MODELLING OF IMPACTS FROM METEOROID STREAMS

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ABSTRACT

A significant part of meteor activity is associated with meteor streams. Meteoroid streams are accumulations of meteoroids with nearly identical heliocentric orbits. Relative to Earth all particles of a given meteor stream have nearly the same impact directions and velocities.
This paper describes the development and applications of two software tools for investigations of meteoroid streams and their applications to orbiting spacecraft. The new tools allow calculations of the number of impacts from meteoroid streams for user selected mass thresholds and time periods. In a second step the resulting number of penetrations through a shield of given thickness can be predicted. Reference calculations for normal stream flux activities and assumed Leonid-Meteoroid-Storm activities are given. Potential extensions of the tool are discussed.

1. GENERAL INFORMATION

In view of the risks posed by impacting particles to orbiting spacecraft, especially for long-term missions like the International Space Station (ISS), increased demand for reliable analysis tools has been raised from industry and agencies. The improvement of space environment models and hypervelocity impact damage predictions allows better spacecraft shielding designs. The enhancements in environment models are not limited to space debris, but also include the natural particle environment.

For a realistic and accurate meteoroid environment model, one has to work in a heliocentric frame and consider anisotropy in the meteoroid influx to Earth. Since 1981 several observers have counted meteors during extended periods of observation time. These counts have been processed, as described in [1], and they are presented as a homogeneous set of some 50 meteor streams, for all major and many minor meteoroid streams. Together with the sporadic background, these give an accurate picture of meteor activity for any solar longitude.

Meteoroid streams can be important, for the assessment of spacecraft damage due to exposure to the interplanetary solid particle flux, as the showers or storms tend to have higher velocities than the sporadic background or space debris impacts to low Earth orbit (LEO) satellites. Meteoroid streams can have impact velocities of up to 72 km/s natural dust have a mean velocity of about 20 km/s while the velocities for space debris impacts to LEO satellites are 'only' around 10 km/s. Because the kinetic energy is proportional to v^2 (where v is the velocity), one can see that a stream meteoroid might have a much higher damaging power than a piece of space debris with the same mass. Plasma generation on impacts depends on velocity more like v^4 and so the increased velocities pose an even more enhanced plasma risk.

Two PV-WAVE based software tools were developed to produce reference values for meteoroid streams, for different parameters like minimum particle mass, threshold thickness for penetration and impact angles. The programmes, the applications and some reference calculations for normal stream flux activities and an assumed Leonid-Meteoroid-Storm are presented in the following section.

2. MICRO-METEOROID MODELS

2.1 Grün Sporadic Model

The natural micro particle environment can be described by the model from Grün et al [2]. This model is the present standard reference model. It is the baseline for the simulation of micro-meteoroid fluxes and is used in the STREAM.PRO program. This model considers an omni-directional particle flux F(m), computed for a randomly oriented plate situated on a virtual point fixed with respect to the Earth at the target orbit altitude.

2.2 Meteoroid Stream According to Jenniskens

The model for meteoroid streams according to P. Jenniskens [1] is based on data collected by a large number of observers over a 10 years period, from observation sites in both the Northern and the Southern Hemisphere. N. McBride [3] describes how Jenniskens parameter have to be implemented into a numerical application. In summary the stream geometry and activity at shower or strom maximum is defined by:

- The solar longitude $\lambda_\odot$ at shower/storm maximum $\lambda_{\odot max}$

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- The maximum Zenithal Hourly Rate ZHR_{max}, which is the number of 'visible' meteors seen after various observer and location related corrections have been applied
- Apparent radiant position in RA (right ascension of the radiant) and Dec (declination of the radiant)
- the geocentric meteoroid velocities, defined as the final geocentric velocity v_∞ as the meteoroids reach the top of the atmosphere
- The shape and width (duration) of the storm

The Zenithal Hourly Rate (ZHR) is the hourly rate of meteors seen by a standard observer under optimum conditions for each stream described in [1]. A meteor storm is just an intense meteor outburst with Zenithal Hourly Rates above 1000.

3. DAMAGE EQUATIONS

Damage equations used for modelling describe the interaction between microparticles and spacecraft structures. The spacecraft structure can be either a single wall (e.g. aluminium) or a multiple wall (e.g. when a specific micro-particle shielding or thermal protection (MLI) is applied to the basic structure). The damage equations, which are largely derived from experiments, are treated in two separate groups:

- Ballistic limit equations, yielding the critical impacting particle size above which the structure fails. Different equations have to be used for single and multiple wall structures.
- Damage size equations, yielding the crater size of semi-infinite targets and the hole diameter of punctured targets (generally thin walls).

For the new software tool the single wall ballistic limit equation was implemented.

3.1 Single Wall Ballistic Limit Equation

The Single Wall Ballistic Limit Equation yields the critical impacting particle size above which the structure fails. Where the parametric equation is:

$$d_{p,lim}=[t_t/(0.26*\rho_p^{\ 0.519}*v^{0.875}*(\cos\alpha)^{0.875})]^{0.947} \quad (1)$$

Symbols used in the equation:

- Particle Diameter (d_p) in cm
- Impact velocity (v) in km/s
- Thickness of Target (t_t) in cm
- Impact angle (α) in ^{o}
- Density of Particle (ρ_p) in g/cm^3

4. METEOROID STREAMS

A significant part of meteor activity is associated with meteor streams causing meteoroids to enter the Earth's atmosphere at similar entry velocity and at nearly parallel trajectories, which cause the meteor to radiate from a virtual point in the sky that is called the radiant. These meteoroids have a common origin, usually -if not always- they are the debris from the decay of, sometimes extinct, short-period comets. The annual streams are those streams that occur every year, over a period of days, when Earth passes the orbit of the parent comet, see Fig.1. The meteor rates vary as a function of the Earth's position in its orbit, increasing to a peak and decreasing again.

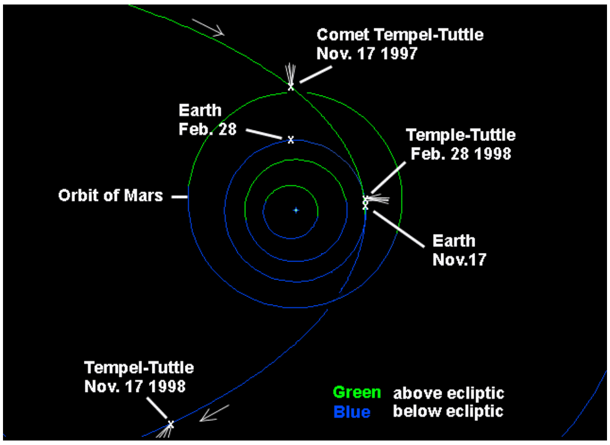

Fig. 1. Earth passing comet Temple-Tuttle's orbit. The material lost by this comet is responsible for the annual Leonid stream.

The comet Temple-Tuttle, is about 4 km in diameter and orbits the sun with a period of just 33 years. The perihelion passage occurred on 28 February 1998. In 1998 the Earth passed through this region in space on the 17 November. Because of the retrograde orbit of P/Temple-Tuttle, the Leonids approach the Earth with velocities around 72 km/s.

4.1 Meteoroid Stream Parameter

4.1.1 Stream Mass Flux According To McBride

As presented in [3], the cumulative particle flux F(m) in [particles/m^2/s] with mass greater or equal m in [kg] can be described by

$$F(m)=k*m^{-\alpha} \quad (2)$$

- m is the minimum meteoroid mass in [kg]
- k is a constant

- α is the mass distribution index

The cumulative flux for any solar longitude $\lambda_{\odot}$ is given as

$$F(m)= F(m)_{max}*10^{-b*|\lambda_{\odot}-\lambda_{\odot max}|} \quad (3)$$

For most known normal streams the parameters α, k and b are presented in [3]. For an assumed meteoroid storm the parameters α, k and b have to be recalculated. Needed are the stream velocity, the ZHR_{max}, the meteor distribution index χ, the meteoroid mass at a given visual magnitude (which usually is assumed as 0.5) and the full width at half maximum (FWHM), defining the storm duration. The formulas used for the calculations are:

$$\alpha=2.3*\log(\chi) \quad (4)$$

The value 2.3 reflects the relationship between meteoroid mass and meteor visual magnitude.

Generally the abundance of meteors increases with decreasing brightness, and the ratio χ of meteor numbers in two neighbouring magnitude bins is constant.

$$k=N(0)/M^{-\alpha}_{m=0.5} \quad (5)$$

N(0) is the cumulative flux for zero magnitude meteors. N(0) depends on the meteoroid velocity, ZHR_{max} and the probabilities to observe meteors at certain magnitudes (see [3] for further explanation). $M_{m=0.5}$ describes the meteoroid mass for the given visual magnitude of 0.5.

$$b= -(\log(0.5)/t) \quad (6)$$

$$t=(FWHM/(360/365)/2) \quad (7)$$

t represents the storm duration. Calculated with a given FWHM in [days]. b describes the meteoroid stream slopes of the log-lin activity profiles. Most streams have symmetrical profiles and the slopes are described by a single value of b. Because b is changing with the stream or storm duration it has to be calculated here.

4.2 Application of the new Software Tools

The model presented above was implemented into new software tools. They allow to produce reference values and reference plots not only for meteoroid streams, but also for assumed meteoroid storms. In addition one can take a closer look at a certain solar longitude range. The program AKC.PRO derives meteoroid stream parameter values, which are necessary to calculate quantitative fluxes for streams or storms. The resulting values can then be used in the program STREAM.PRO, which calculates the penetration stream flux, the cumulative meteoroid stream flux and the Zenithal Hourly Rate.

4.2.1 Zenithal Hourly Rate

For normal stream activities [1] the STREAM.PRO tool provides the result in Fig.2.

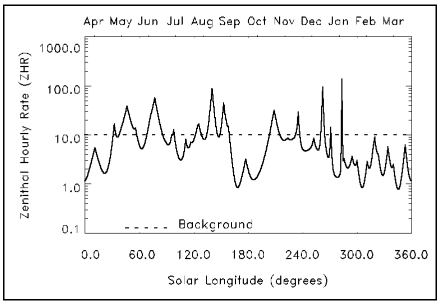

Fig. 2. Zenithal Hourly Rate summation for the 50 meteoroid streams given in [1] with normal activities for a whole year and a background reference value of 10.

For an assumed Leonid storm with storm parameters ZHR_{max}=1000 b=4.88, α=1.22, k=1.44*10^{-18}, and FWHM=0.125 (3 hours), the STREAM.PRO program produces the results shown in Fig.3. If one compares Fig.2 and Fig.3, the increased activity during the Leonids (solar longitude of 235.1) is clearly visible. In this calculation the normal Leonid stream was completely replaced by the storm.

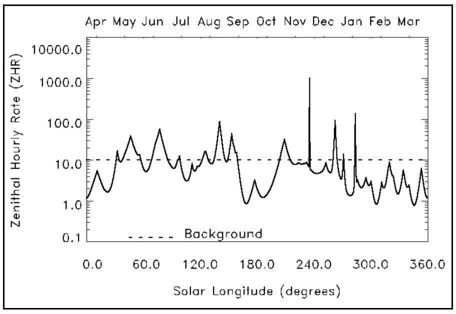

Fig. 3. Zenithal Hourly Rate summation for the 50 given meteoroid streams, for a whole year with an assumed Leonid storm (ZHRmax=1000) at a solar longitude of 235.1 and a background reference value of 10.

4.2.2 Mass Dependent Stream Flux

Fig.4. and Fig.5. present the sum for the annual meteoroid stream fluxes in [particles/m^2/s] with a minimum particle mass of 10^{-6} kg. Fig.5. shows a close up for the Meteoroid Stream Flux within a solar longitude plot range between 200 and 280 degrees.

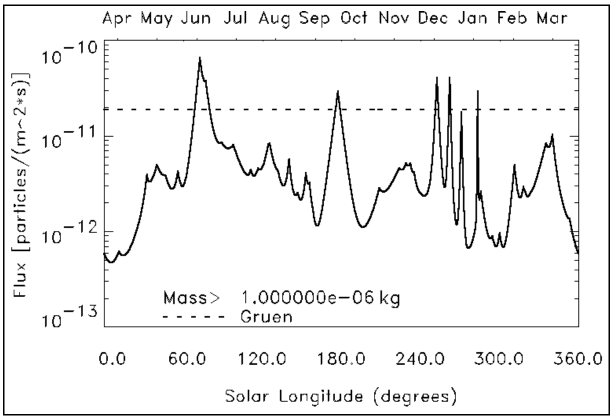

Fig. 4. Annual Meteoroid Stream Flux with particle masses equal or larger than 10^{-6} kg. The dashed line gives the results of the background reference model [2] for comparison.

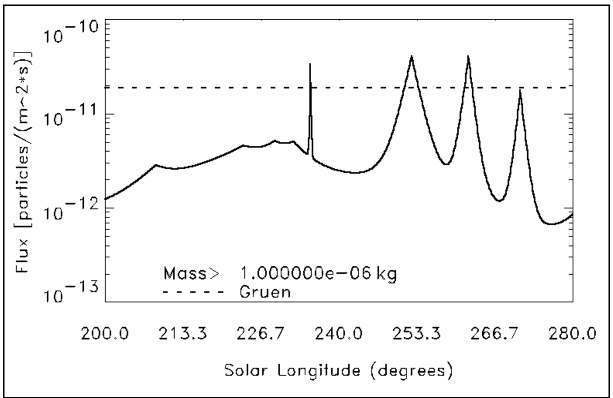

Fig. 5. Flux for masses equal or larger than 10^{-6} kg in a solar longitude range of 200 and 280 degrees and a Leonid storm with a ZHR_{max} value of 1000. The dashed line gives the results of the background reference model [2] for comparison.

4.2.3 Penetration Stream Flux

The Penetration Stream Flux is the flux of particles that are able to penetrate a specific target. Penetration Stream fluxes depend on the given target thickness and impact angle, where 0° means a perpen-dicular impact. Fig.6. shows the Penetration Stream Flux with target thickness t_t=0.1 cm, impact angles α=0° and for normal stream activity.

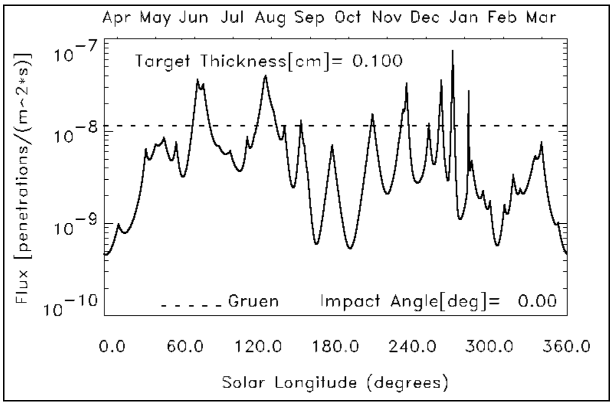

Fig. 6. Annual Penetration Stream Flux for a given 0.1 cm target thickness and a 0° impact angle. The dashed line gives the results of the background reference model [2] for comparison.

5. CONCLUSION

Two new software tools, STREAM.PRO and AKC.PRO, were developed and applied to investigate Meteoroid-Streams and -Storms, as well as Meteoroid Stream-Models & Meteoroid-Storm-Models. Depending on the ZHR-predictions, risk analysis can be made for future streams and storms. Furthermore other SW-tools, like ESABASE/DEBRIS, can be verified.

Because of its modular structure, future enhancements and applications can easily be implemented in the STREAM.PRO tool. One improvement could be an option to study interactions between the impact generated plasma and electrostatically charged spacecraft surfaces. Other possibilities are the implementation of different damage equations and an extension to study correlations between impact fluxes and spacecraft anomalies.

6. REFERENCES

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3. McBride N., Modelling The Meteoroid Environment, Adv.Space Res., 20, 1513-1516, 1997