system, explicitly integrating the orbits of emitted particles to develop a ~ 2.5 TB database of cometary dust orbits, and a set of tools to access these data. The model is able to well describe observed cometary trails in the infrared and reproduce the ZHR profiles, timings and durations of meteor storm events at the Earth. For cometary trails, our model of the 67P/Churyumov-Gerasimenko trail agrees with observations in brightness if a high dust-to-gas mass ratio of 3-4 is assumed, and also with the trail profiles. This requires, however, very low ejection velocities. Meteor storms and outbursts for Leonids and Draconids were investigated: in years in which the stream passes directly through the position of the Earth, we are able to generally model features of the ZHR profile. Maximum ZHR is usually within a factor of 2-3, and the timing of the storm at the Earth is usually within 5-30 minutes of the observed time.

In particular, there are four important sets of information needed to accurately model these cometary streams: the comet orbit; the ejection velocity of particles from the comet; the mass distribution of emitted particles; and the dust production rate of the comet. Additionally information in general about the dust emission from the comet, including the locations of discrete emission regions on the comet; the perihelion distance at which cometary activity and dust emission begin; and the dust-to-gas ratio. Our test cases demonstrate how it is important to have accurate information on these parameters. The meteor storm study demonstrates how crucial the comet orbit can be: even the relatively small differences in the comet orbits from JPL HORIZONS and MODUST can signficantly affect the results. We expect that in most cases this will not affect whether a stream is present at a give location, but may significantly affect the flux of particles detected - and therefore, the magnitude of the risk they pose to spacecraft.

IMEX provides an unprecedented database of streams, with the ability to predict for the first time their locations relative to spacecraft. As well as the main calculation, the supporting tools allow the user to create an overall understanding of the encounter between the spacecraft and each stream. The resulting information will enhance the understanding of the spacecraft hazard environment.

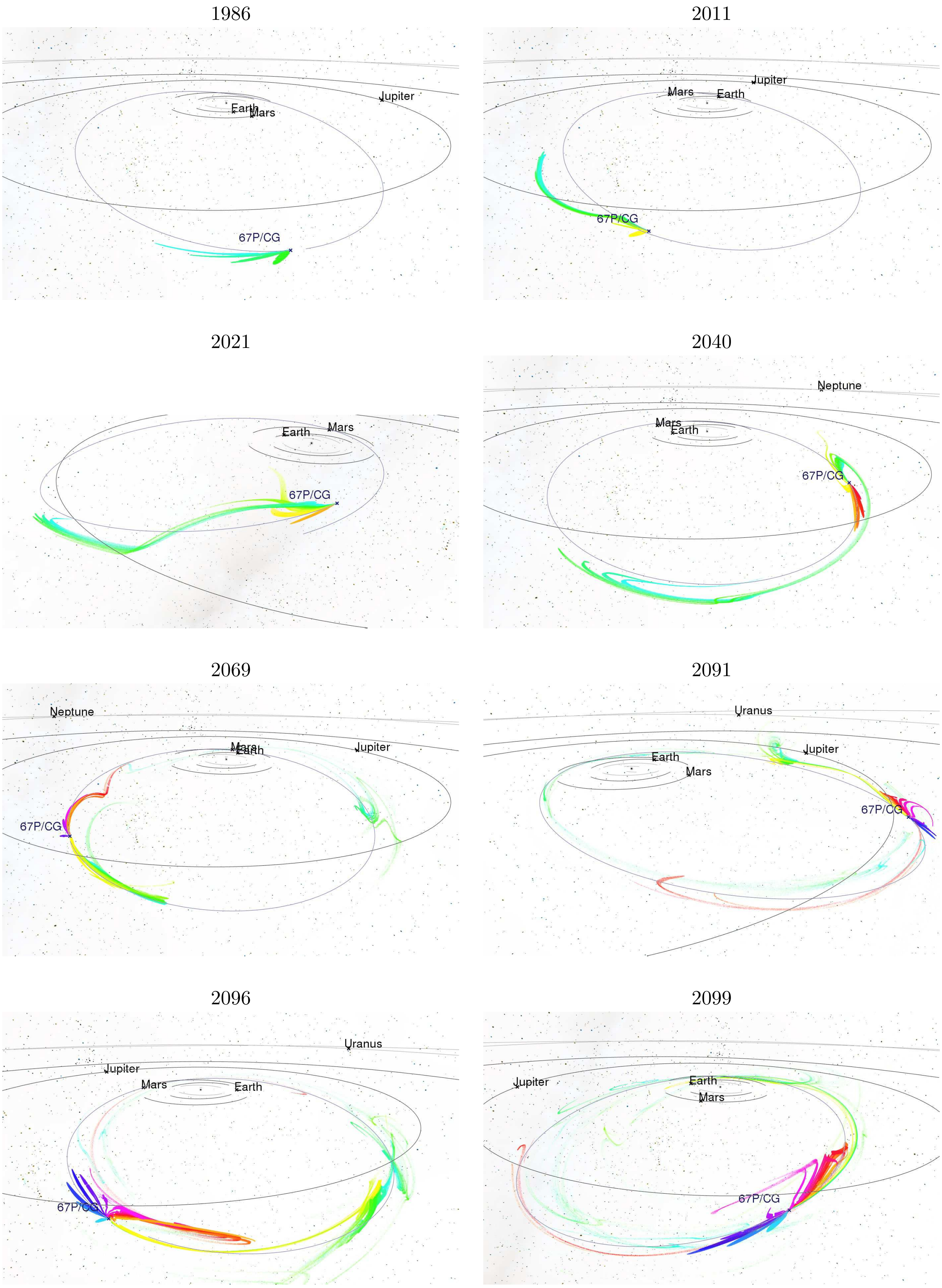

Figure 1: *Development of the meteoroid streams of comet 67P/Churyumov-Gerasimenko between 1986 and 2099. Colors are particles released during different apparitions (green particles are oldest, blue particles are youngest). We also show the orbits of eight planets and the comet. We see evidence of close encounters with Jupiter that disperse particles and warp the stream. In 2069 the tail end of the red streams behind the comet display gaps that are indicative of Mars' near passage through the stream in January 2062 (Vaubaillon and Colas, 2005). These are stills from a video of the whole stream from 1959 to 2100 that can be viewed at* `https://vimeo.com/128363607`.

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