Modeling the meteoroid environment as seen by spacecraft

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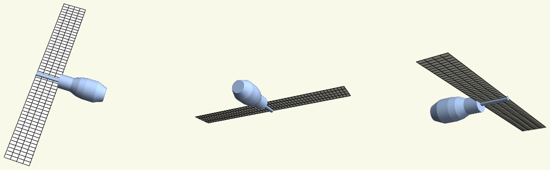
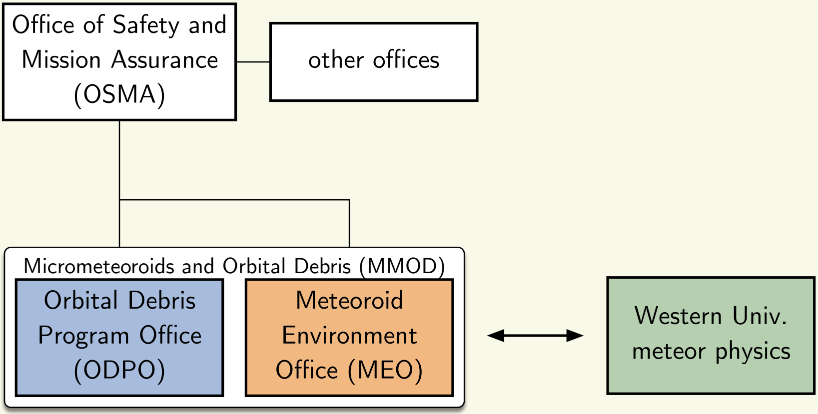
Western University Physics & Astronomy Colloquium
12 September 2019

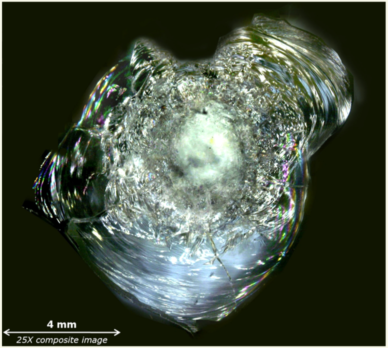


Outline

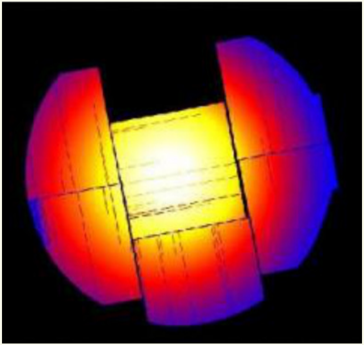
What is the Meteoroid Environment Office?



Why does the MEO exist?



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



The loss of a section of the MOS1 CCD sensor of the XMM-Newton telescope following an impact. Image credit: ESA

Why does the MEO exist?

diameter	KE	damage
BB gun		
0.04 cm	7 J	spacesuit
0.1 cm	105 J	delicate components
bowling ball		
0.3 cm	3 kJ	sturdier components
watermelon at terminal velocity		
1 cm	105 kJ	mission-critical
small wrecking ball		

grade stainless loose ball bearings by Oleksandr Panasovskyi from the Noun Project
strike by Noah Mormino from the Noun Project
watermelon by Blaise Sewell from the Noun Project

Why does the MEO exist?

Spacecraft require protection such as a Whipple shield:

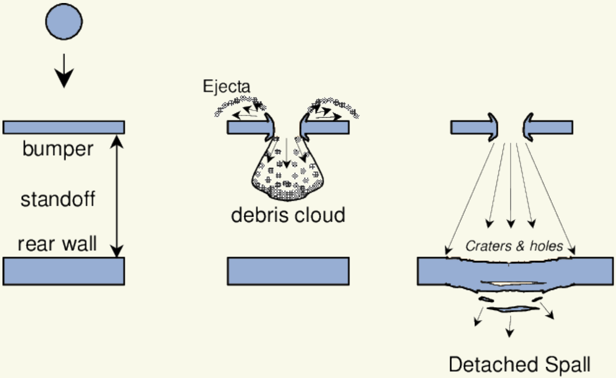
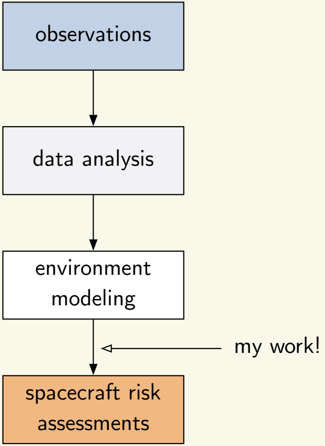


Diagram adapted from Ryan & Christiansen (2015)

Too much shielding = wasted weight

What does the MEO do?



- all-sky network, comet observations, lunar impacts, Geostationary Lightning Mapper
- individual meteor reductions, shower flux measurements, using ablation models to obtain densities
- meteor shower stream modeling
- engineering models of the sporadic complex (MEM) and meteor showers (shower forecast)

What does the MEO do?

	Meteoroid Engineering Model (MEM)	shower forecasts	"sky falls"
what does it model?	sporadic complex	meteor showers	individual bright events
how important is it to spacecraft?	95-99% of risk	1-5% of risk	$\sim$ 0% of risk
what form does it take?	software that users download and run	annual report and data files	individual emailed reports
what is it used for?	spacecraft design	operational mitigation	keeping the public informed

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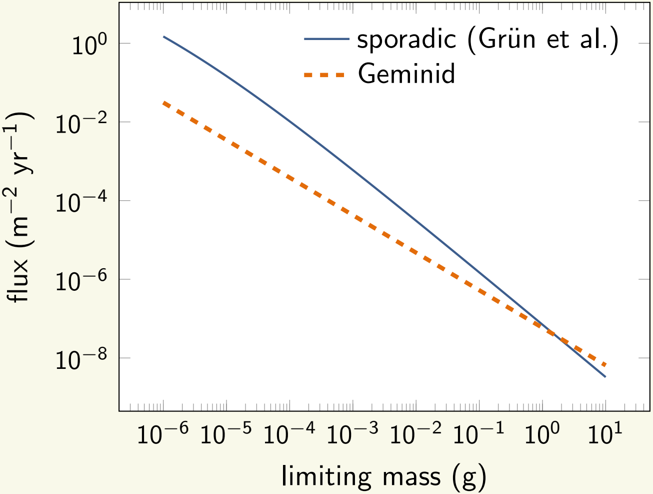
Sporadic and shower meteoroids

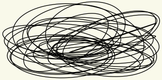
Photographs by David Kingham

Sporadic and shower meteoroids

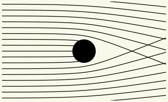


Meteoroid Engineering Model (MEM)

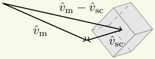
MEM does the following:



models meteoroid orbits



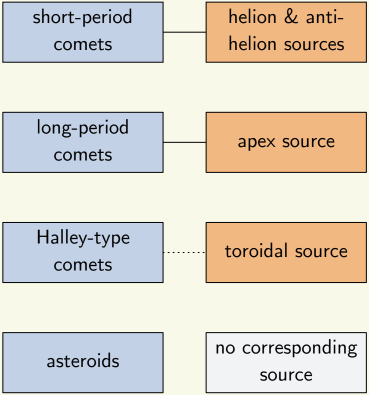
determines the local environment



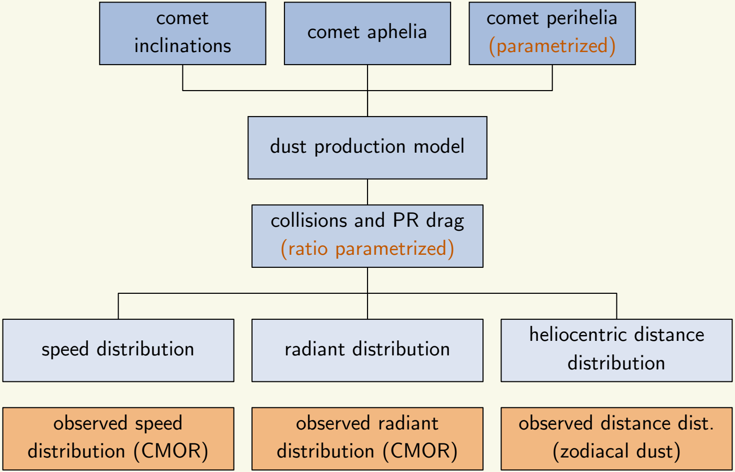
outputs the environment relative to a spacecraft

Jones (2004)

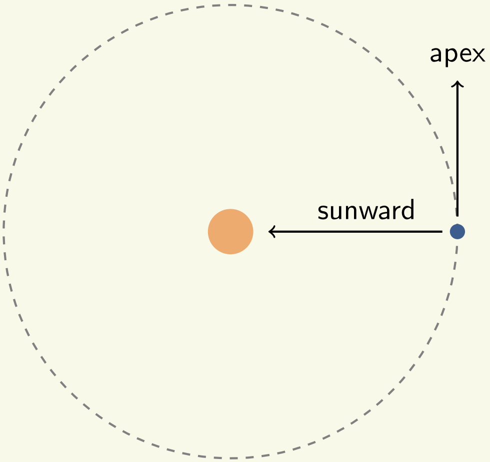
- MEM ...
  - is not purely empirical
  - is not an N-body simulation
  - is a physics-based model calibrated to match observations
- Jones (2004) linked parent populations to observed distributions, taking radiative forces and collisions into account
- Orbital populations mostly the same since 2004



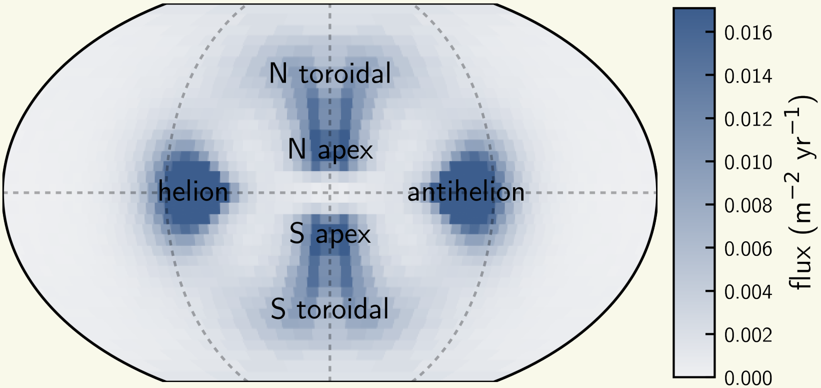
Jones (2004)


comet inclinations
comet aphelia
comet perihelia (parametrized)
dust production model
collisions and PR drag (ratio parametrized)
speed distribution
radiant distribution
heliocentric distance distribution
observed speed distribution (CMOR)
observed radiant distribution (CMOR)
observed distance dist. (zodiacal dust)

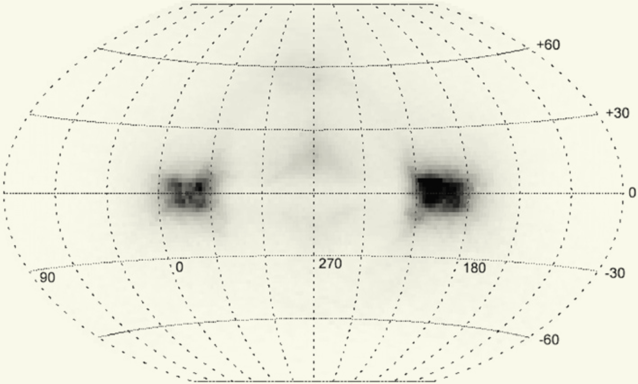
Coordinate system



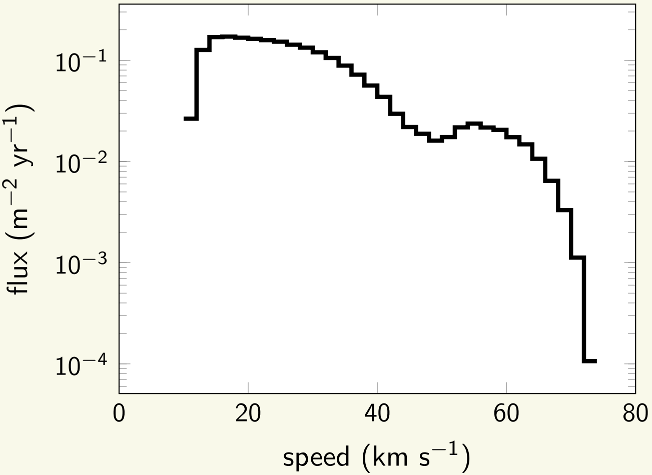
Radiant distribution



Observed radiant distribution
Campbell-Brown (2008)

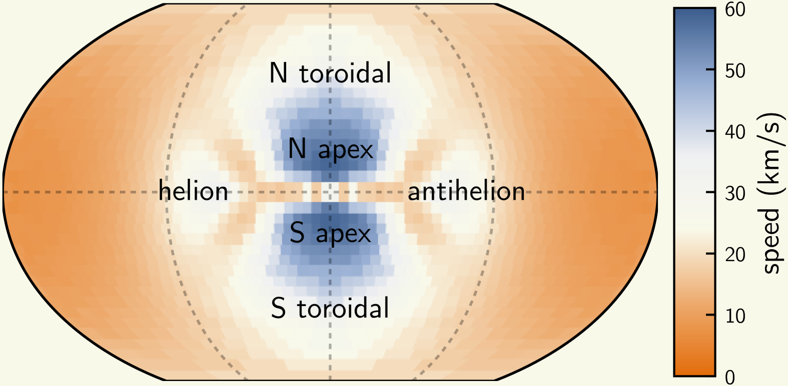


Speed distribution

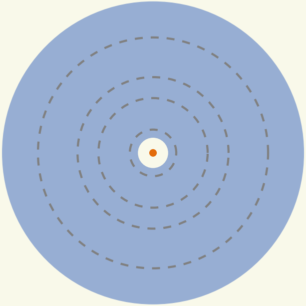


Velocity distribution

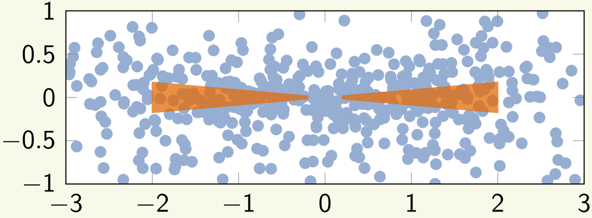
$$\frac{d}{d\theta}\frac{d}{d\phi}\frac{dF}{dv} \neq \frac{1}{F}\frac{dF}{d\theta} \times \frac{1}{F}\frac{dF}{d\phi} \times \frac{dF}{dv}$$



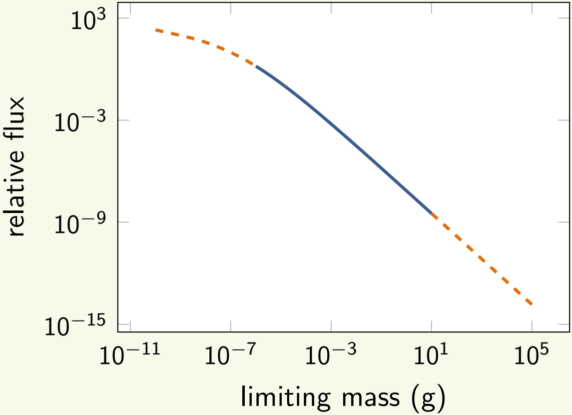
Limitations



- Limited to inner Solar System: 0.2 – 2 au
- Limited to ecliptic plane: within $\sim 5^\circ$ of the ecliptic

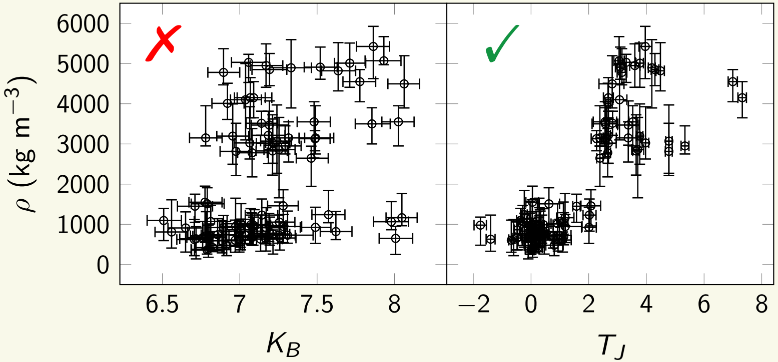


Limitation: 1 μg - 10 g



Meteoroid densities

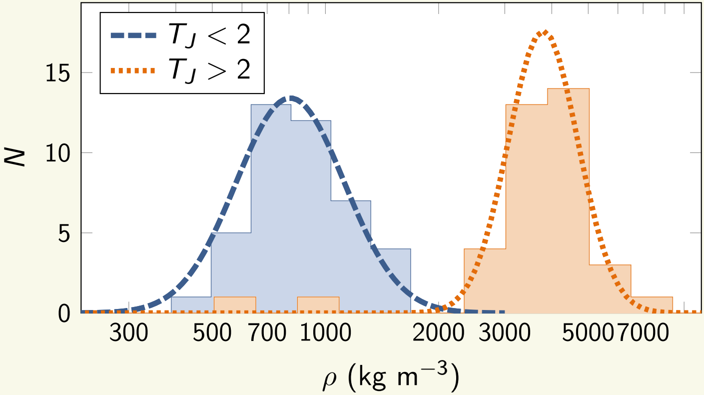
- Kikwaya et al. (2011) constrained densities for ~ 100 small meteoroids using ablation modeling.
- T_J appears to be a better proxy for density than K_B:



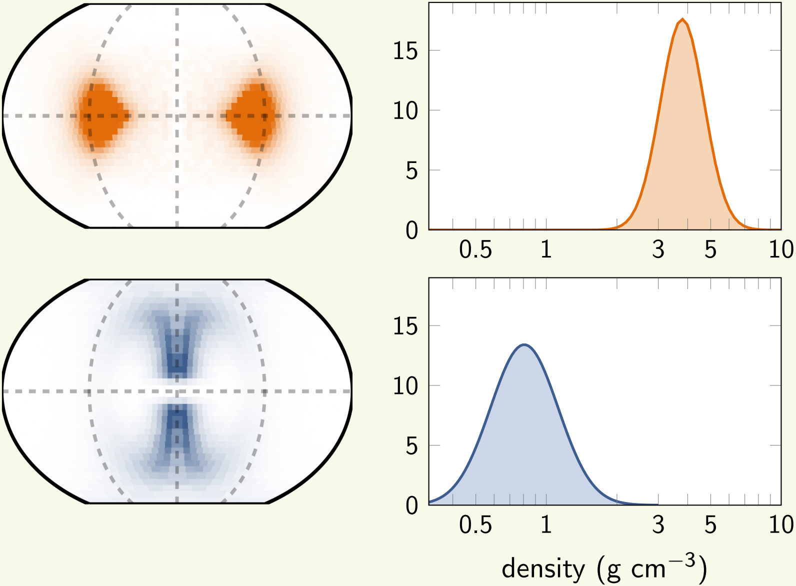
Density distribution

Moorhead et al. (2017)

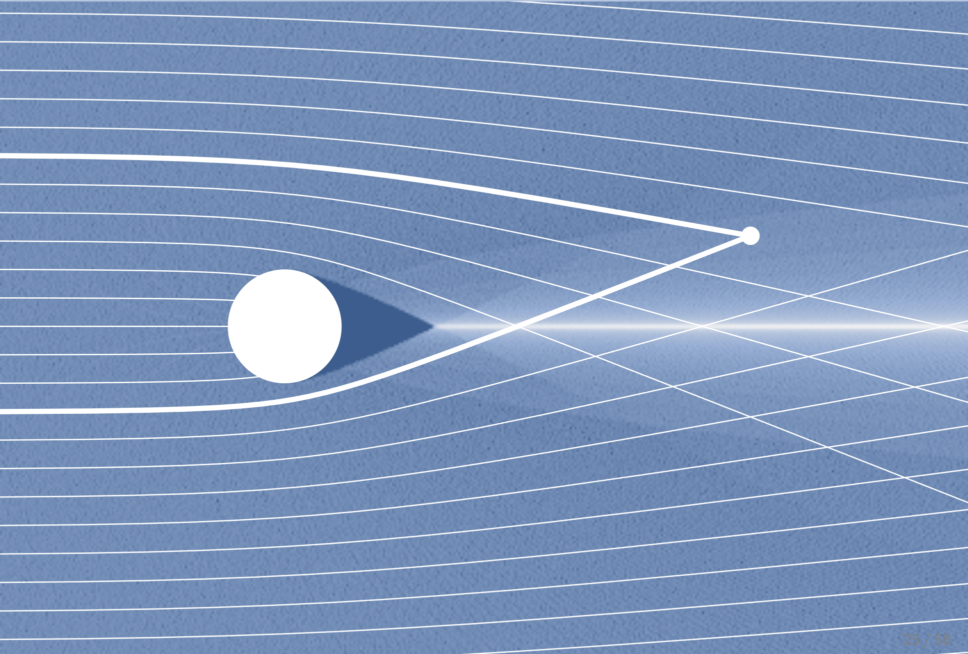
- We divide meteoroids into two groups and assign a density distribution to each:
  - $T_J < 2$ – HTCs, NICs – apex and toroidal
  - $T_J > 2$ – JFCs, asteroids – helion/antihelion



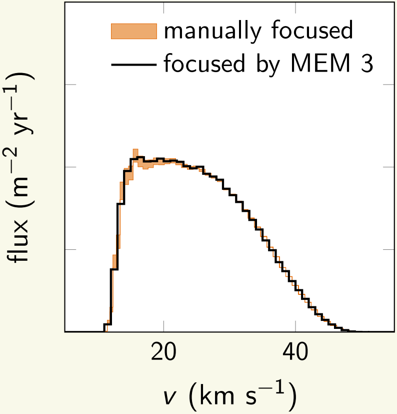
Density distribution



Local effects: gravitational focusing and shielding



Local effects: gravitational focusing and shielding



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

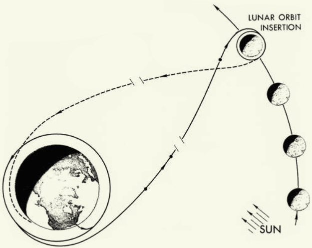
Overall, energy and angular momentum are conserved:

$$\frac{\text{flux}_1}{\text{flux}_2} = \left(\frac{\text{speed}_1}{\text{speed}_2}\right)^2$$

Local effects: gravitational focusing and shielding

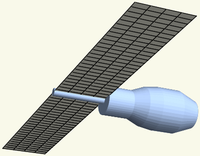
Grav. focusing is applied when your spacecraft within the Hill radius of a planet

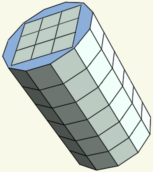
Massive bodies include all the inner Solar System planets and the Moon (but not asteroids, Martian moons, etc.)



Validation: *in situ* data

We used two sets of *in situ* data to validate MEM 3:
Pegasus and the Long Duration Exposure Facility (LDEF)





In each case we use the largest penetration or crater data available
(0.4 mm deep or 1 mm wide)

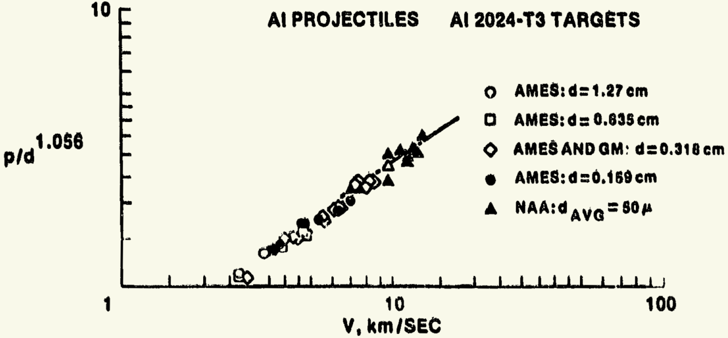
Validation: *in situ* data

Ballistic limit equations (BLEs) 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

BLE uncertainties



- CP BLE derived from Al-on-Al impacts at relatively low speeds
- scatter is $\lesssim 30\%$
- behavior at high speeds?
- behavior for non-metal particles?

Validation: *in situ* data

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

crater diameter:

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

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

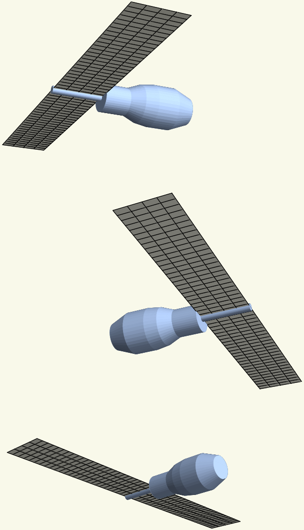
crater depth:

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

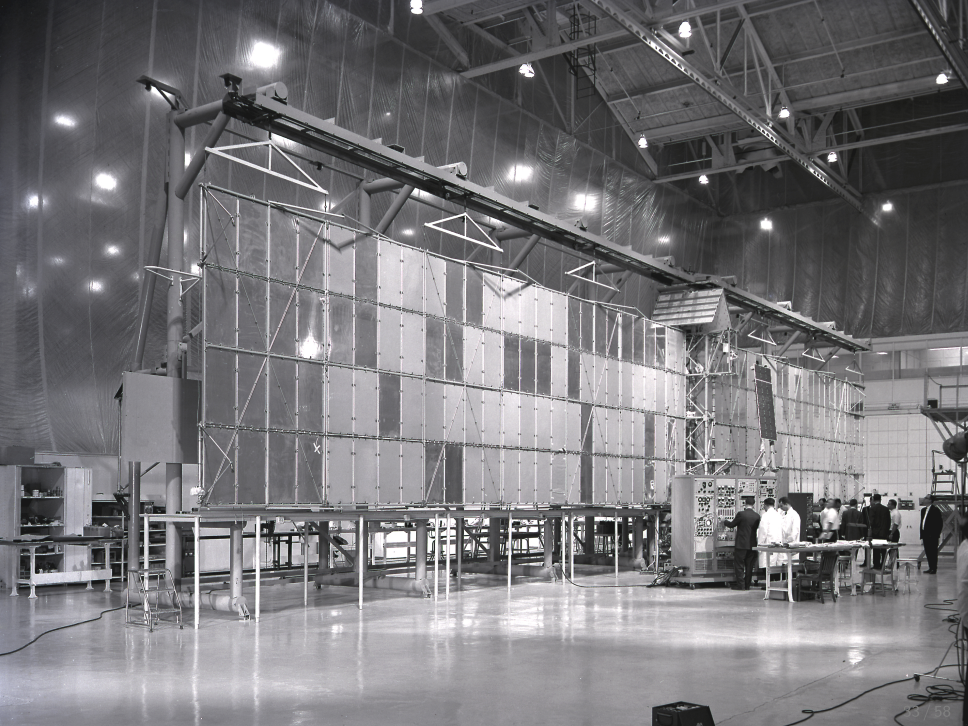
penetration thickness:

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

Pegasus



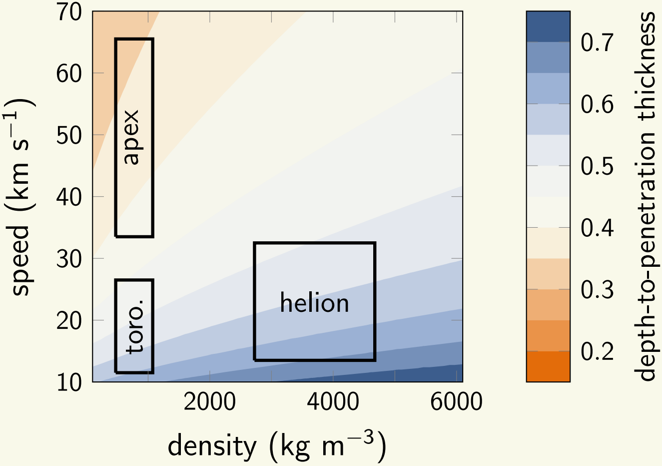
- **Year(s) data collected:**
  1965
- **Detection method:**
  penetration detectors
- **Relevant area:**
  over 200 m^2 (0.4 mm panels)
- **Attitude:**
  attitude information lost (assume randomly tumbling)
- **Material:**
  2024-T3 Al alloy



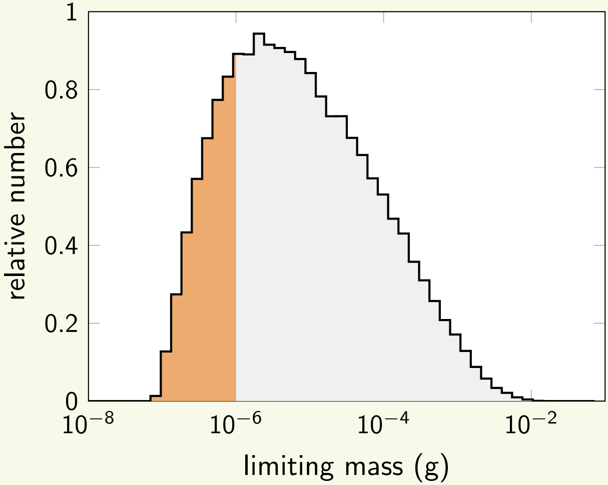
Pegasus: limiting penetration thickness

Cour-Palais: $p/t = 1/1.8 = 0.\overline{5}$

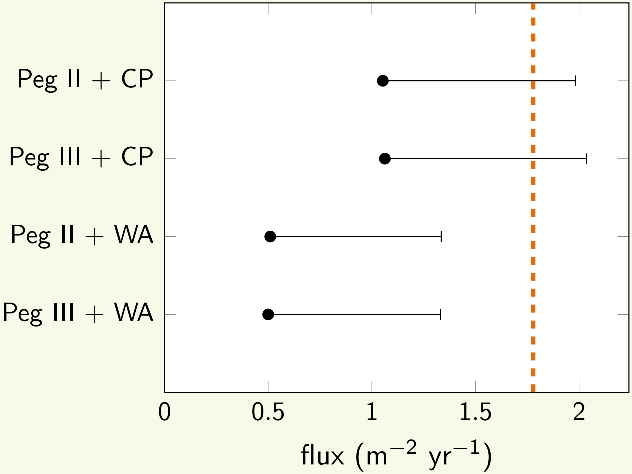
Watts & Atkinson:



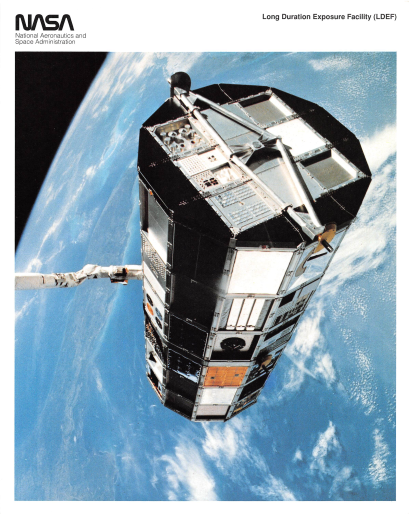
Pegasus: limiting masses



Pegasus results

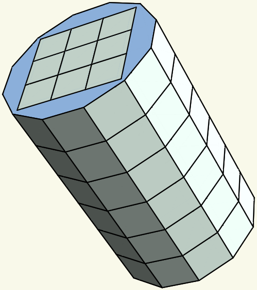


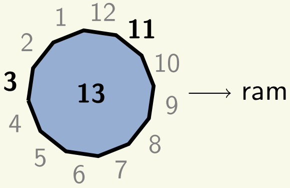
Long Duration Exposure Facility (LDEF)



- **Year(s) data collected:**
  1984 – 1990
- **Detection method:**
  examination of panels
- **Relevant area:**
  10.8 m^2
- **Attitude:**
  constant relative to orbit
- **Material:**
  6061-T6 Al alloy

Long Duration Exposure Facility (LDEF)



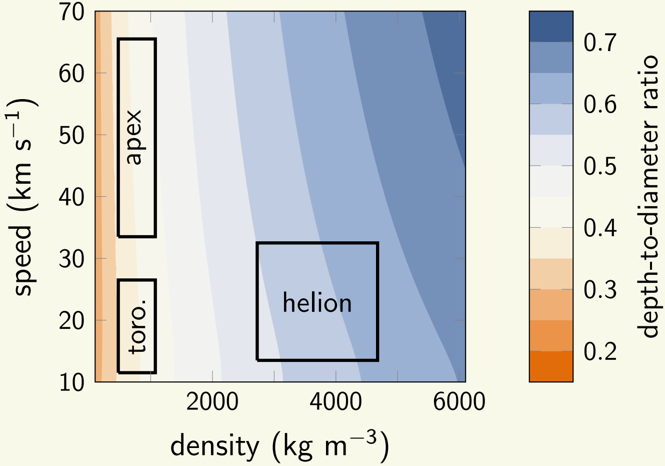


- Interested in largest craters (100 μm)
- Significant orbital debris present
- Orbital debris estimate available on three sides from smaller craters on CME

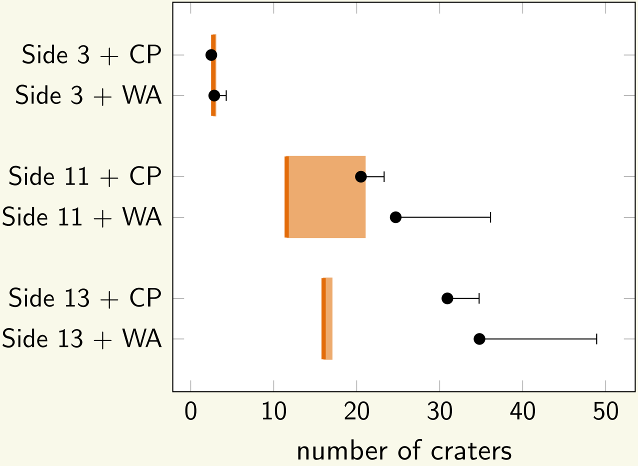
LDEF: depth-to-diameter ratio

Cour-Palais: $p/d = 0.5$ (based on observed morphology)

Watts & Atkinson:



LDEF results

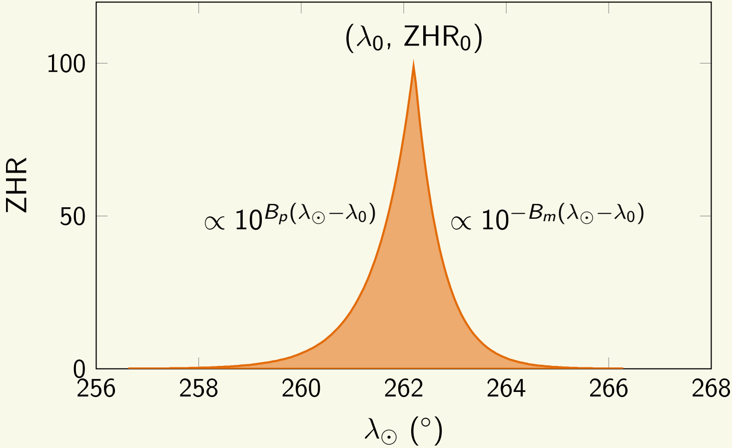


Summary: MEM

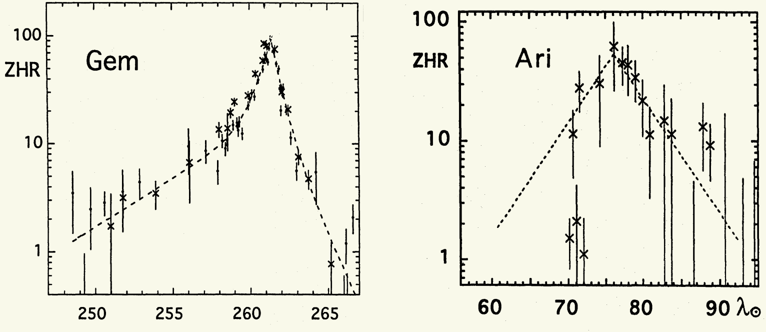
- The core of MEM is a dynamical model that recreates the sporadic sources
- Gravitational focusing and shielding and the spacecraft's motion and orientation are taken into account
- We have recently added a new bulk density distribution based on ablation modeling
- MEM 3 has now been validated against *in situ* data (Pegasus and LDEF)

Shower forecasting

- MEM's environment is time-invariant
- MEO shower forecast provides time-dependent shower fluxes
- These are derived from hourly rates (ZHRs)

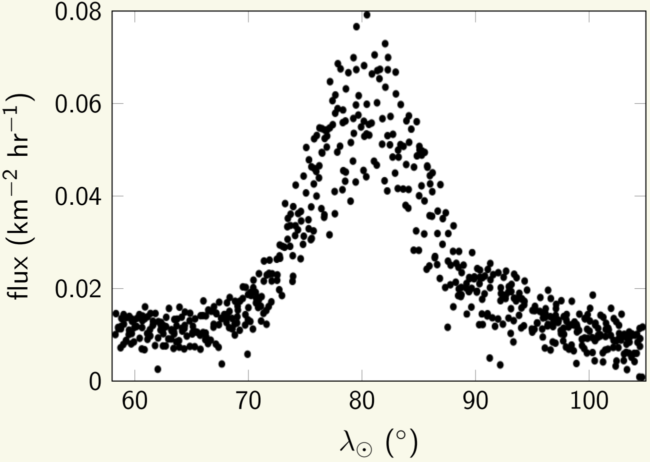


Original forecast parameters from Jenniskens (1994)



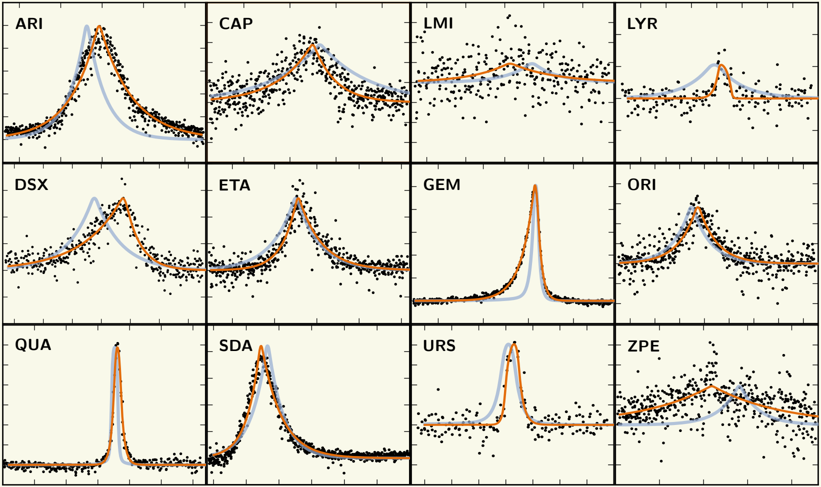
Plots from Jenniskens (1994)
Visual observations in both the northern and southern hemispheres.

14 years of CMOR data

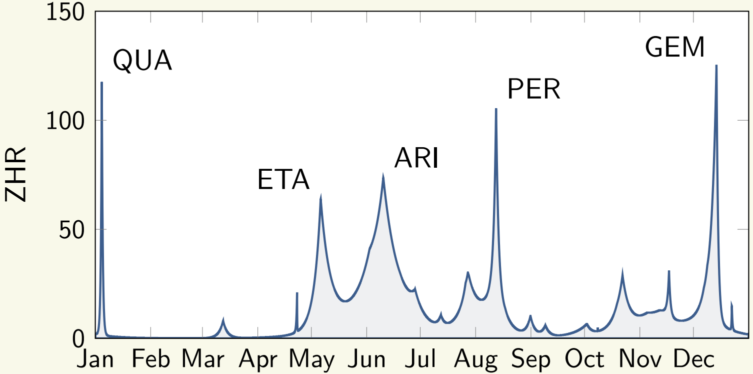


Improved showers

We were able to improve the activity profiles for 12 showers:



Total shower ZHR profile



ZHR to flux

Koschack & Rendtel, 1990

First, convert ZHR to magnitude-limited flux:

$$f_{6.5} = \frac{\text{ZHR} \cdot (13.1r - 16.5)(r - 1.3)^{0.748}}{37200 \text{ km}^2}$$

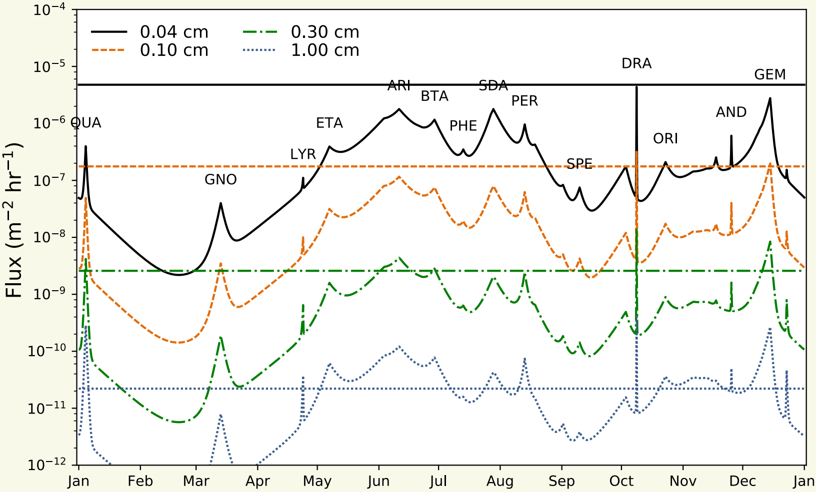
Second, convert magnitude-limited flux to mass-limited flux:

$$f_{\text{mg}} = f_{6.5} \cdot r^{9.775 \log_{10}\left(29 \text{ km s}^{-1} / v_{\text{TOA}}\right)}$$

Finally, scale to desired mass:

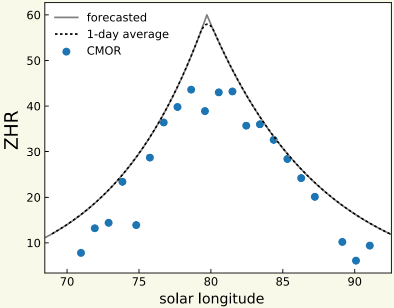
$$f_m = f_{\text{mg}} \left(\frac{m}{1 \text{ mg}}\right)^{-2.3 \log_{10} r}$$

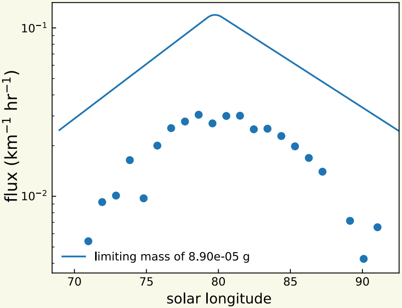
Total shower flux profile



Population indices

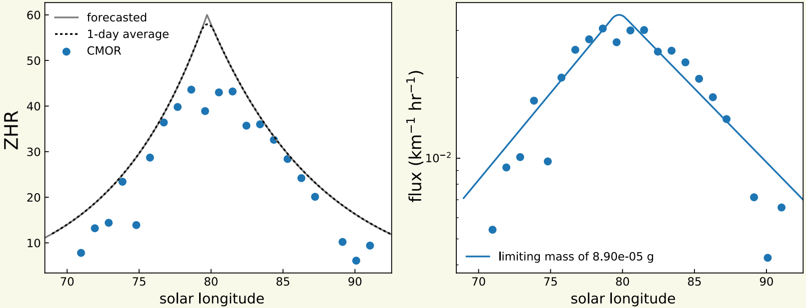
Arietids, $r = 2.7$
(value from default forecast list)





Population indices

Arietids, $r = 2.1$
(closer to Bruzzone et al., 2015)

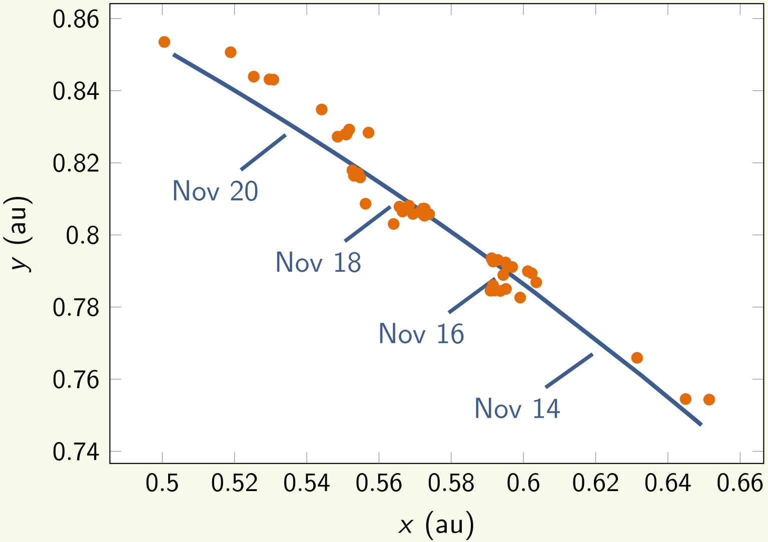


Variable showers

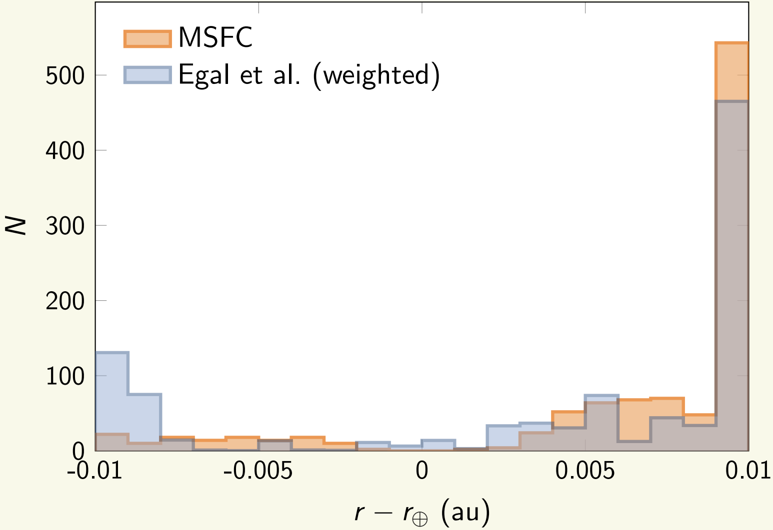
Artist's rendition of the 1833 meteor storm, from Bible Readings for the Home Circle.

1999 Leonids photo graphed from aircraft. NASA Ames/ISAS/ Shinsuke Abe and Hajime Yano

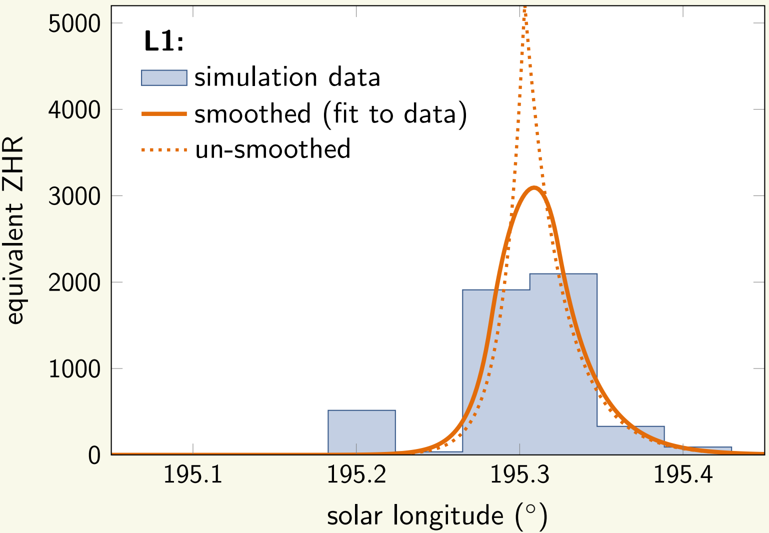
MSFC stream model



The Egal stream model
2018 Draconids

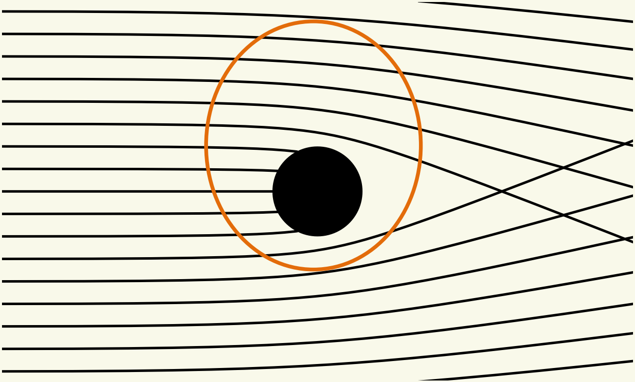


2018 Draconid advisory



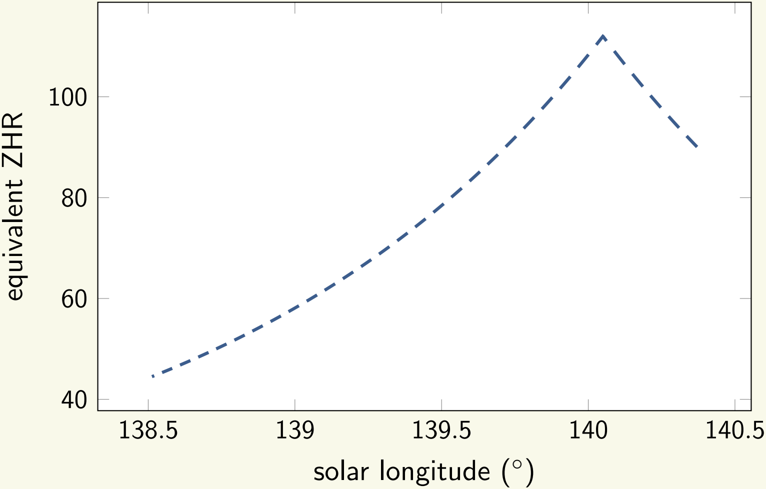
New forecast capabilities

Flux and apparent direction of meteoroid flux varies with spacecraft position:



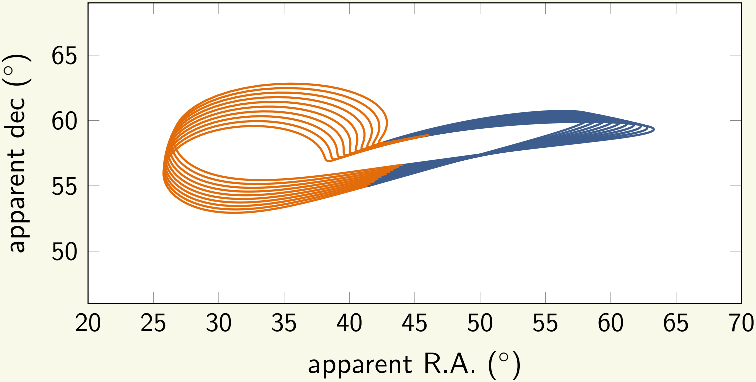
Spacecraft-specific rate

Perseid ZHR encountered by an ISS-like spacecraft:



Aberrated radiant and radiant drift

The shower radiant drifts in R.A. and dec.
The *apparent* radiant also depends on spacecraft speed
(this is the aberrated radiant)



Summary: shower forecast

- Shower forecasts are used by spacecraft operators to determine whether mitigation is necessary.
- Lower fidelity than MEM
- Shower parameters based on typical shower activity and numerical models of shower streams
- Forecast capabilities have been expanded recently to tailor results to specific spacecraft