Modeling hazardous meteoroids with NASA's Meteoroid Engineering Model (and shower forecasts)

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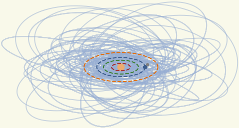
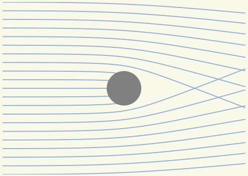
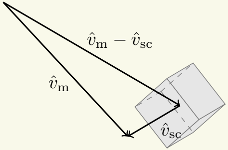
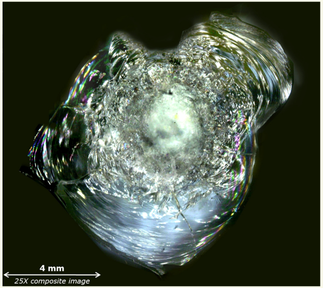
NASA/GSFC Heliophysics Science Division Seminar
6 March 2020







Meteoroids damage spacecraft.



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		

meteoroid impact crater image provided by the NASA/JSC Hypervelocity Impact Technology (HVIT) Team
grade stainless loose ball bearings by Oleksandr Panasovskyi from the Noun Project
strike by Randomhero from the Noun Project
watermelon by Blaise Sewell from the Noun Project
wrecking ball crane by Gan Khoon Lay from the Noun Project

Spacecraft require protection against meteoroids such as a Whipple shield.

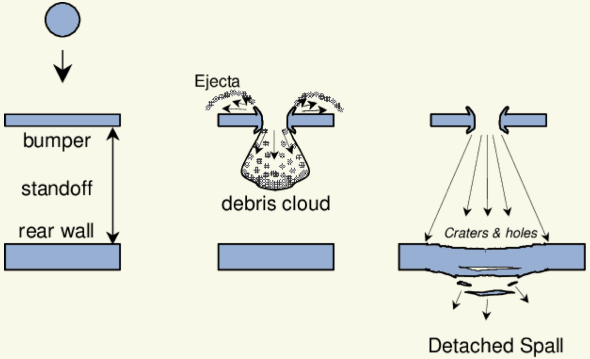
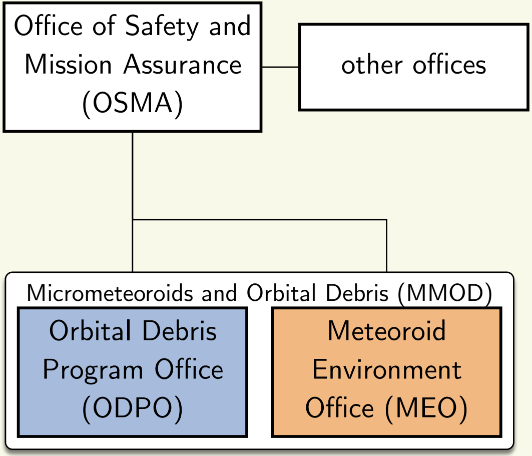


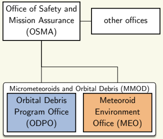
Diagram adapted from Ryan & Christiansen (2015)

Too much shielding = wasted weight

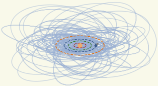
The MEO models the meteoroid environment to support risk assessments and hazard mitigation.



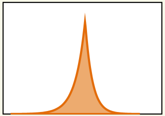
Outline of this talk



Meteoroid Environment Office (MEO):
What is the MEO?
What does the MEO do?



Meteoroid Engineering Model (MEM):
description, recent improvements,
comparison with observations



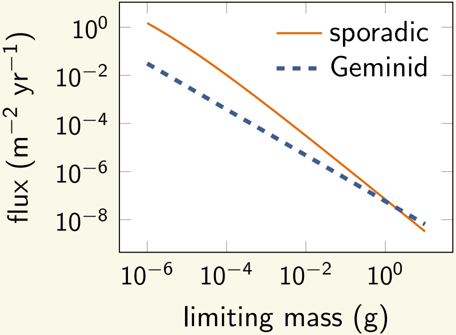
Meteor shower forecasting:
description, recent improvements

We model shower and sporadic meteoroids separately.

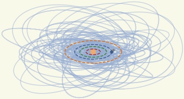
Photographs by David Kingham

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

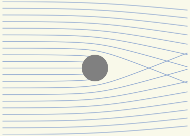
Sporadic meteors occur at any time, have varied orbits, and pose more risk.



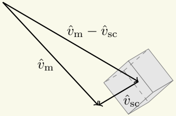
The Meteoroid Engineering Model (MEM) does the following:



models meteoroid orbits



determines the local environment

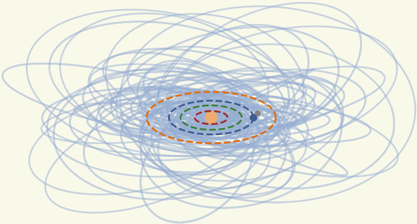


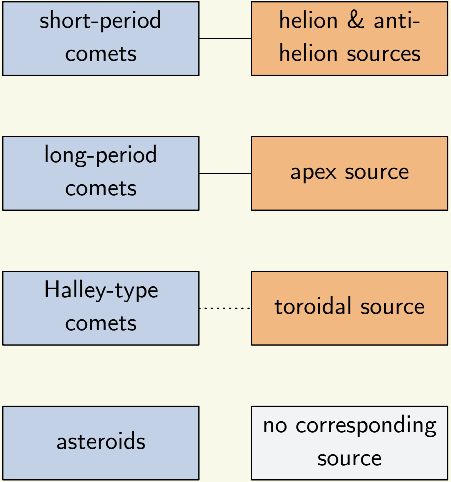
outputs the environment relative to a spacecraft

MEM's meteoroid orbits are derived from comets.

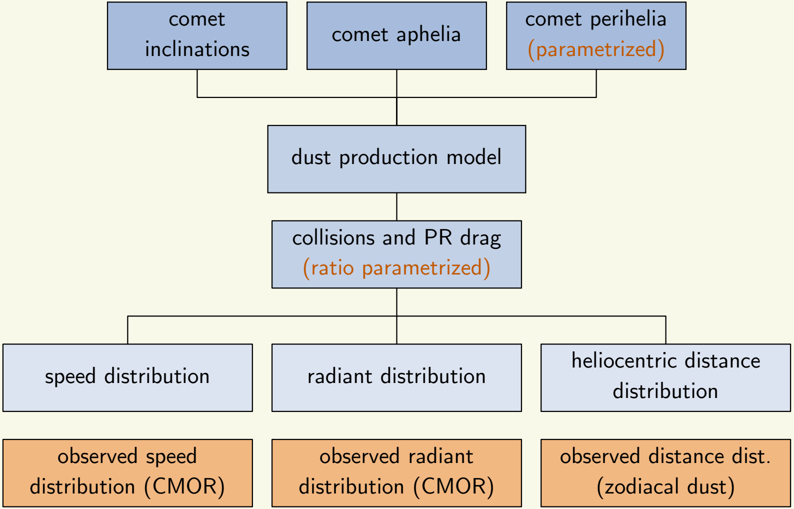
Jones (2004) linked parent populations to observed distributions, taking radiative forces and collisions into account.

These orbits have not changed since 2004.

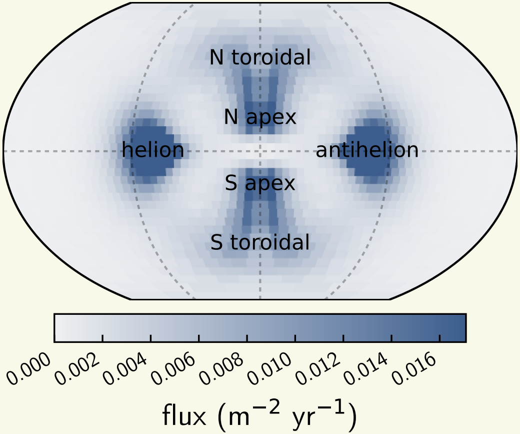




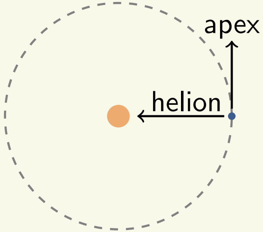
Meteoroid orbits evolve due to radiation and collisions.



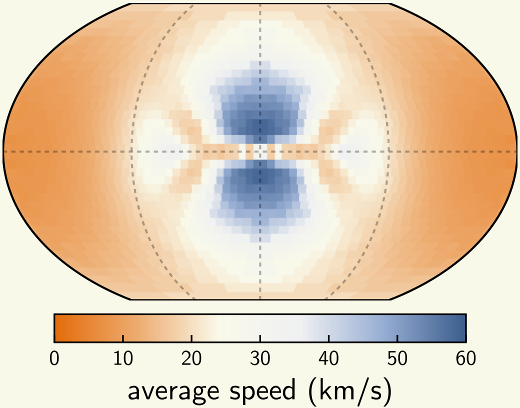
Meteoroid directionality is not isotropic.

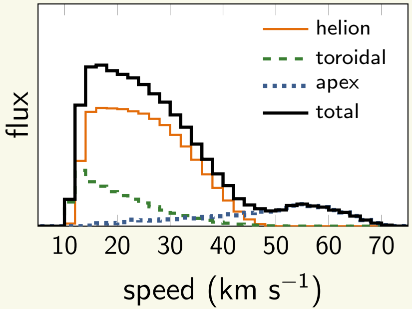


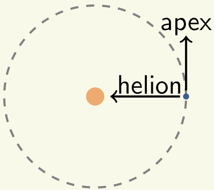
The three orbit populations appear as six "sources" (three pairs) in this directional map.



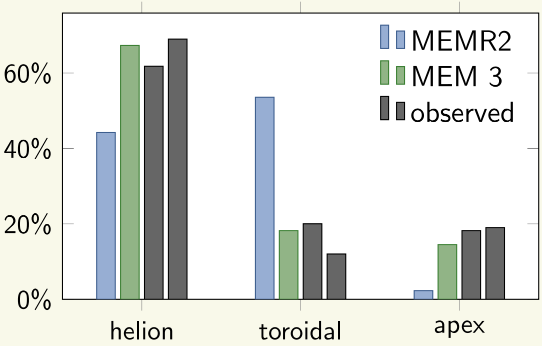
Each population has its own speed distribution.

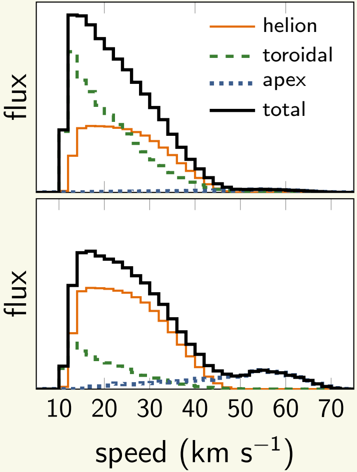






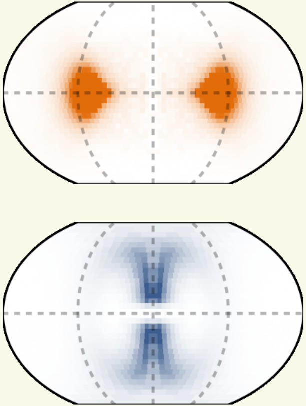
The sources have been reweighted to match Campbell-Brown (2008).

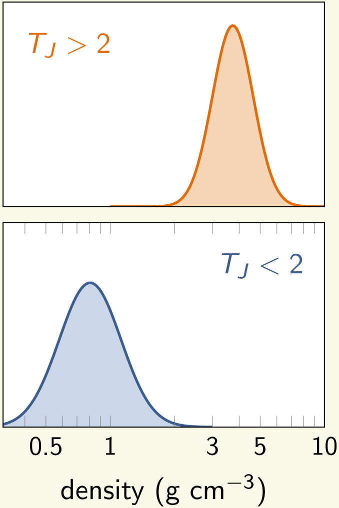




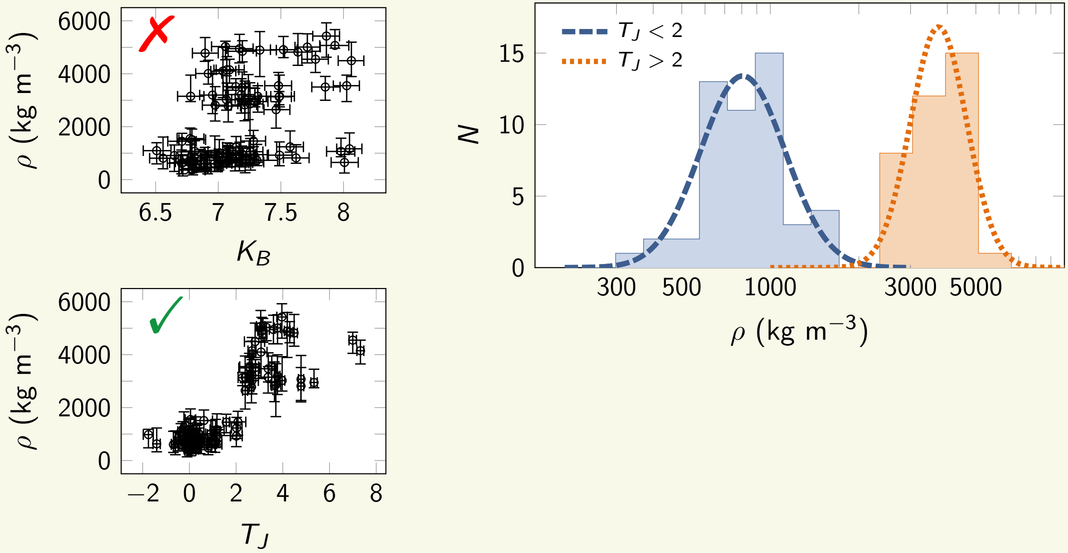
This re-weighting of the orbital populations changes the speed distribution.

The meteoroid sources also have different bulk densities.

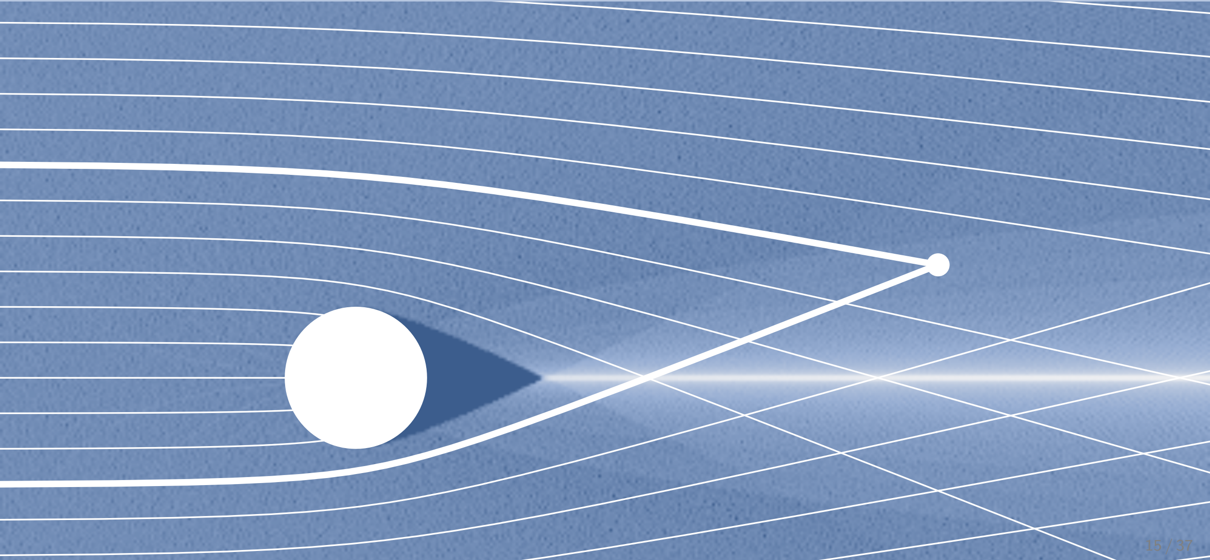




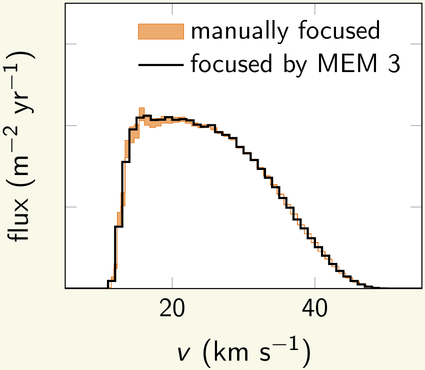
Meteoroid densities are based on Kikwaya et al., 2011.



MEM modifies local environments by including gravitational focusing and planetary shielding.



MEM 3 conserves energy and angular momentum



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

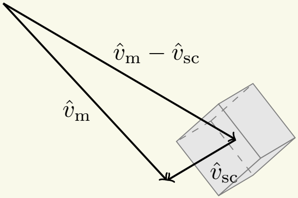
Overall, energy and angular momentum are conserved:

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

MEM 3 passes this test; MEMR2 does not.

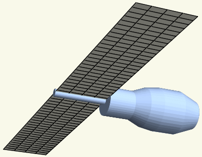
See, e.g., Jones & Poole, 2007

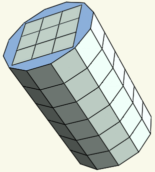
MEM outputs the environment seen by a spacecraft.



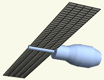
MEM quotes the meteoroid flux, speed, and direction relative to a spacecraft trajectory.

Thus, we used *in situ* data to validate MEM: specifically, Pegasus and the Long Duration Exposure Facility

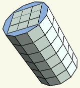




We ran MEM 3 for two *in situ* missions.

Pegasus 

- **Year(s) data collected:**
  1965 (no orbital debris)
- **Purpose:**
  measure meteoroid flux
  before the Apollo missions
- **Detection method:**
  penetration detectors
- **Relevant area:** over 200 m^2
- **Attitude:** info lost
  (assume randomly tumbling)
- **Altitude:** 441 – 740 km

LDEF 

- **Year(s) data collected:**
  1984 – 1990 (debris present)
- **Purpose:**
  measure long-term space environment effects
- **Detection method:**
  examination of panels
- **Relevant area:** 10.8 m^2
- **Attitude:**
  constant relative to orbit
- **Altitude:** 500 km

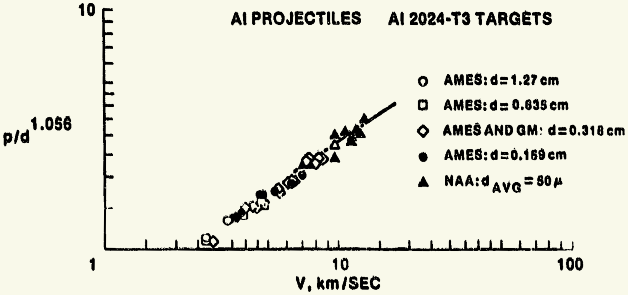
MEM's outputs are designed to be used with damage equations.

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:

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

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

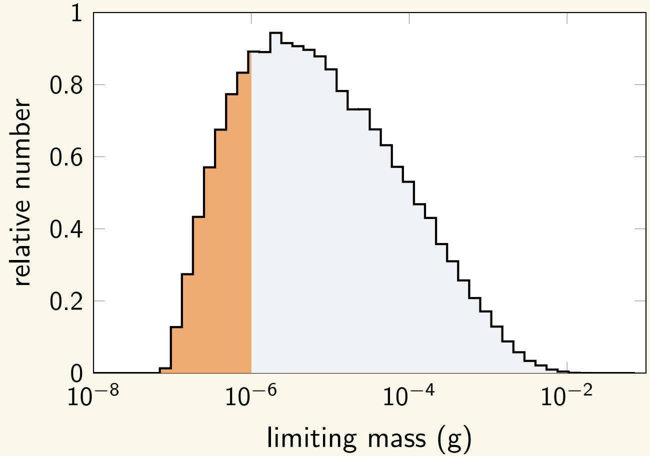
crater depth:

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

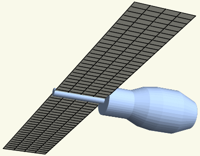
penetration thickness:

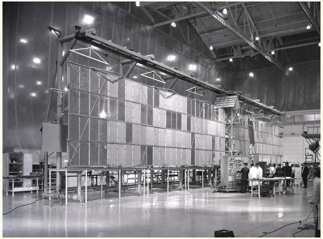
$$t_t = \frac{fd}{4} \left(\frac{1}{6} \frac{\rho}{Y_t} \left(c_{0,t} + \frac{s(v_\perp - v_0)}{1 + \sqrt{\rho_t/\rho}} \right) (v_\perp - v_0) \right)^{1/3} + \frac{fd}{4} \frac{v_\perp}{v_0} \sqrt{\frac{Y_t}{\sigma_t}}$$

We'll need to extend MEM beyond its mass range for both missions.

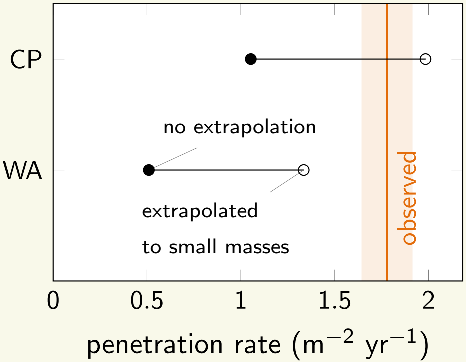


MEM 3 underpredicts the rate measured by Pegasus.

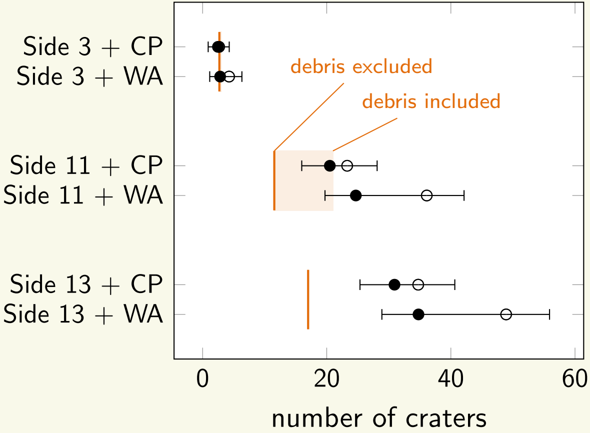


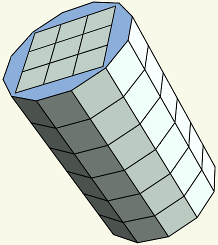


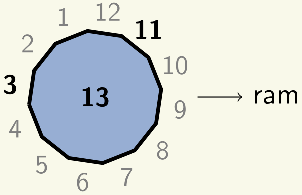
We used two damage equations (CP vs. WA) and two mass extrapolation methods (solid vs. open).
In 3/4 cases, MEM 3 is lower.



MEM 3 overpredicts the number of craters on LDEF.

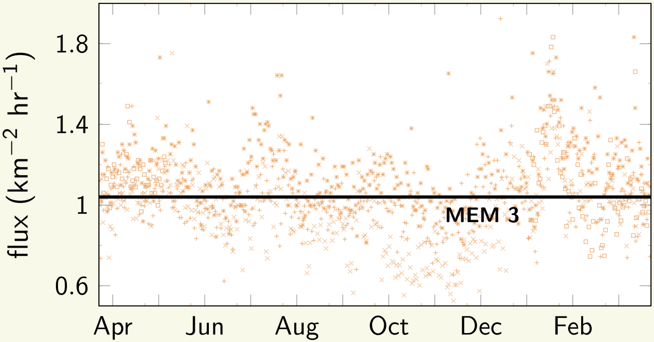




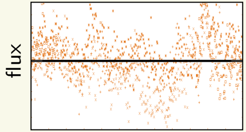


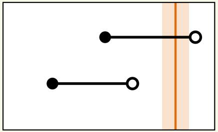
MEM 3 matches the observed meteor flux at Earth.

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

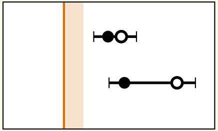


MEM 3 matches the combination of data that is available.





penetration rate



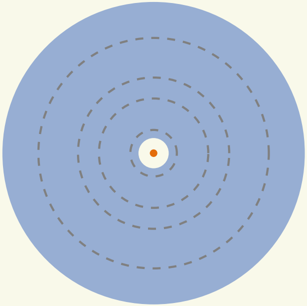
number of craters

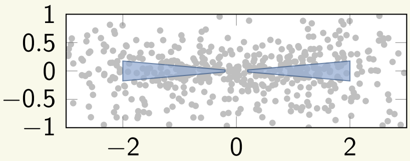
MEM is a physics-based meteoroid environment model that is designed to support spacecraft risk assessments.

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.

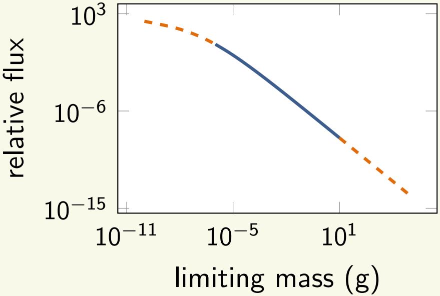




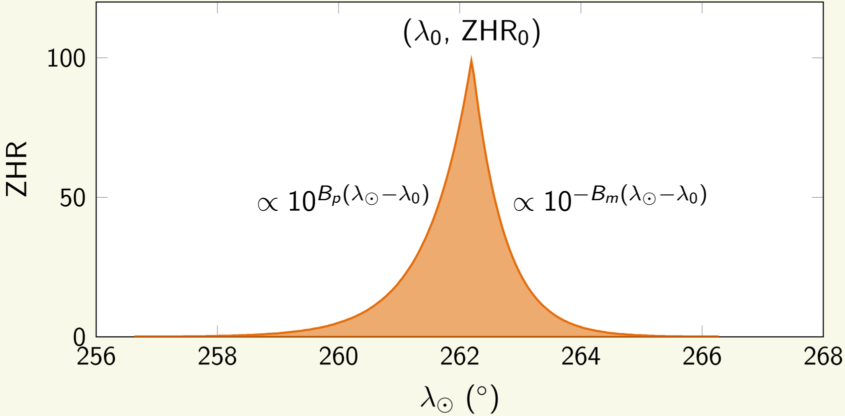
Limited to inner solar system: 0.2 – 2 au

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

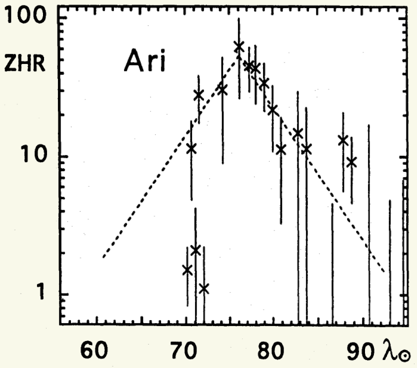
Limited to $> 10^{-6}$ g



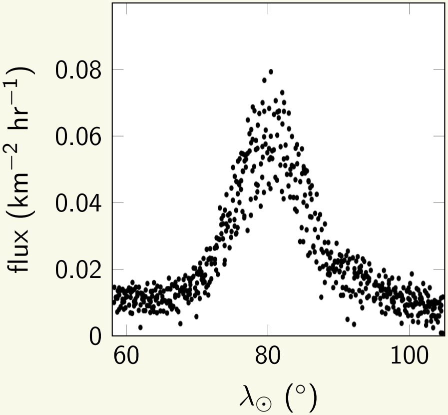
MEM does *not* include meteor showers; those are covered separately in our shower forecasts.



The shower activity profile is critical for forecasting.

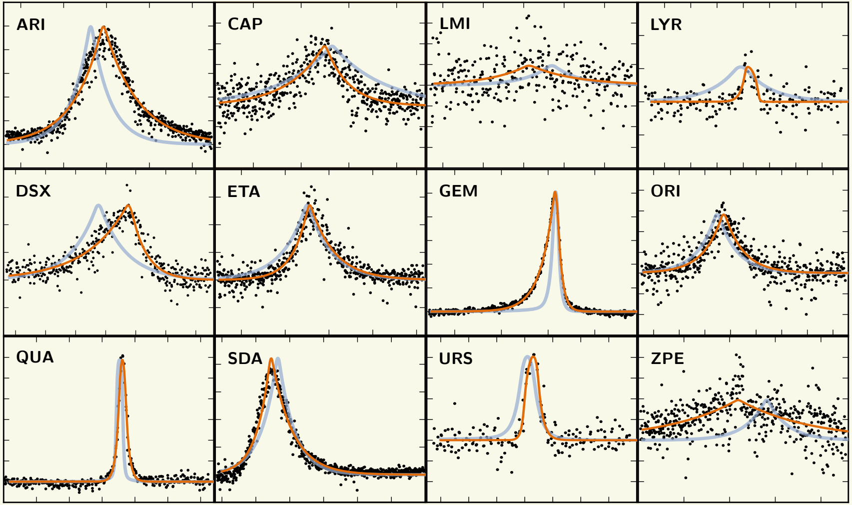


visual observations,
Jenniskens (1994)

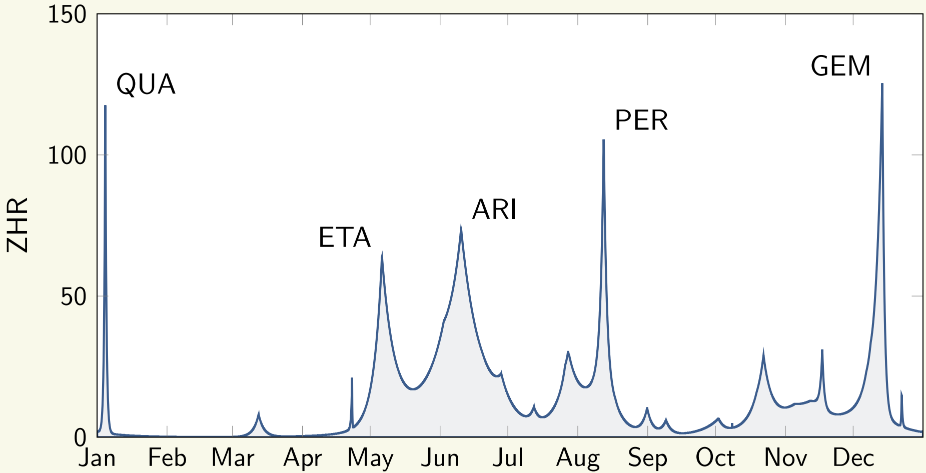


CMOR observations,
Moorhead et al. (2016)

Using CMOR data, we were able to improve the activity profiles for 12 major showers.



We use these profiles to forecast shower activity over the course of a year.



However, ZHR is the *visual* rate; we must convert to flux (Koschack & Rendtel, 1990).

First, convert ZHR to magnitude-limited flux:

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

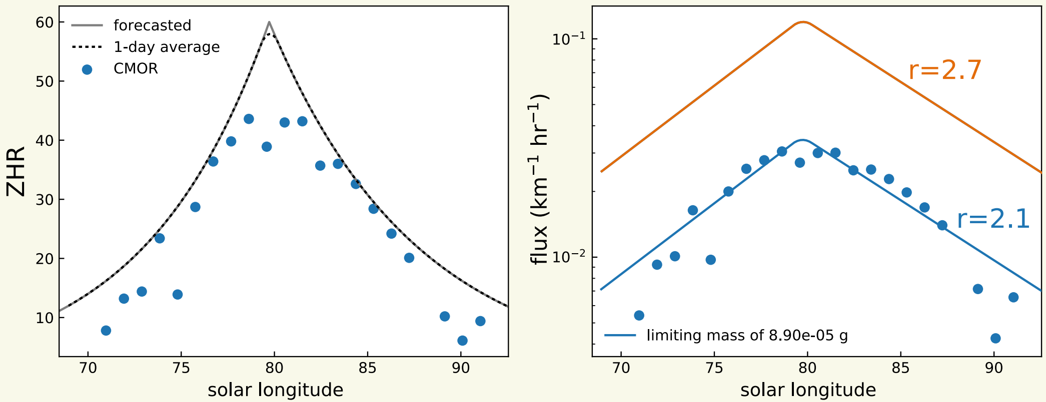
Second, convert magnitude-limited flux to mass-limited flux:

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

Finally, scale to desired mass:

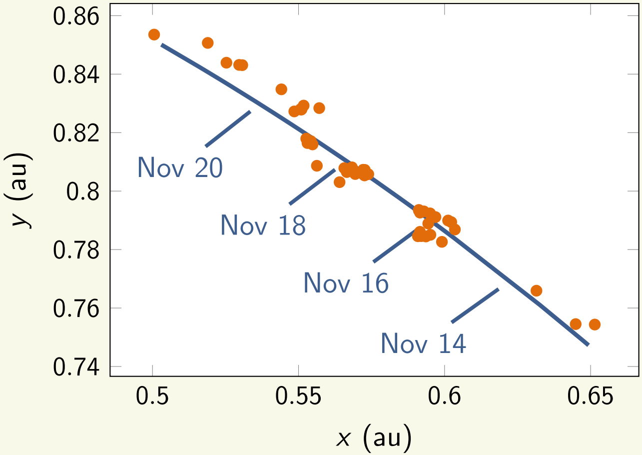
$$f_m = f_{\mathrm{mg}} \left(\frac{m}{1\ \mathrm{mg}}\right)^{-2.3 \log_{10} r}$$

An incorrect population index results in an incorrect prediction.



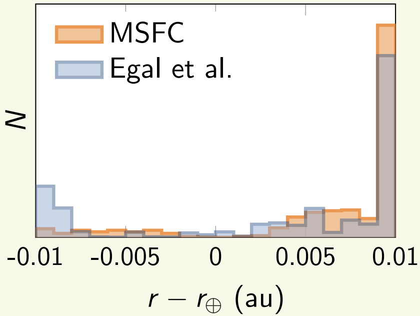
We conduct numerical simulations in order to predict shower outbursts.

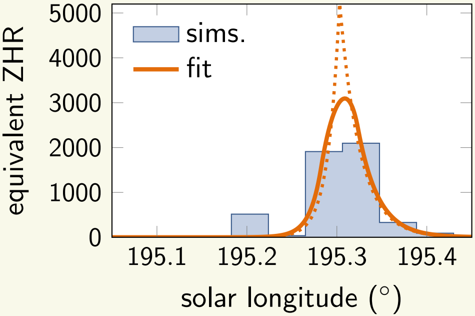
MSFC stream model results for the Leonids in 2019



Particularly tricky showers may require more extensive modeling.

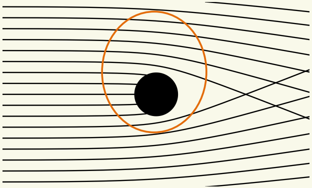
We and colleagues at the University of Western Ontario conducted detailed simulations of the Draconids in advance of our 2018 and 2019 forecasts.



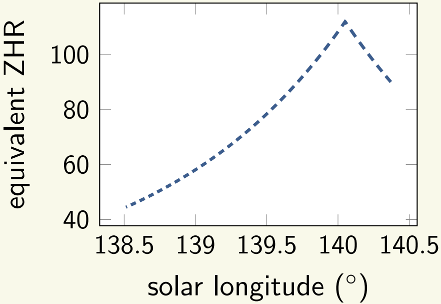


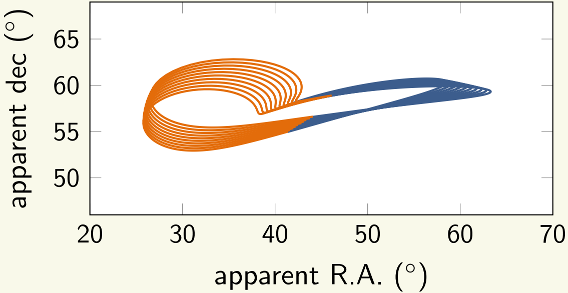
Based on these simulations, we issued an advisory for the Sun-Earth L1 point.

We can now also generate spacecraft-specific forecasts.

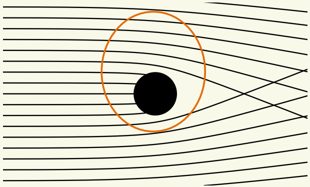


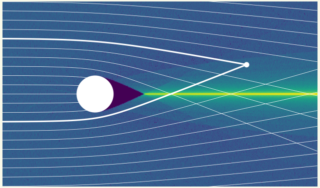
Meteoroid flux and apparent direction (aberrated radiant) vary with spacecraft position.





MEM and our forecasts are beginning to converge.





Both MEM and the forecasts include many of the same algorithms.

We are looking at merging the two code bases to better align the two models.