Meteor storms and showers with the IMEX model

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The Interplanetary Meteoroid Environment for Exploration (IMEX) provides a model of meteoroid streams in the inner solar system. It is primarily designed to provide hazard estimations for interplanetary spacecraft. However, such a model is also suited for studying the impact of recently created meteoroid streams at the Earth. It also allows us to study meteor storms, and to automatically determine the streams that can be observed at the Earth at any time. Here we describe the application to Leonid meteor storms of 1999-2002, and provide the results of the automatic stream determination for 2015.

1 Introduction

Active comets release dust grains that produce trails of particles and meteoroid streams in the vicinity of their orbits. Reach et al. (2007) found that greater than 80% of Jupiter family comets observed in the infrared by the Spitzer space telescope show evidence of cometary trails. These trails consist of cometary material released during the most recent comet apparitions that forms structures (meteoroid streams) near the orbit of the parent comet. Initially, these particles remain very near the comet. Over time, radiation and gravitational forces disperse these particles away from the comet orbit.

Meteor showers at Earth are also evidence of cometary dust production. However, these narrow, dense trail structures create meteor storms at the Earth with durations of hours (Kresak et al., 1993). Meteor showers are generally caused by meteoroid streams that develop over longer time periods, and have durations of days or weeks at the Earth.

The Interplanetary Meteoroid Environment for Exploration (IMEX) model characterizes cometary trails at any point in space in the inner solar system. As an ESA funded project, the model is specifically designed to provide one tool for the assessment of the dust hazard on long duration interplanetary missions. The model has also practical use for evaluating meteor storm activity at planetary bodies, or for understanding the dynamics of meteoroid streams in the solar system. There is additionally an interstellar dust module (Sterken et. al., 2013; Strub et. al., 2013). Herein we describe the applicability of the cometary streams model to the meteoroid environment at Earth.

2 The IMEX Model

The IMEX model consists of a database of the orbits of dust grains from 420 short-period comets: 362 Jupiter family comets, 40 Halley-type comets and 18 Encke-type comets. Dust is emitted when each comet is within 3 AU of the Sun. Comets are omitted if they are always outside of 3 AU (required for dust emission within our model), if they do not provide information on the cometary magnitude (used to calculate the dust production rate), or if they have an eccentricity of 1. The orbits for 20 major comets are constructed from JPL HORIZONS data. The remaining comets have orbits integrated under gravity and radiation forces (but not cometary non-gravitational forces) using the MODUST code (Rodmann, 2006), from starting states given by HORIZONS.

Dust is emitted between 1850 and 2080 for Jupiter family and Encke type comets, and between 1700 and 2080 for Halley type comets. Cometary fragments have different starting dates dependent on their expected creation dates. These particles are emitted at 8 different sizes between 100 µm and 1 cm, with bulk density 1000 kgm^{-3}, and ejection velocities determined using the model of Crifo and Rodionov (1997). Next, the particles were integrated using solar and planetary gravity, radiation pressure and Poynting Robertson effect (including a factor for solar wind drag of 0.3 (Gustafson, 1994) using a Runge-Kutta-Nyström 7(6) integrator with a variable step size (Dormand and Prince, 1978). The particles are saved several times per orbit along their trajectories, between

1980 and 2080. The integrations were performed using the Constellation distributed computing platform (Aerospaceresearch.net).

The result is a database of 2.7 TB that provides the trajectories of ~0.5 million particles per mass, per comet, between 1980 and 2080. The trajectories of all particles can be reconstructed at any time within this period using Kepler orbit interpolation or integration. Further details of the IMEX dust emission process and trajectory calculations are given in Soja et al. (2015).

3 Leonid storms at Earth

IMEX provides trails of very recently released cometary particles. It can therefore model meteor storms, rather than annual meteor showers. We examined Leonid meteor storms during 1999–2002. We determined the particles from comet 55P/Tempel-Tuttle that pass near to the Earth. Next, we computed the number of particles at the Earth, by counting all particles within a 'test circle' around the Earth with a radius equal to the distance the Earth travels in 15, 30 or 60 minutes. We then constructed profiles of the Zenith Hourly Rate as a function of time (or solar longitude). These were used to assess the accuracy of the model compared with the ZHR, duration and timing of observed meteor storms, using International Meteor Organization visual data for comparison (Arlt et. al., 1999, 2000, 2001, 2002). We used the methods and tables of Koschack and Rendtel (1990), which provide a conversion between the spatial number density of particles with mass > 10^{-6} kg and the ZHR for meteors with visual apparent magnitudes m < 6.5. However, this method is highly dependent on the population index r. Since we do not know how the mass distribution of the stream at the Earth relates to the mass distribution at the comet, we instead determine the magnitude of the meteor created by each IMEX-modeled meteoroid in the Earth's atmosphere using the formula from Jenniskens (1994). We exclude particles that create a meteor with a magnitude > +6.5. The contributions to the ZHR from each particle mass are summed. The resulting ZHR profile for 2001 is given in *Figure 1*.

The model is able to reproduce the peak time of each of the two events on 18 November 2001, as well as the approximate maximum and the duration of the storm. The profile, however, is not matched well. There are various reasons why this could occur. First, the profile is dependent on the size of the test circle inside which

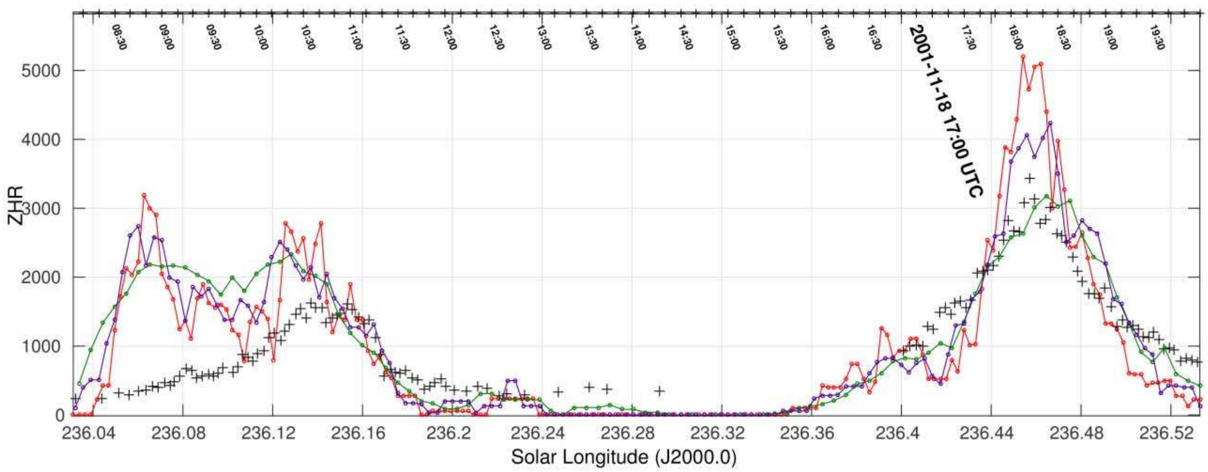

Figure 1 – ZHR profile for particles of comet 55P/Tempel-Tuttle (Leonids) on 18 November 2001. Black crosses represent IMO visual data (Arlt et. al., 2001). IMEX profiles for test circles around the Earth of 15 minutes (red), 30 minutes (blue) and 60 minutes (green) are given by the lines.

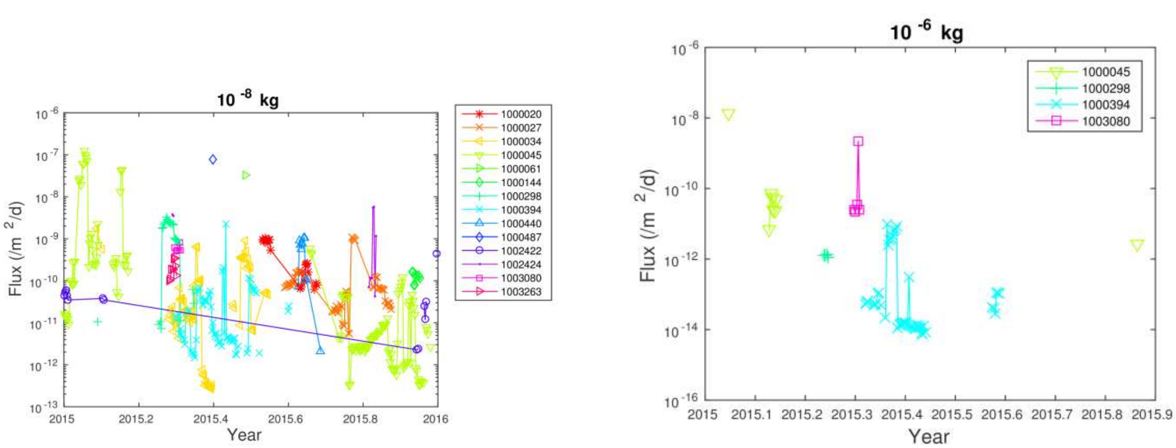

Figure 2 – Streams at the Earth during 2015, for 10^{-8}kg and 1.39×10^{-6} kg particles. Numbers in the legend are NASA NAIF identification numbers for each comet.

particles are selected at the Earth. Larger circles provide a smoother distribution, with a lower peak. Additionally, inaccuracy in the emission conditions at the comet (including the ejection speed, the heliocentric distances at which emission occurs, and the emission location on the comet) can alter the profile. We have already tested lower emission speeds and find that they struggle to provide any flux at the Earth, because the stream is too narrow to intersect it. The current model is most successful in modeling events in which the Earth crosses directly through the center of the stream. Glancing encounters are less well modeled. Such information will be used to help determine how the ejection parameters can be modified to improve the results.

4 IMEX at the Earth in 2015

The major goal of the IMEX model is the automatic detections of streams that intersect a spacecraft or planet.

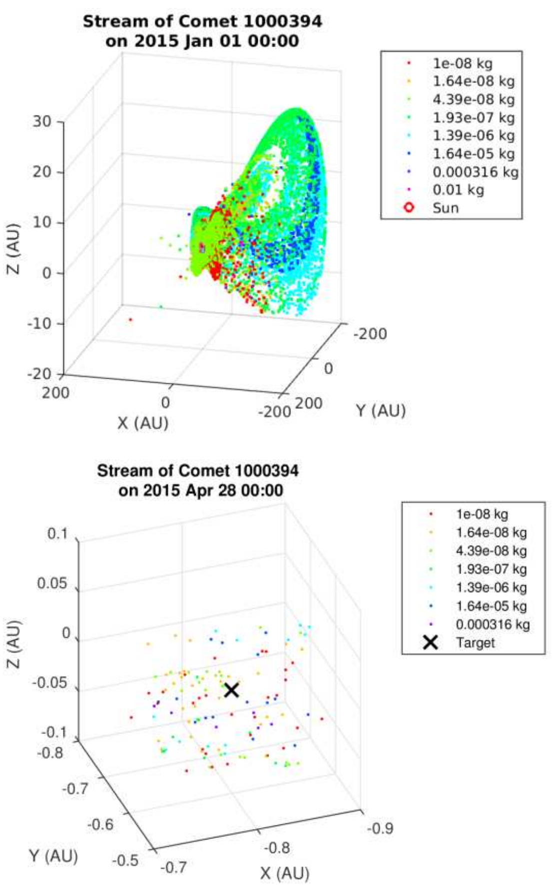

Figure 3 – Dust of comet 73P/ Schwassmann-Wachmann 3 (1000394) in 2015. (*a*) Heliocentric dust distribution on 1 January 2015. (*b*) Dust at the Earth on 28 April 2015.

We use the model to find the streams that intersect Earth each day at time 00:00:00 from 1 January to 31 December 2015. At each day we determine the comets that have dust at Earth, and calculate the flux, and the impact velocity of their dust particles on to the Earth. We provide the flux as a function of time, per comet, for 10^{-8} kg particles (*Figure 2a*) and 1.39×10^{-6} kg particles (*Figure 3b*). We find that 14 comets have 10^{-8} kg dust particles in the vicinity of the Earth, and 4 have 1.39×10^{-6} kg dust particles near the Earth: 45P/Honda-Mrkos-Pajdusakova (1000045), 252P/LINEAR (1000298), 73P/Schwassmann-Wachmann 3 (1000394), and P/2009 WX51 (Catalina) (1003080).

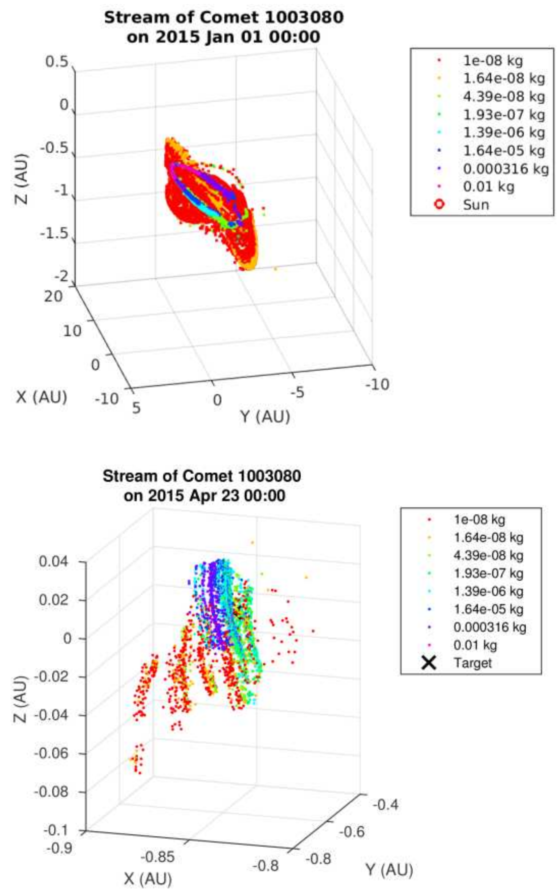

Figure 4 – Dust of comet P/2009 WX51 (Catalina) (1003080) in 2015. (*a*) Heliocentric dust distribution on 1 January 2015. (*b*) Dust at the Earth on 23 April 2015.

However, not all these comets produce distinct streams at the Earth. The streams of many Jupiter family comets are disrupted by gravitational interactions with Jupiter. This increases the dispersion of these particles away from the orbits of their parent comets. An animation of the formation and evolution of the trail of Rosetta target comet 67P/Churyumov-Gerasimenko[1] demonstrates how Jupiter is active in warping and disrupting dust streams. For some comets, the effect is more dramatic, as seen in *Figure 3* for comet 73P/Schwassmann-Wachmann 3. In this case a fraction of the stream has been perturbed into orbits that reach the outer solar system, forming a dumbbell-like structure. This behavior is also observed for comets 45P/Honda-Mrkos-Pajdusakova, 252P/LINEAR, and to a lesser extent for P/2009 WX51 (Catalina) (*Figure 4*). In the case of comet 73P, the resulting dust at the Earth does not represent a dust stream. Thus, the resulting right ascension and declination at the Earth have a broad range, and these particles are not likely to be observed at Earth as an enhancement from a discrete radiant direction. In the cases of comets 1000045, 1003080 and 1000298 there is

[1] Available at https://vimeo.com/128363607

a collimated stream at or near the Earth. The stream of comet 1000298 does not intersect the Earth during 2015. The stream of 45P intersects once on January 18 2015 (where (RA ∈(324º, 326º), DEC ∈(-16º, -14º)). The stream of P/2009 WX51 intersects twice on April 22-23 (RA ∈(38º,29º), Dec ∈(+34º,+36º)), while on April 24 the Earth appears to hit the edge of a stream. These are therefore comets whose streams can create several meteors appearing from a similar location in the sky (radiant). Further work would be required to determine if the accuracy of the orbits of the comets significantly affects these results.

5 Summary

The now complete IMEX streams model provides a comprehensive database of cometary trails and streams in the inner solar system. It is able to describe meteor storms and outbursts at the Earth to a peak timing within ~20 minutes, as well as matching in some cases the duration and zenith hourly rate of the profile, when compared to visual meteor observer rates. IMEX can additionally be used to automatically determine comet dust streams that can intersect the Earth in the future.

Acknowledgment

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References

Arlt R., Bellot Rubio L., Brown P. and Gyssens M. (1999). “Bulletin 15 of the International Leonid Watch: First Global Analysis of the 1999 Leonid Storm”. *WGN, Journal of the IMO*, **27**, 286–295.

Arlt R. and Gyssens M. (2000). “Bulletin 16 of the International Leonid Watch: Results of the 2000 Leonid Meteor Shower”. *WGN, Journal of the IMO*, **28**, 195–208.

Arlt R., Kac J., Krumov V., Buchmann A. and Verbert J. (2001). “Bulletin 17 of the International Leonid Watch: First Global Analysis of the 2001 Leonid Storms”. *WGN, Journal of the IMO*, **29**, 187–194.

Arlt R., Krumov V., Buchmann A., Kac J. and Verbert J. (2002). “Bulletin 18 of the International Leonid Watch: Preliminary Analysis of the 2002 Leonid Meteor Shower”. *WGN, Journal of the IMO*, **30**, 205–212.

Crifo J. F., Rodionov A. V. (1997). “The Dependence of the Circumnuclear Coma Structure on the Properties of the Nucleus”. *Icarus*, **127**, 319–353.

Dormand J. R. and Prince P. J. (1978). “New Runge-Kutta algorithms for numerical simulation in dynamical astronomy”. *Celestial Mechanics*, **18**, 223–232.

Gustafson B. A. S. (1994). “Physics of Zodiacal Dust”. *Annual Review of Earth and Planetary Sciences*, **22**, 553–595.

Jenniskens P. (1994). “Meteor stream activity I. The annual streams”. *Astronomy & Astrophysics*, **287**, 990–1013.

Koschack R. and Rendtel J. (1990). “Determination of spatial number density and mass index from visual meteor observations (I)”. *WGN, Journal of the IMO*, **18**, 44–58.

Kresak L., (1993). “Cometary dust trails and meteor storms”. *Astronomy & Astrophysics*, **279**, 646–660.

Reach W. T., Kelley M. S. and Sykes M. V. (2007). “A survey of debris trails from short-period comets”. *Icarus*, **191**, 298–322.

Rodmann J. (2006). “Dust in circumstellar disks”. PhD Thesis, Combined Faculties for the Natural Sciences and for Mathematics of the University of Heidelberg, Germany.

Soja R. H., Sommer M., Herzog J., Agarwal J., Rodmann J., Srama R., Vaubaillon J., Strub P., Hornig A., Bausch L., Grün E. (2015). “Characteristics of the dust trail of 67P/Churyumov-Gerasimenko: an application of the IMEX model”. *Astronomy & Astrophysics*, **583**, A18, 11 pages.

Sterken V. J., Strub P., Soja R. H., Srama R., Krüger H. and Grün E. (2013). “Development of a high resolution interstellar dust engineering model - overview of the project”. European Planetary Science Congress 2013, held 8-13 September in London, UK.

Strub P., Sterken V. J., Soja R. H., Srama R., Krüger H. and Grün E (2013). “Development of a high-resolution interstellar dust engineering model - technical implementation for fast simulations”. European Planetary Science Congress 2013, held 8-13 September in London, UK.