Overview of the Meteoroid Environment

Slides by Althea Moorhead

With occasional adds by Bill Cooke

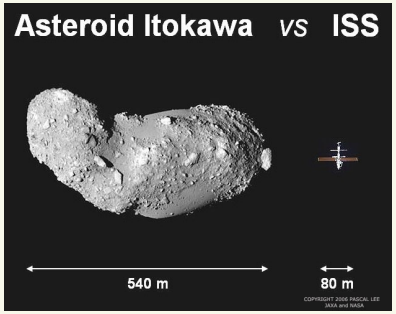
How NASA handles space debris



Meteoroids and meteors



Man-made orbital debris



Earth-approaching asteroids

OSMA

SMD

Meteoroid Environment Office (MSFC)

Orbital Debris Program Office (JSC)

Planetary Defense Coordination Office/Center for Near Earth Object Studies (HQ/JPL)

Brief history of the MEO

Only NASA meteoroid program since 1970, when the meteoroid group at Johnson Space Center was disbanded.

MSFC was point of contact and locus of knowledge for USG efforts to mitigate risks of the 1998-2002 Leonid meteor storms.

Studies conducted after Columbia determined NASA had lost practically all of its meteoroid expertise.

Established by NASA Headquarters Office of Safety and Mission Assurance (OSMA) at beginning of FY05 as the NASA organization responsible for meteoroid environments pertaining to spacecraft engineering and operations.

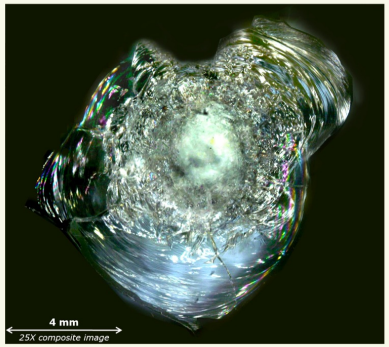


Damage potential

Diameter	Energy	Destructive Equivalent	Expected Damage
0.4 mm	54 J	Air gun	Wires severed, ESD, radiator or suit damage
1 mm	840 J	Pistol	Attitude disturbance, penetration of weaker materials
3 mm	23 kJ	Rifle	Significant material damage, possible TPS failure
1 cm	840 kJ	A vehicle at highway speeds	Catastrophic damage
2.7 cm	16 MJ	Armor-piercing rounds	Catastrophic damage

From the NASA Meteoroid Handbook
(https://ntrs.nasa.gov/api/citations/20200000049/downloads/20200000049.pdf)

Space debris poses the greatest hazard to humans or vehicles once they are in space!



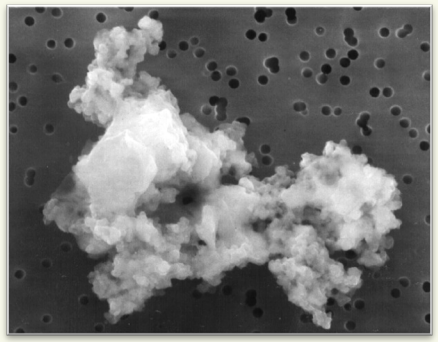
Meteoroid impact crater on shuttle window. Image provided by the NASA/JSC Hypervelocity Impact Technology (HVIT) Team.

“Impact” upon spacecraft operations

Spacecraft	When	Cause	Consequences
Mariner IV	1967 September 15	Unknown meteor stream between Earth and Mars	Large number (thousands) of small impacts ripped away MLI and torqued spacecraft about roll axis
STS-51/Discovery	1993 August	Perseid meteor outburst	Launch delayed due to inability to forecast shower intensity
Olympus (ESA commsat)	1993 August 11	Perseid hit on array/ESD	Satellite tumbled out of control; fuel exhausted in attempt to recover. Moved into disposal orbit 200
XMM-Newton (ESA X-Ray)	2001 September 17	Sporadic hit	27 pixels destroyed; more damage induced by impacts in October 2000, August 2002, and March 2005
Chandra	2003 November 15	Sporadic hit	Sudden spacecraft attitude change
Landsat 5	2009 August 13	Perseid meteor outburst	Temporary loss of control due to ESD disturbance of gyro
Artemis P1	2010 October 14	Sporadic hit	Part of boom and sphere 2 cut away; change in spacecraft CG.
GOES-13	2013 May 22	Sporadic hit	Attitude change caused spacecraft to enter safe mode, which was exited 7 days later.
MMS	2016 February 2	Sporadic hit	Impact destroyed one of four solar array shunt resistors

Environment Overview

Terminology



Meteoroids

- Chunks of rock and ice out in space.
- About the size of a boulder or smaller (1 meter upper limit).



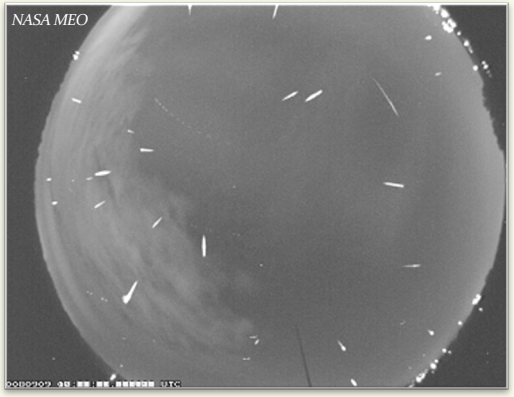
Meteors

- Streaks of light that you see as a meteoroid *ablates*, or burns up, in the Earth's atmosphere.
- Commonly called a 'shooting star' or 'falling star'.



Meteorites

- What is left of the meteoroid/asteroid if it survives the trip through the atmosphere and hits the Earth.
- Made of silicate minerals and/or iron-nickel.



Fireballs or Bolides

- Bright meteors.
- Peak magnitude brighter than Venus, m_{app} = -4.



Superbolides

- VERY bright meteors.
- Peak magnitude brighter than the full Moon, m_{app} = -17.
- Detectable by ground and space-based sensors.

Sources of meteoroids



Comets (>90%)



Asteroids

Meteoroids can also come from the Moon or other planets, but this is VERY rare.

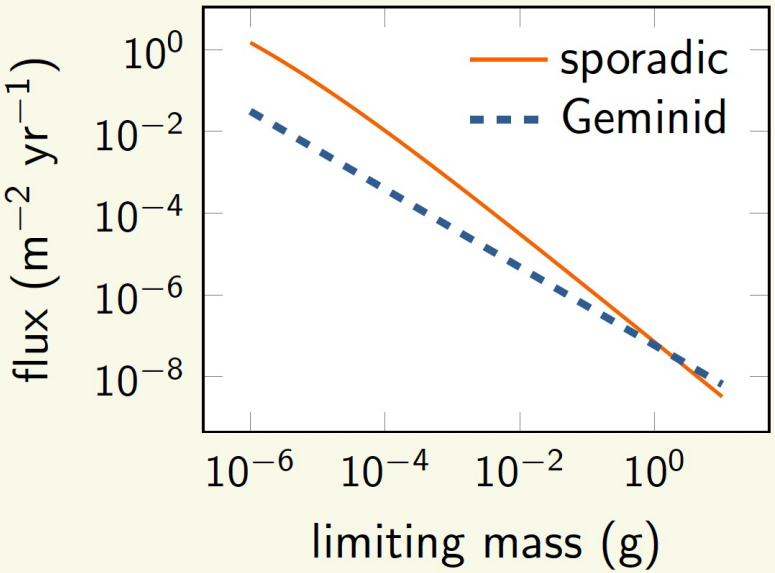
Shower and sporadic meteoroids



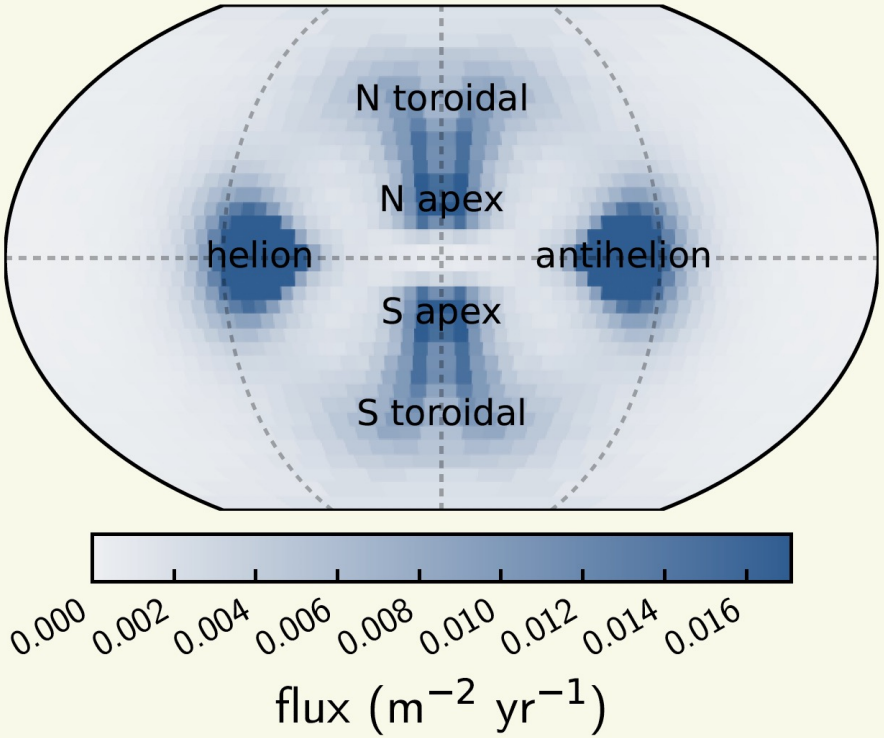
Photographs by David Kingham

Shower meteors occur at a certain time of year and share similar orbits.

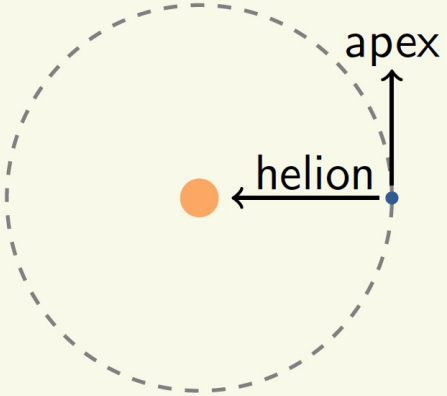
Sporadic meteors occur at any time, have varied orbits, and pose more risk.



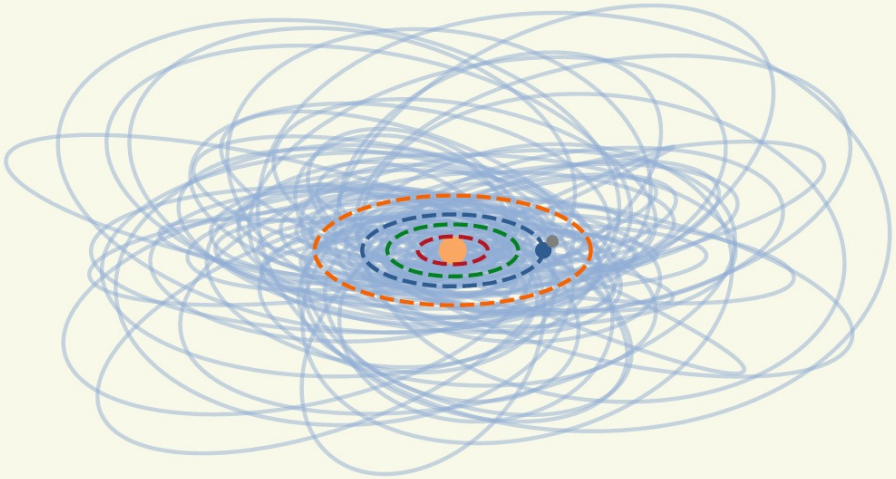
Meteoroid directionality is not isotropic.



The three orbit populations appear as six "sources" (three pairs) in this directional map.

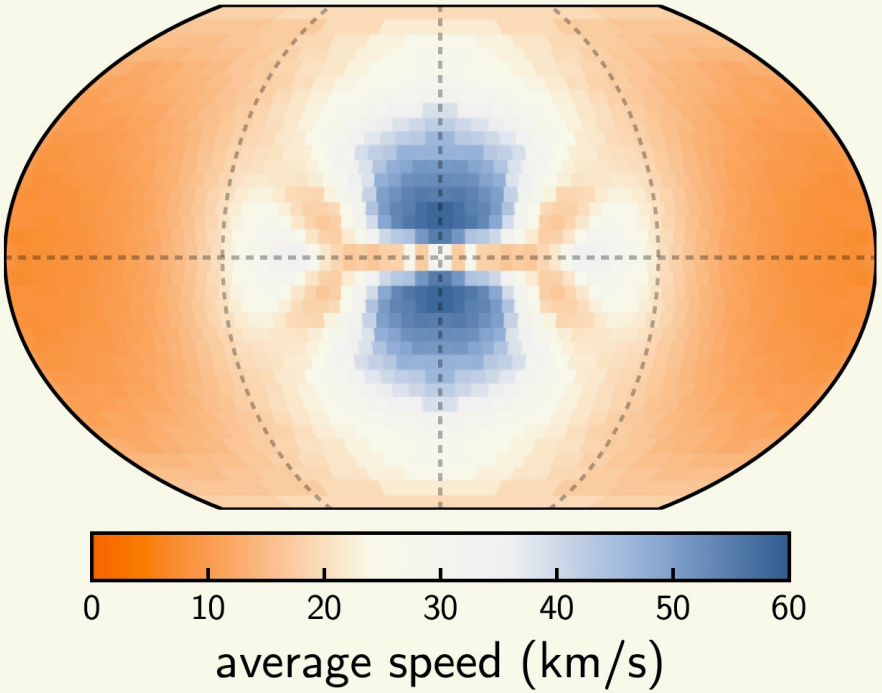


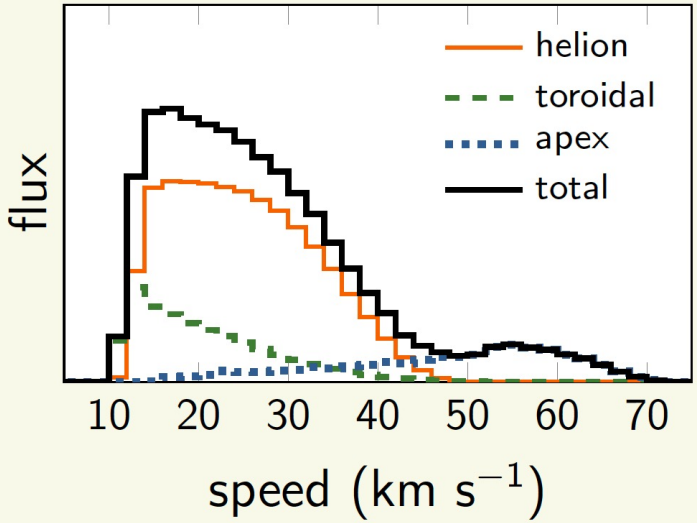
The sources can be dynamically linked to specific classes of objects.

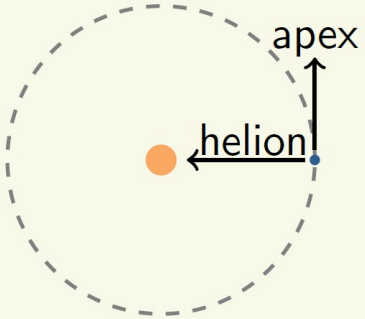


short-period comets	helion & anti-helion sources
long-period comets	apex source
Halley-type comets	toroidal source
asteroids	no corresponding source

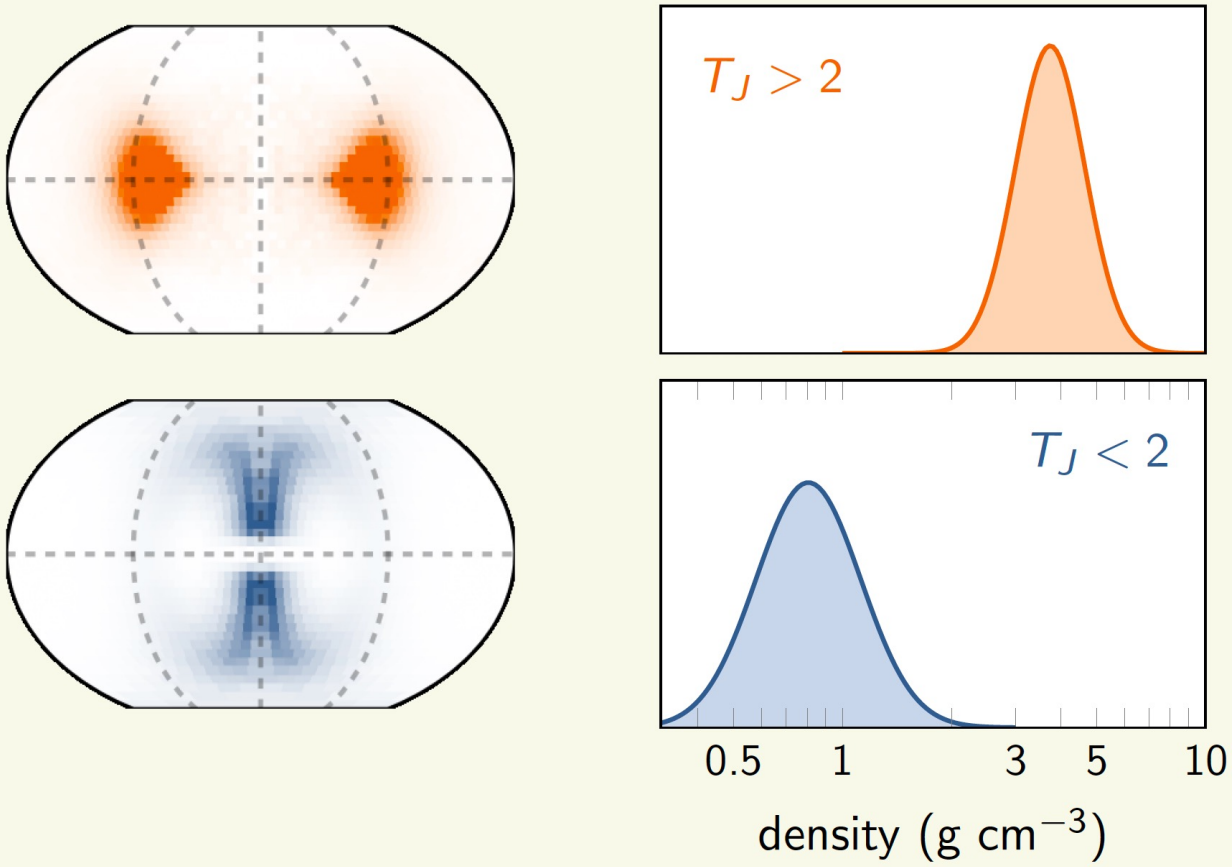
Each population has its own speed distribution.







The meteoroid sources also have different bulk densities.



Meteor shower terminology

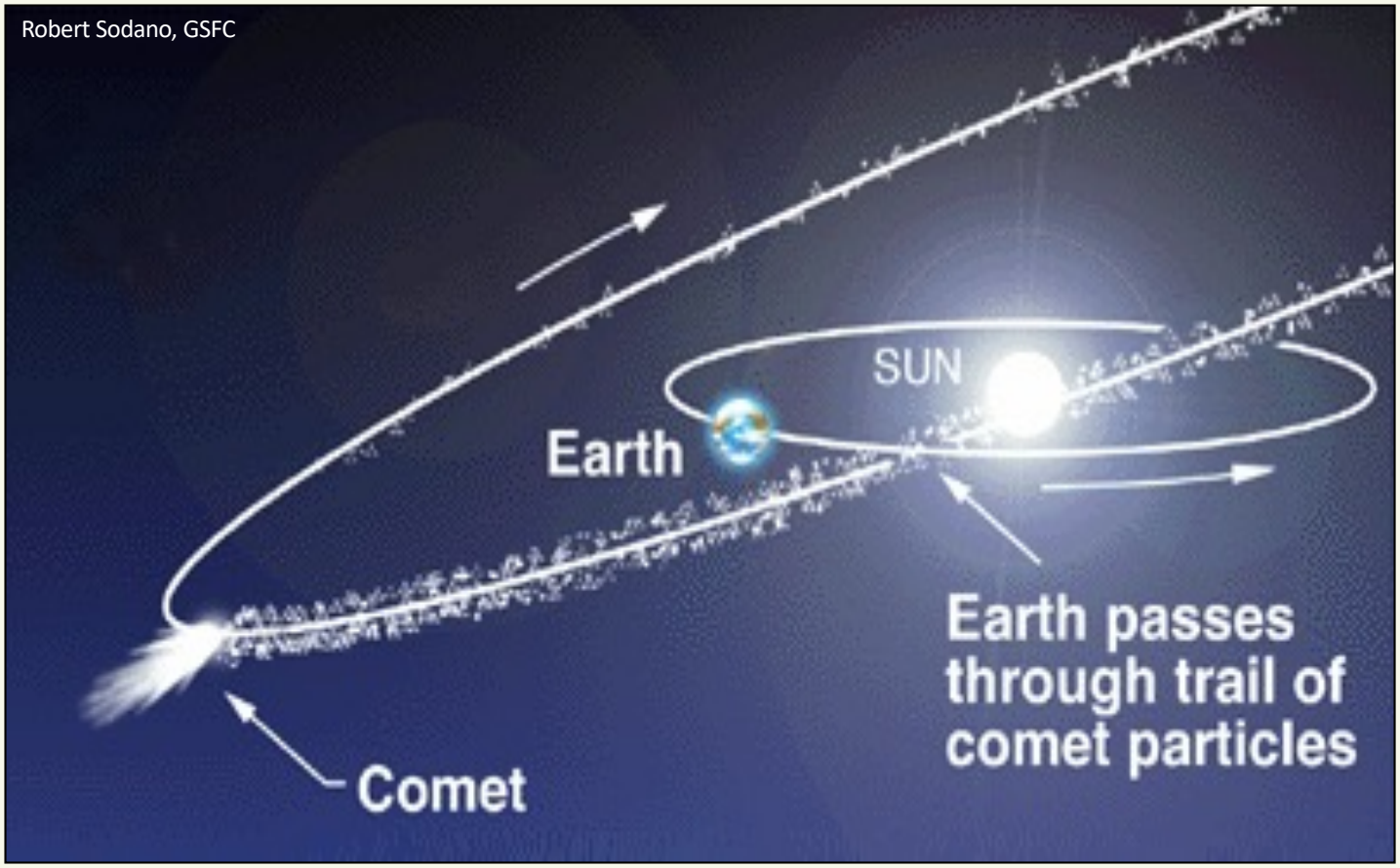
Meteor shower – short-term enhancement of meteor rates generated by encounter with particles produced by specific comets/asteroids. Named for constellation in which radiant is located.

Meteor outburst – any instance of a meteor shower exhibiting greater than "normal" activity.

Meteor storm – shower in which hourly rate > 1000.

ZHR - the number of meteors a single observer would see in an hour of peak activity if the radiant is at the zenith, assuming the conditions are excellent and the observer has perfect vision (never occurs in reality).

Meteor showers occur when the Earth encounters debris trails of a comet or asteroid.



Some annual meteor showers

Shower (3 letter code)	Activity	Peak	Radiant		ZHR
			α	δ	(meteors/hr)
Quadrantids (QUA)	Dec 28 - Jan 12	Jan 04	230°	+49°	120
Lyrids (LYR)	Apr 16 - Apr 25	Apr 22	271°	+34°	18
η-Aquariids (ETA)	Apr 19 - May 28	May 06	338°	-01°	70*
June Bootids (JBO)	Jun 22 - Jul 02	Jun 27	224°	+48°	Var
South. δ-Aquariids (SDA)	Jul 12 - Aug 23	Jul 30	340°	-16°	16
α-Capricornids (CAP)	Jul 03 - Aug 15	Jul 30	307°	-10°	5
Perseids (PER)	Jul 17 - Aug 24	Aug 13	48°	+58°	100
Draconids (DRA)	Oct 06 - Oct 10	Oct 08	262°	+54°	Var
Southern Taurids (STA)	Sep 10 - Nov 20	Oct 10	32°	+09°	5
Orionids (ORI)	Oct 02 - Nov 07	Oct 21	95°	+16°	25*
Northern Taurids (NTA)	Oct 20 - Dec 10	Nov 12	58°	+22°	5
Leonids (LEO)	Nov 06 - Nov 30	Nov 18	152°	+22°	20+*
Monocerotids (MON)	Nov 27 - Dec 17	Dec 09	100°	+08°	2
σ-Hydrids (HYD)	Dec 03 - Dec 15	Dec 12	127°	+02°	3
Geminids (GEM)	Dec 07 - Dec 17	Dec 14	112°	+33°	120
Dec. Leonis Minorids (DLM)	Dec 05 - Feb 04	Dec 20	161°	+30°	5
Ursids (URS)	Dec 17 - Dec 26	Dec 23	217°	+76°	10

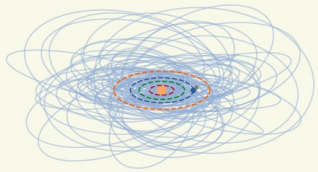
2023

2033

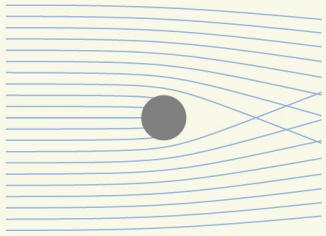
Worth viewing

Models

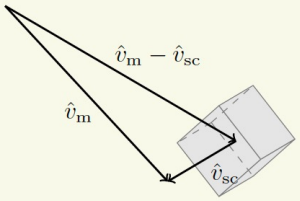
The Meteoroid Engineering Model (MEM) does the following:



models meteoroid orbits

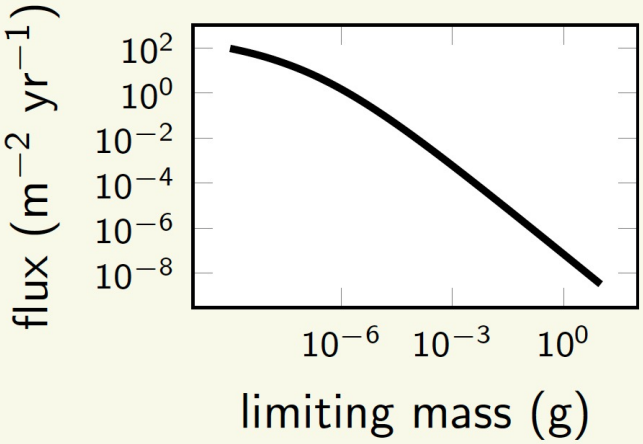


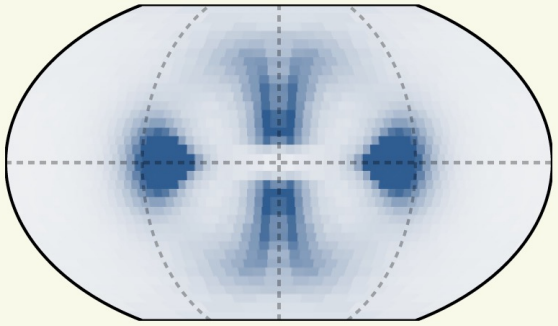
determines the local environment

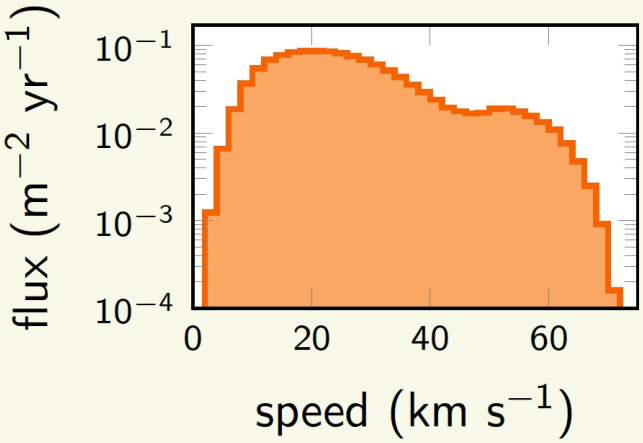


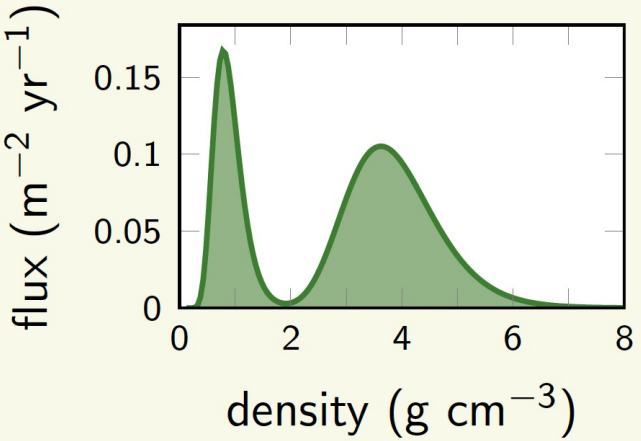
outputs the environment relative to a spacecraft

MEM provides impactor size, angle, speed, and density.

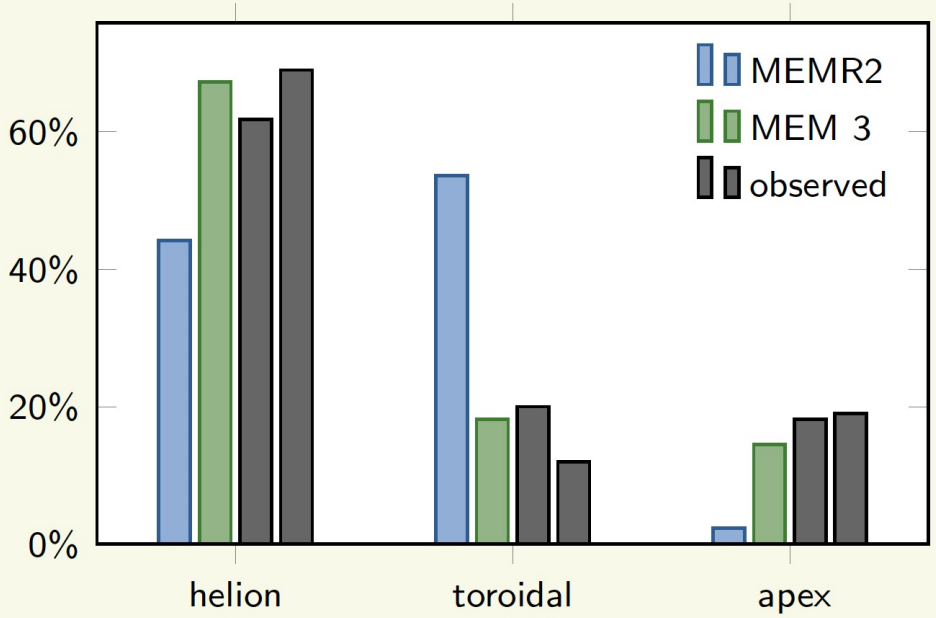


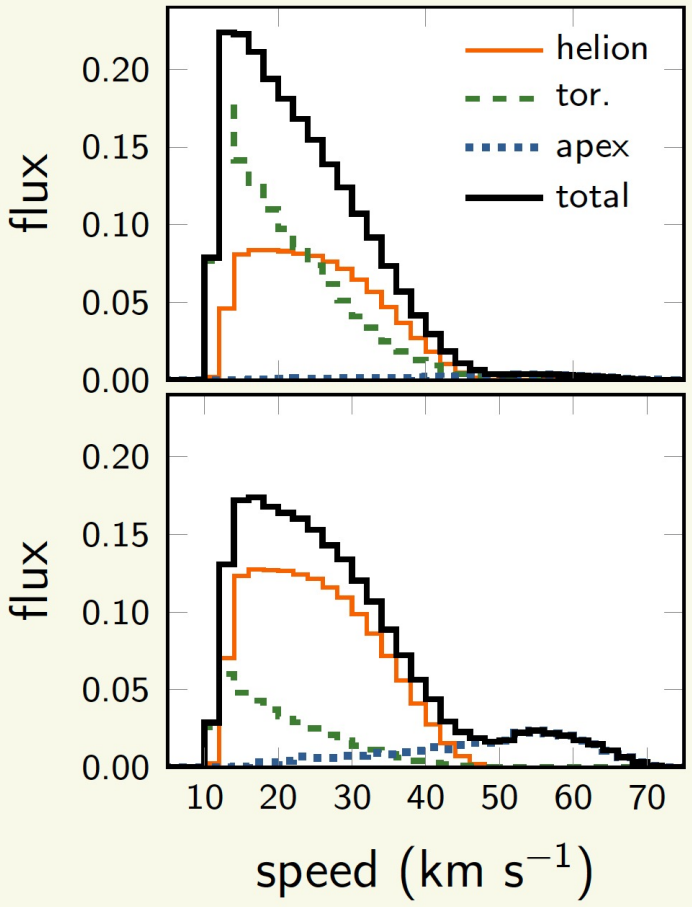






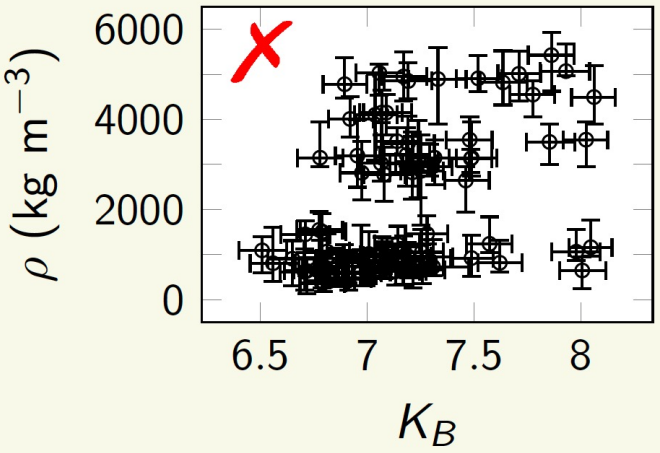
MEM 3's orbital populations match their observed strength at Earth.

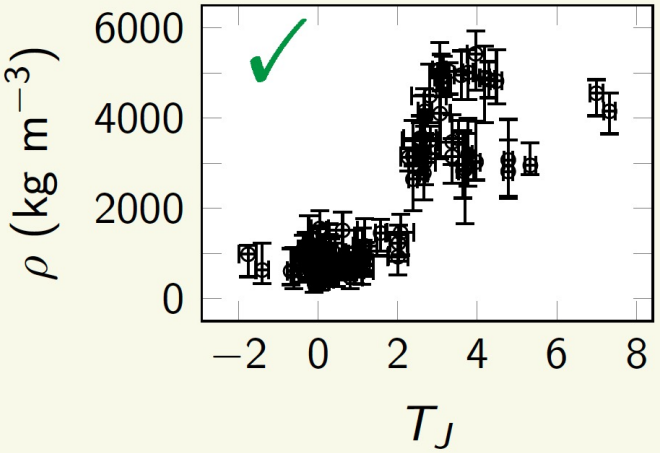


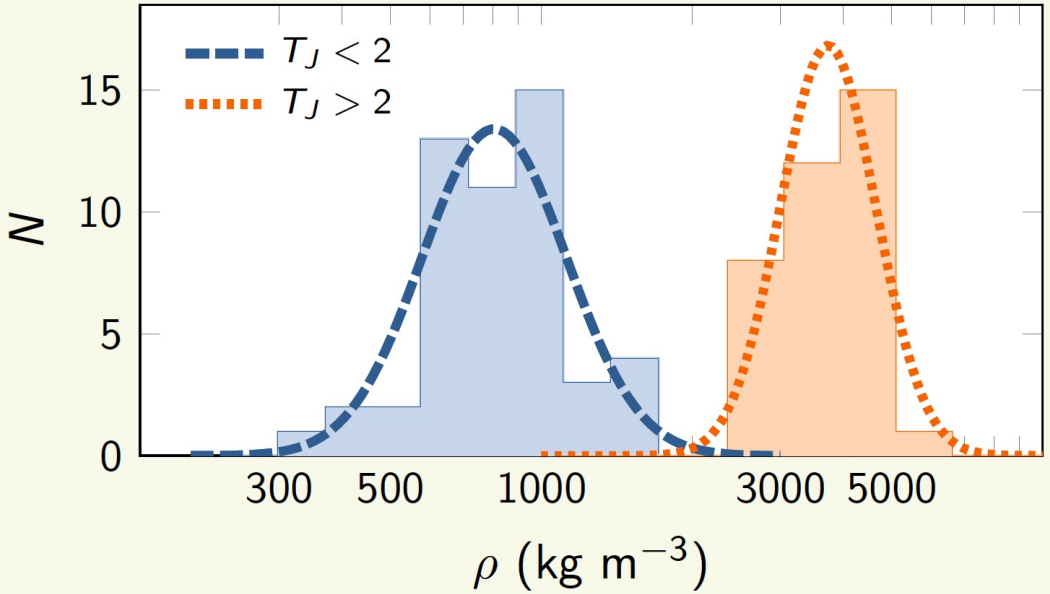


This re-weighting of the orbital populations also changes the speed distribution.

Meteoroid densities are based on Kikwaya et al., 2011.

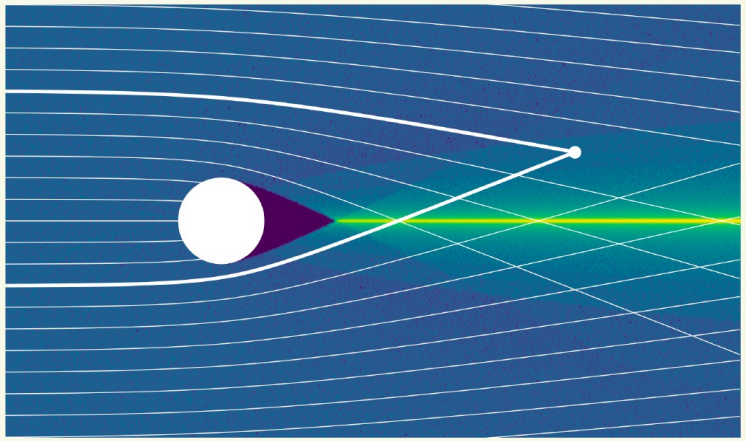


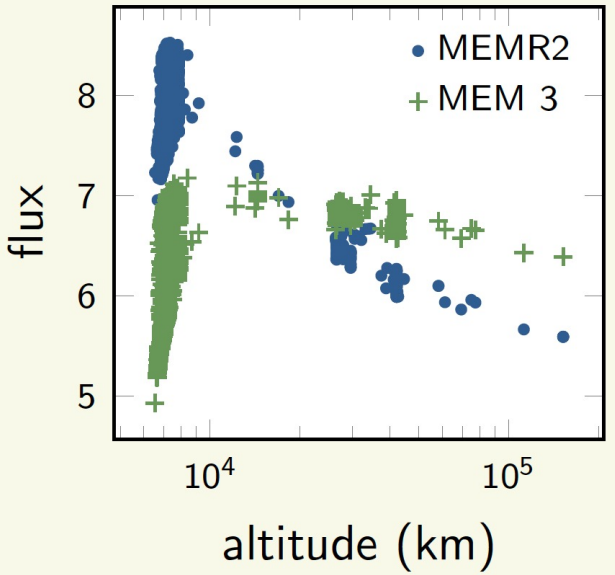




MEM 3's improvements include a correct handling of planetary gravity

Planets (and moons) bend and block the paths of meteoroids

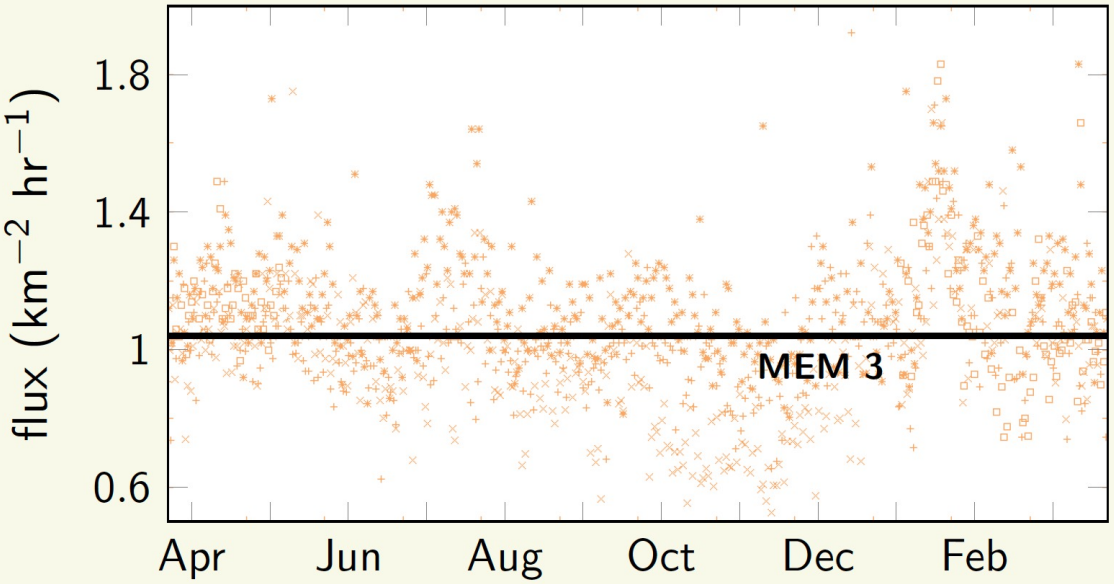




This effect was erroneously large in MEMR2, and has been corrected in MEM 3. The flux is now lower at low altitudes and higher at high altitudes.

MEM 3 matches the observed meteor flux at Earth.

The Canadian Meteor Orbit Radar (CMOR) has been measuring the meteoroid flux at the top of the atmosphere for $\sim$ 15 years



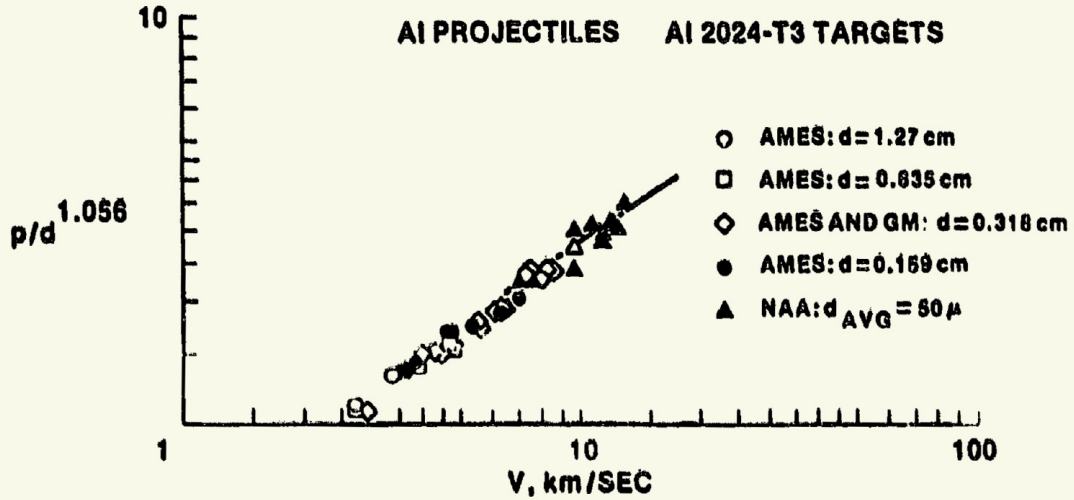
MEM's outputs are designed to be used with damage equations.

Damage equations describe the extent of damage caused by an impact:

$$p_t = 5.24\, d^{19/18}\, \mathrm{BH}^{-1/4} \left(\frac{\rho}{\rho_t}\right)^{1/2} \left(\frac{v_\perp}{c_t}\right)^{2/3}$$

extent of damage	meteoroid properties	target properties
p_t = crater depth	d = diameter	BH = Brinell hardness
	ρ = density	ρ_t = density
	$v_\perp$ = normal speed	c_t = sound speed

It is uncertain how applicable damage equations are to meteoroid impacts.



For instance, the Cour-Palais (CP) BLE is derived from Al-on-Al impacts at relatively low speeds.

- Is the behavior similar at high speeds?
- Is the behavior similar for non-metal impactors?

We use two damage equations to partially account for uncertainty.

We also apply the Watts & Atkinson (WA) BLEs:

crater diameter:

$$d_t = 1.3235 f\, d (c_t/c)^{2/7} (v_\perp/v_0)^{4/7}$$

$$f = \left(1 + \sqrt{2\Delta/d_0}\right)^{-1/3}$$

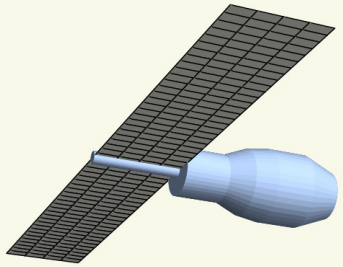
crater depth:

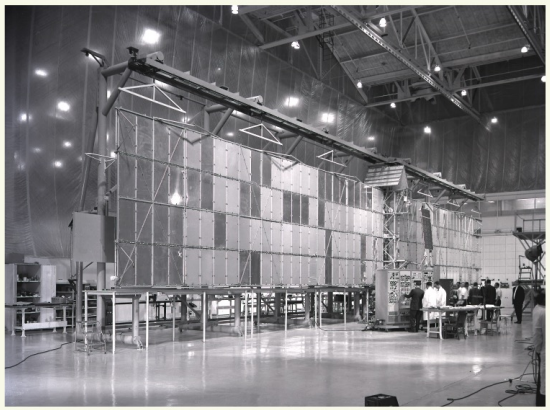
$$p_t = \frac{fd}{4}\left(\frac{4}{3}\frac{\rho}{Y_t}\left(c_{0,t} + \frac{s(v_\perp - v_0)}{1+\sqrt{\rho_t/\rho}}\right)(v_\perp - v_0)\right)^{1/3}$$

penetration thickness:

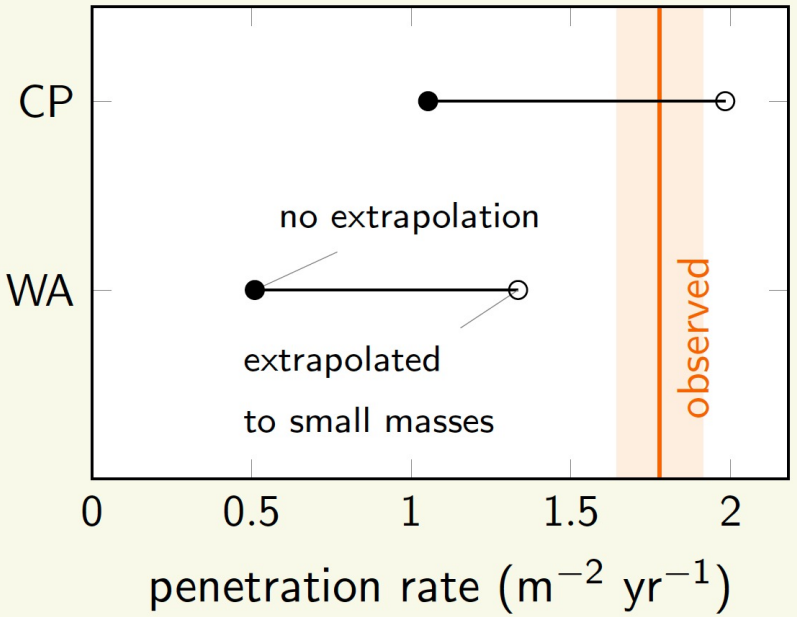
$$t_t = \frac{fd}{4}\left(\frac{1}{6}\frac{\rho}{Y_t}\left(c_{0,t} + \frac{s(v_\perp - v_0)}{1+\sqrt{\rho_t/\rho}}\right)(v_\perp - v_0)\right)^{1/3} + \frac{fd}{4}\frac{v_\perp}{v_0}\sqrt{\frac{Y_t}{\sigma_t}}$$

MEM 3 underpredicts the rate measured by Pegasus.

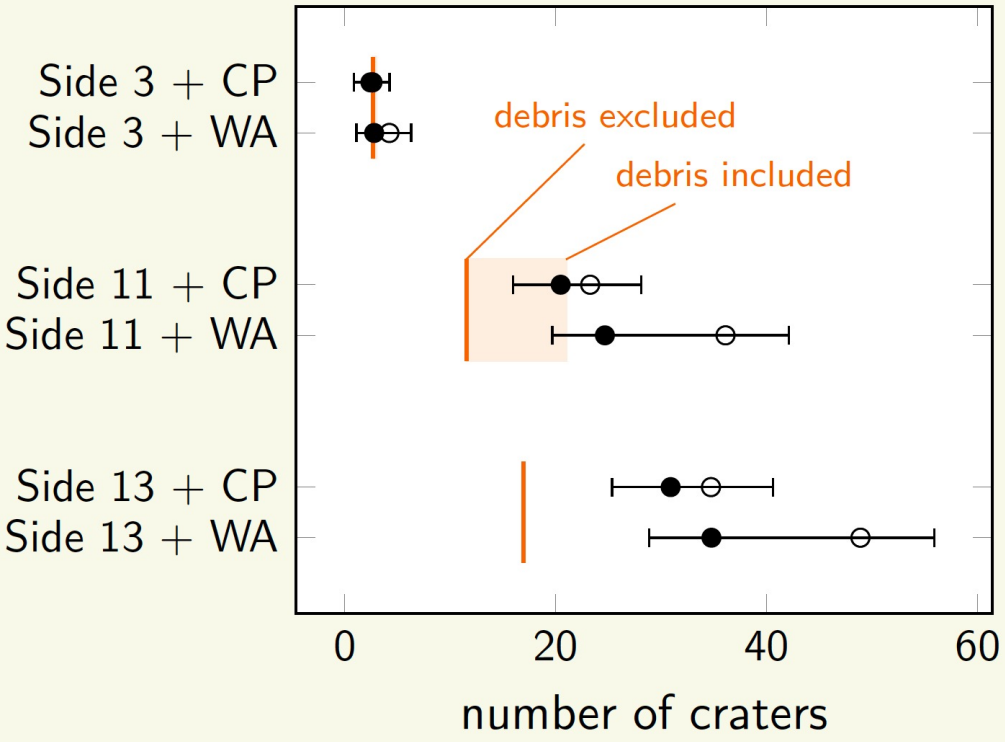


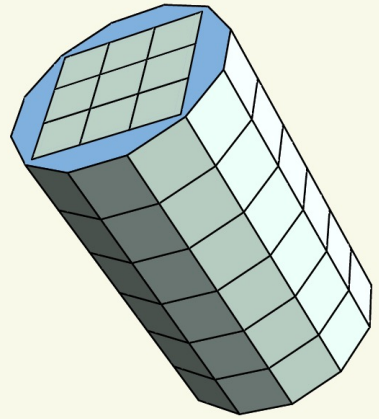


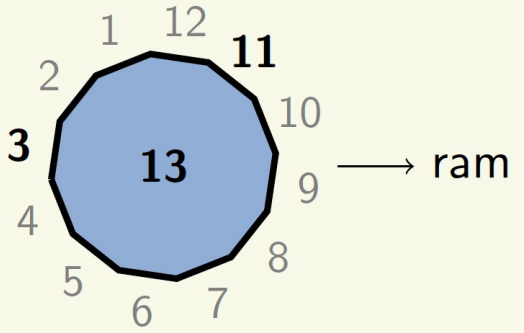
We used two damage equations (CP vs. WA) and two mass extrapolation methods (solid vs. open).
In 3/4 cases, MEM 3 is lower.



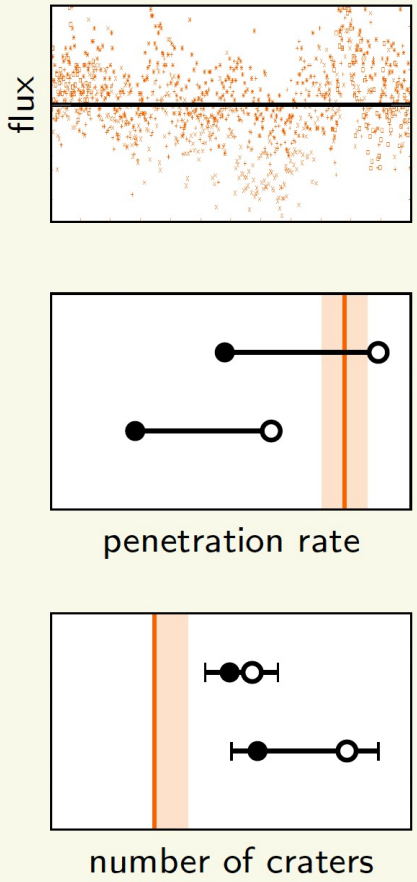
MEM 3 overpredicts the number of craters on LDEF.







MEM 3 matches the combination of data that is available.

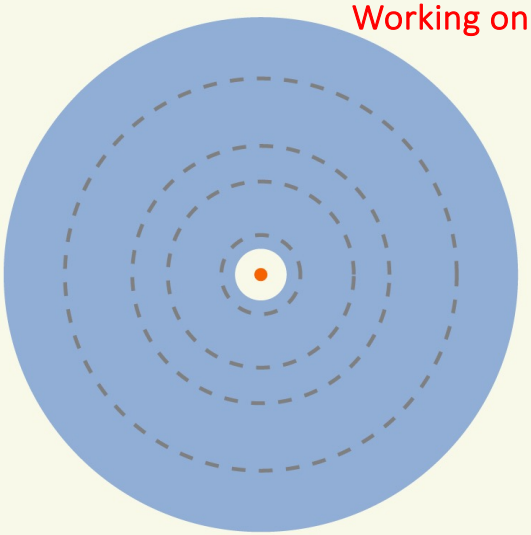


MEM is a physics-based meteoroid environment model that is designed to support spacecraft risk assessments.

The flux at the top of the atmosphere matches radar observations.

MEM 3 lies between the two best sets of *in situ* data we have in the threat regime (1 μg - 1 g).

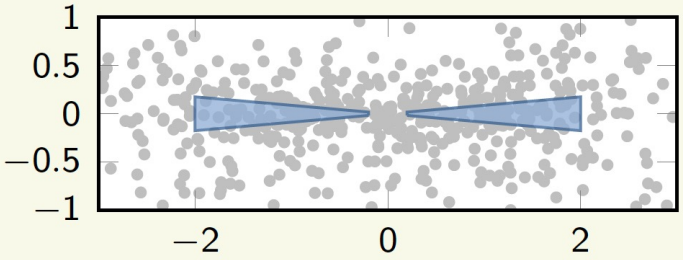
MEM has limitations that we'd like to eventually remove.

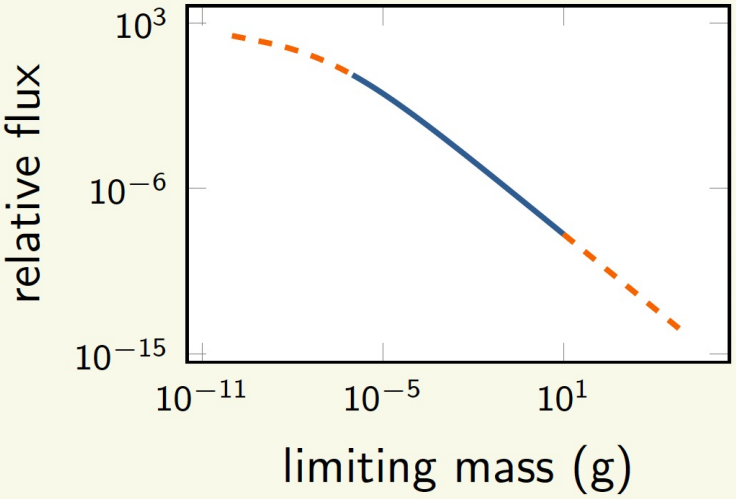


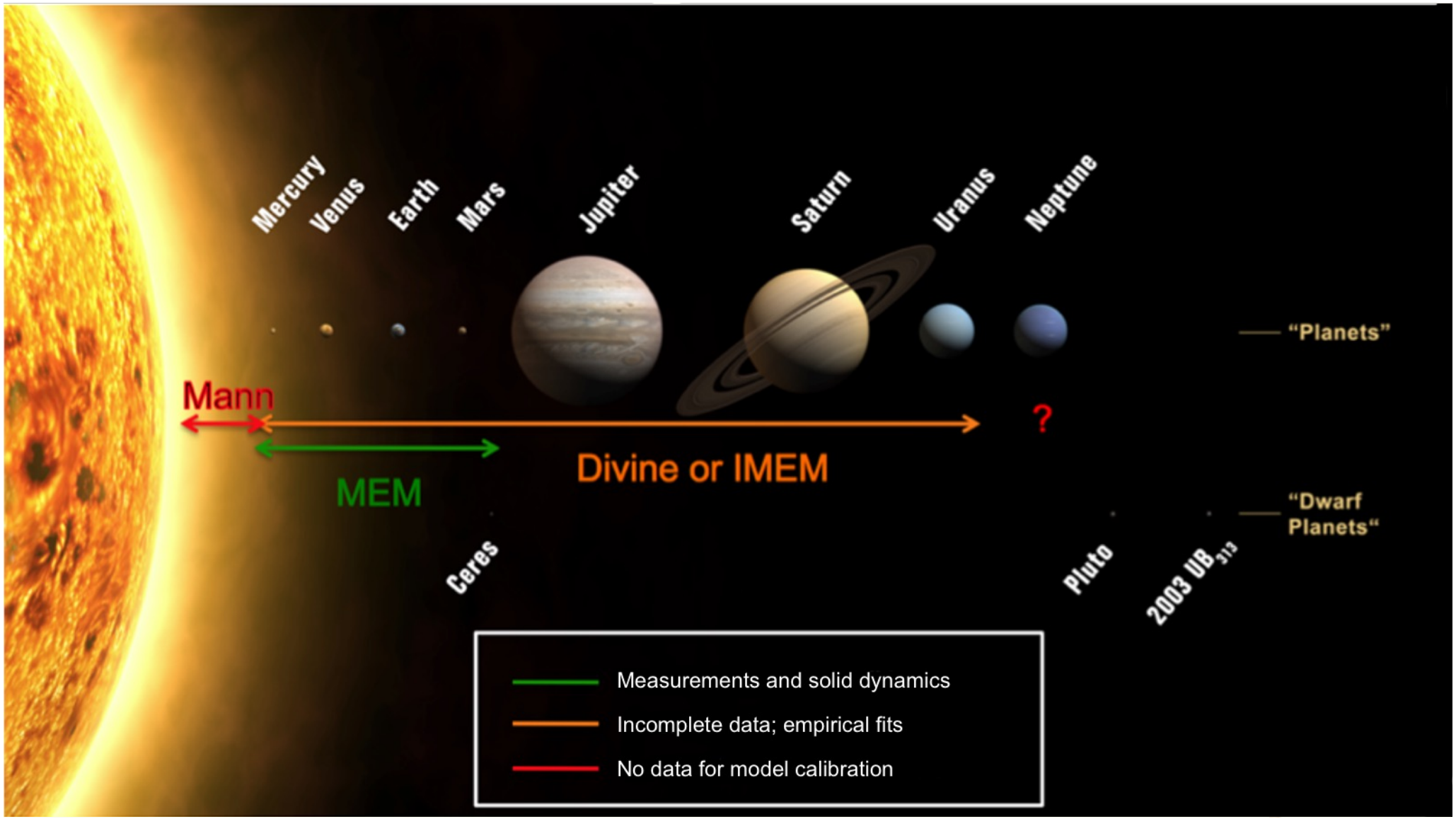
Limited to inner solar system: 0.2 – 2 au

Limited to within $\sim 5^\circ$ of the ecliptic

Limited to 10^{-6} – 10 g



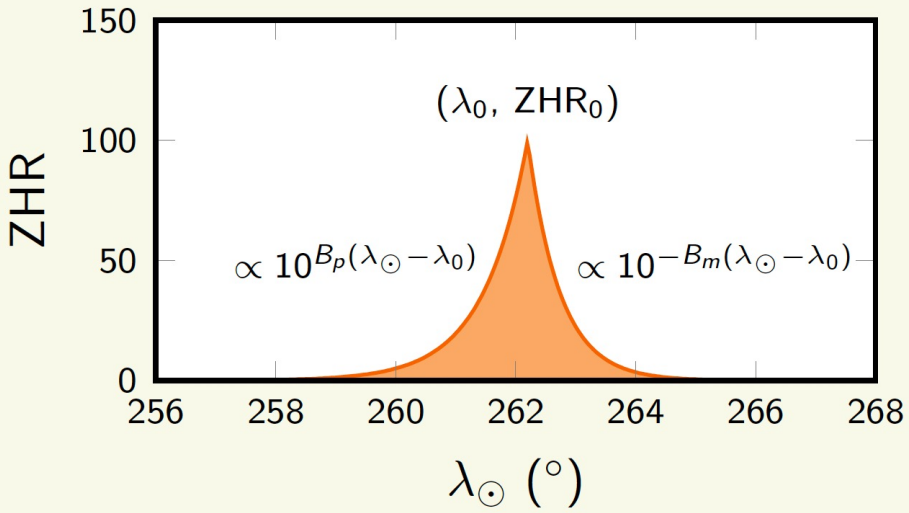


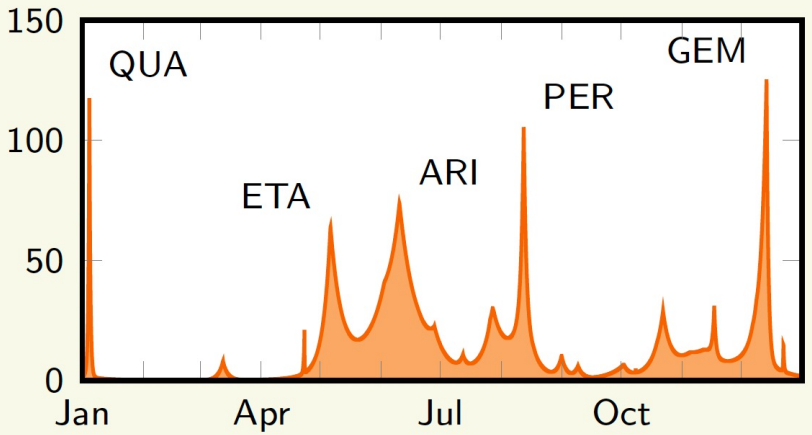

Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
"Planets"
Mann
?
Divine or IMEM
MEM
"Dwarf Planets"
Ceres
Pluto
2003 UB313
Measurements and solid dynamics
Incomplete data; empirical fits
No data for model calibration

Meteor showers are a small but varying fraction of the environment.

Shower meteoroids constitute 1-5% of the risk, but this risk varies with time.

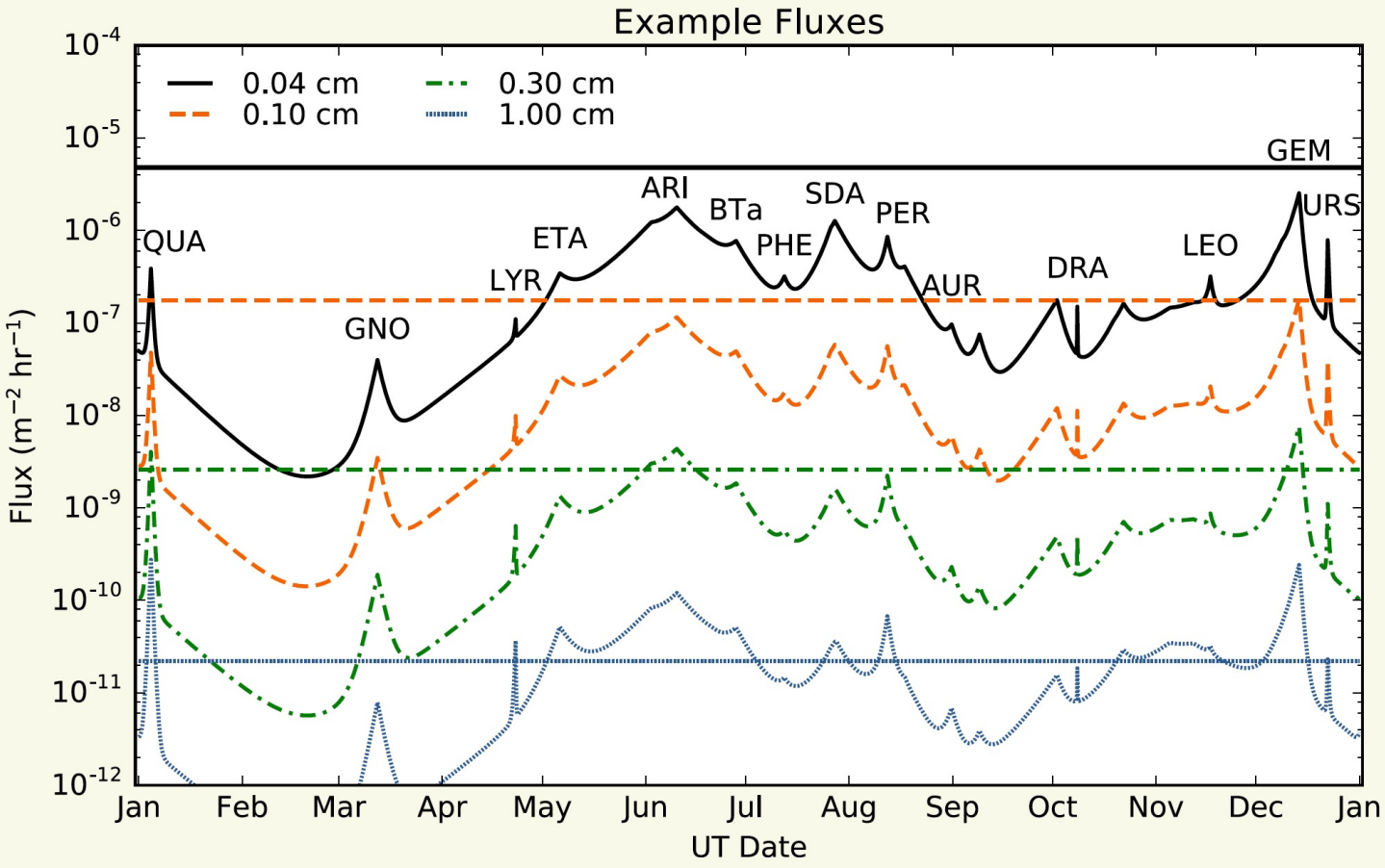
We handle meteor showers in separate "forecasts" that describe their activity over the course of a year





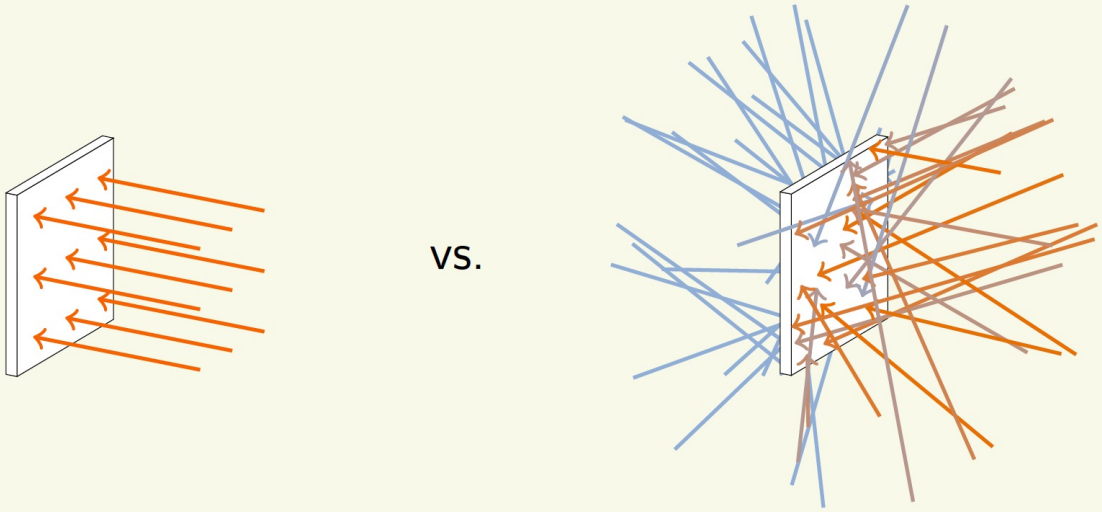
hi

ZHRs are converted to flux for a given altitude and limiting parameter.



Fluxes correspond to a "worst-case scenario" for shower exposure

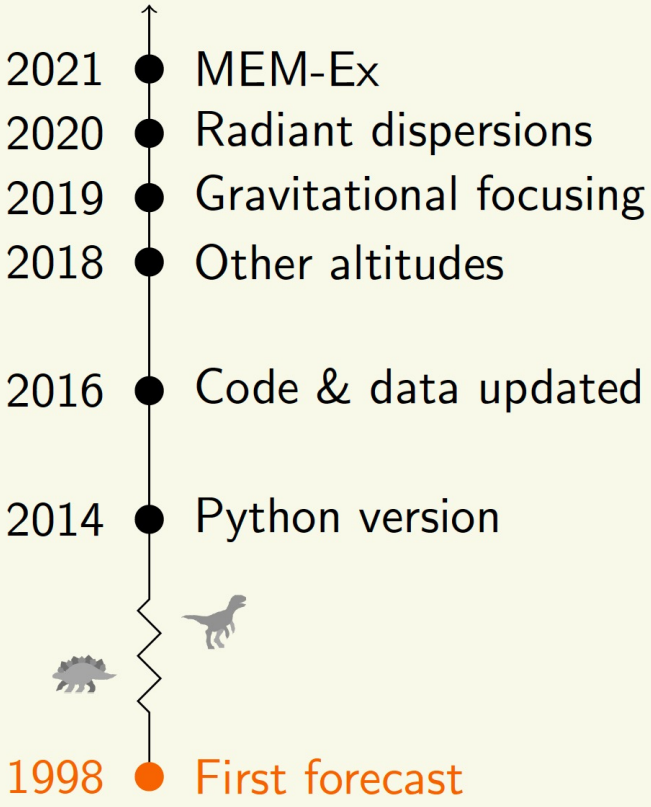
The forecast reports fluxes on a flat plate facing the shower radiant



vs.

This is the worst-case scenario for shower exposure. Although typically showers are a small fraction (0.9% - 15%) of the baseline flux, the risk enhancement can be more significant for a fully exposed element.

The meteor shower forecast code originated in 1998.



Bill created the first version of the forecast code in 1998 (in IDL) and begin issuing meteor shower forecasts

We made some more meaningful updates in 2016.

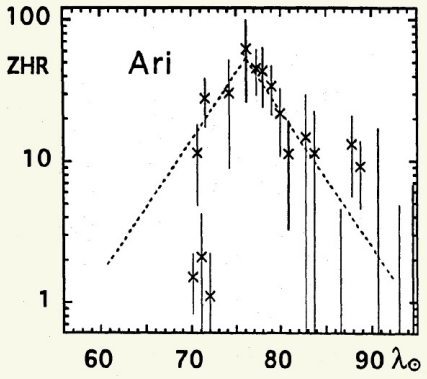
2021 MEM-Ex
2020 Radiant dispersions
2019 Gravitational focusing
2018 Other altitudes

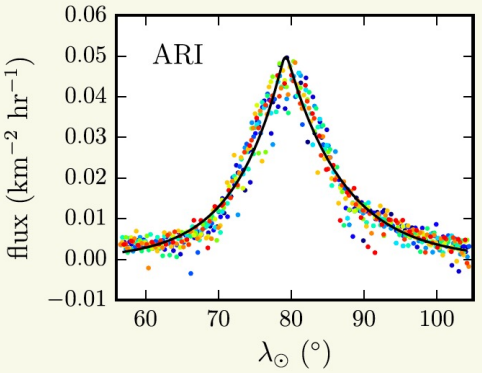
2016 Code & data updated

2014 Python version

1998 First forecast

First, we updated many meteor shower activity profiles using data from CMOR ...



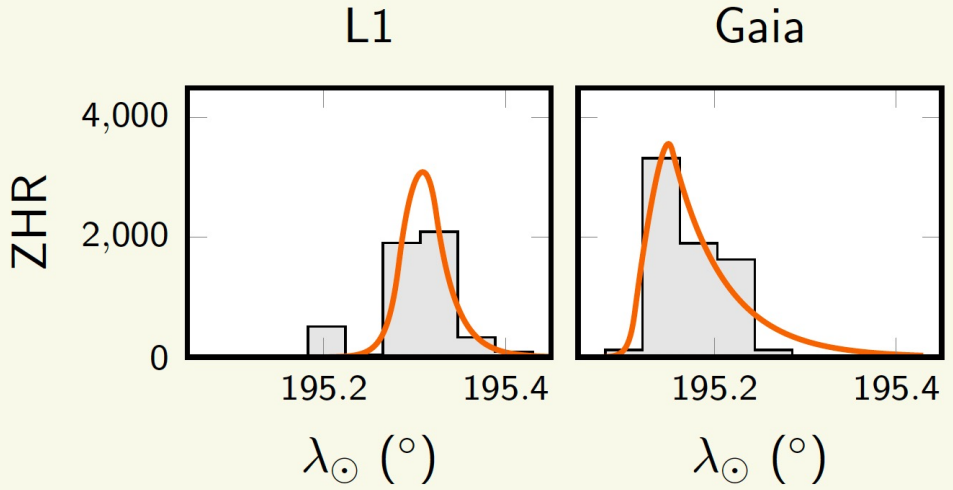


Second, we updated the algorithms. For instance, we improved our calculation of the average shower contribution to the meteoroid flux (Moorhead 2017).

We expanded the code to handle other altitudes in 2018.

2021 MEM-Ex
2020 Radiant dispersions
2019 Gravitational focusing
2018 Other altitudes
2016 Code & data updated
2014 Python version
1998 First forecast

We generalized the code in 2018 to handle additional altitudes, the Moon, and Lagrange points.



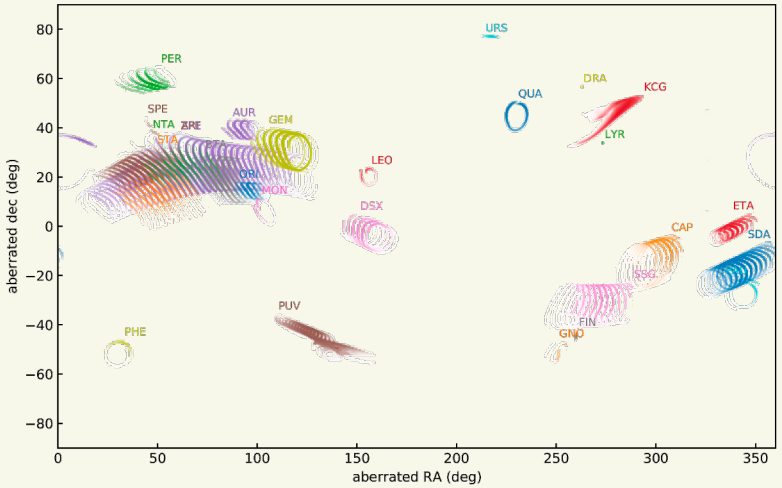
This was done in part to enable a 2018 Draconid forecast near L1 and L2

We incorporated gravitational focusing and shielding in 2019.

2021 MEM-Ex
2020 Radiant dispersions
2019 Gravitational focusing
2018 Other altitudes
2016 Code & data updated
2014 Python version
1998 First forecast

Some spacecraft in elliptical orbits can fly through regions of intense gravitational focusing, increasing shower flux by factors of a few.

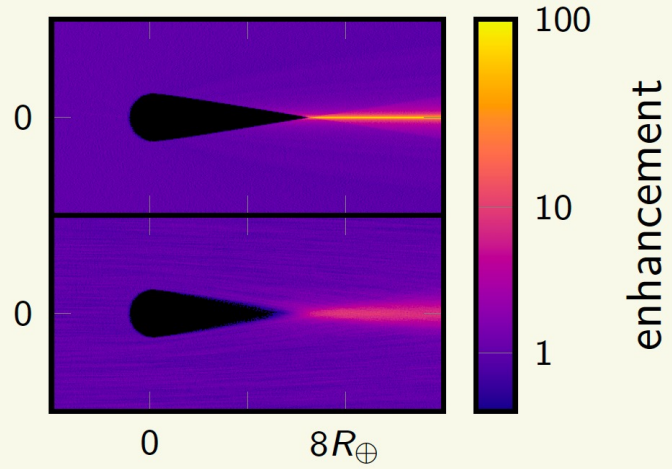
Code also calculates the aberrated shower radiants caused by spacecraft motion.



We are further improving the gravitational focusing.

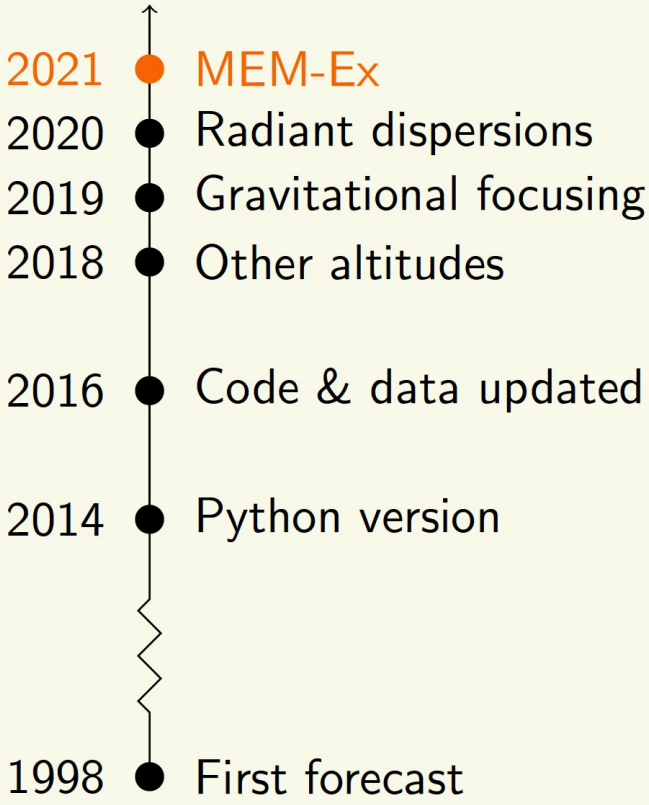
2021 MEM-Ex
2020 Radiant dispersions
2019 Gravitational focusing
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2016 Code & data updated
2014 Python version
1998 First forecast

Gravitational focusing algorithms assume the meteoroid flow is perfectly uniform, but in reality there's some spread.



We have a new algorithm (submitted paper) and will next measure radiant dispersions

Our next step is to create a MEM-like shower model.

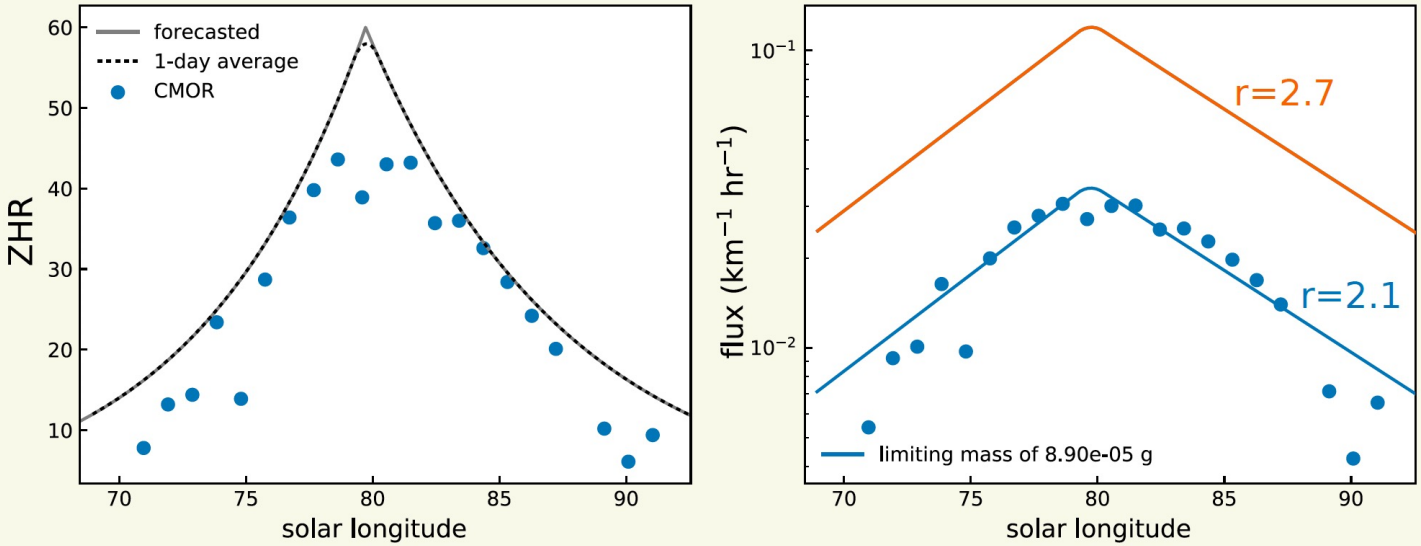


The shower forecast code and MEM are converging in complexity and functionality.

We have begun to make plans for a possible MEM-like shower flux model, tentatively named MEM-Ex (Meteoroid Engineering Model Shower Extension).

We compare the forecasts with observed shower activity.

We compare our forecasted ZHRs and fluxes with observations of major showers.



One such comparison revealed that our Arietid mass index was too steep (now corrected).

Shower summary

We issue:

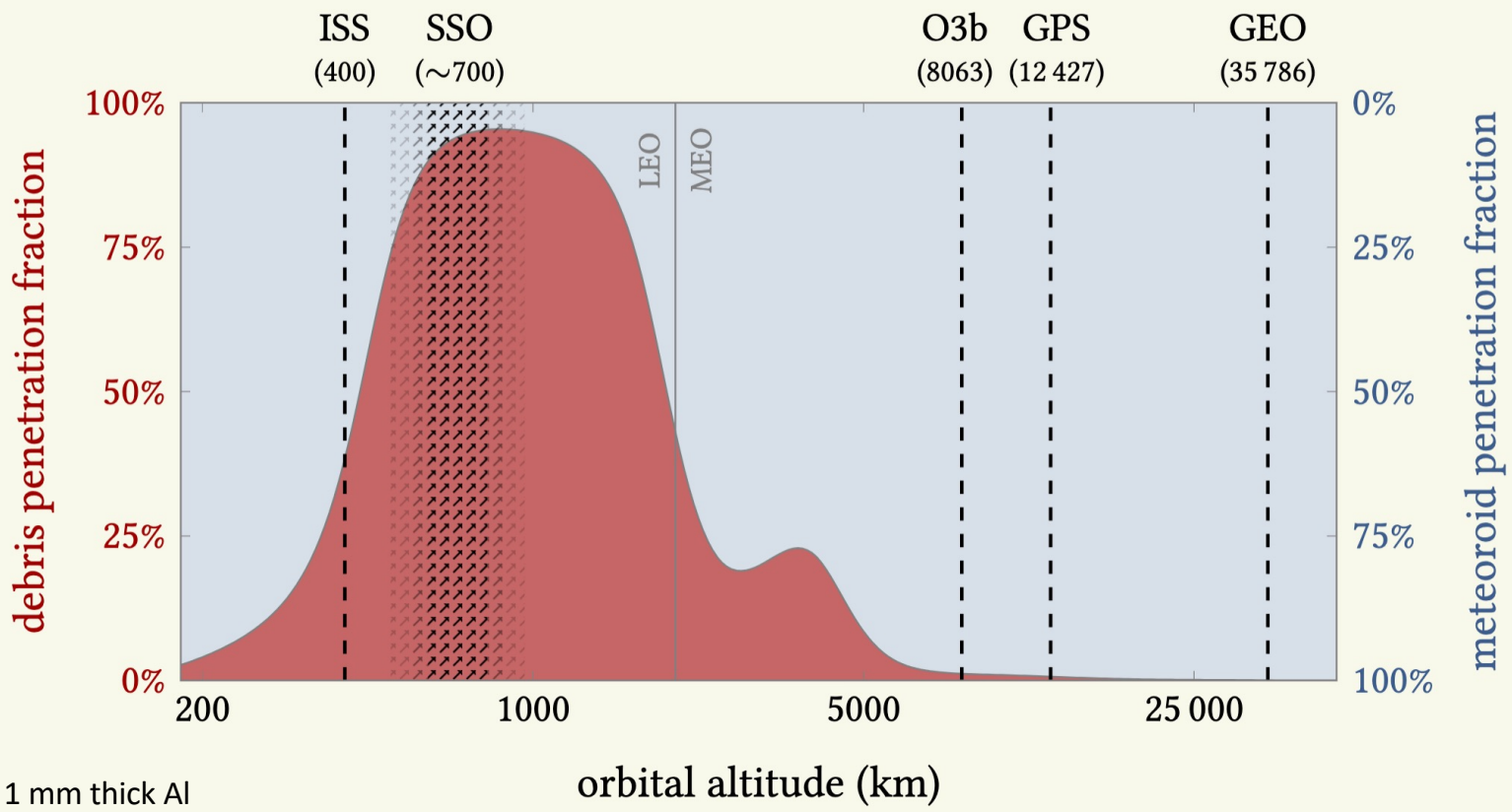
- annual forecasts
- ISS EVA forecasts
- custom spacecraft forecasts on request
- special advisories

The code we use has gradually increased in complexity and fidelity and is beginning to resemble MEM.

Our forecasts are based on both typical shower activity and model predictions. The next major outburst predicted by shower models are the “Finlayids” in 2021.

Meteoroid/Orbital Debris comparison

Comparison of penetrating flux



1 mm thick Al

GEO: geosynchronous orbit
GPS: Global Positioning System
ISS: International Space Station
LEO: low Earth orbit
MEO: medium Earth orbit
O3b: O3b MEO constellation
SSO: sun-synchronous orbit

A. Moorhead, MEO