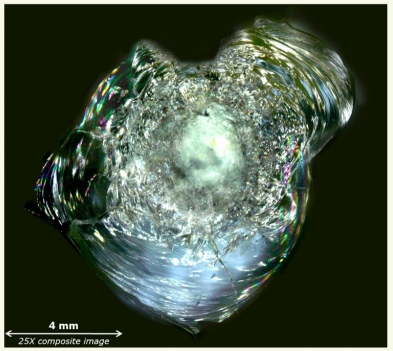
Overview of the Meteoroid Environment

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NASA Meteoroid Environment Office
william.j.cooke@nasa.gov

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)



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

Sources of meteoroids



Comets (>90%)



Asteroids

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

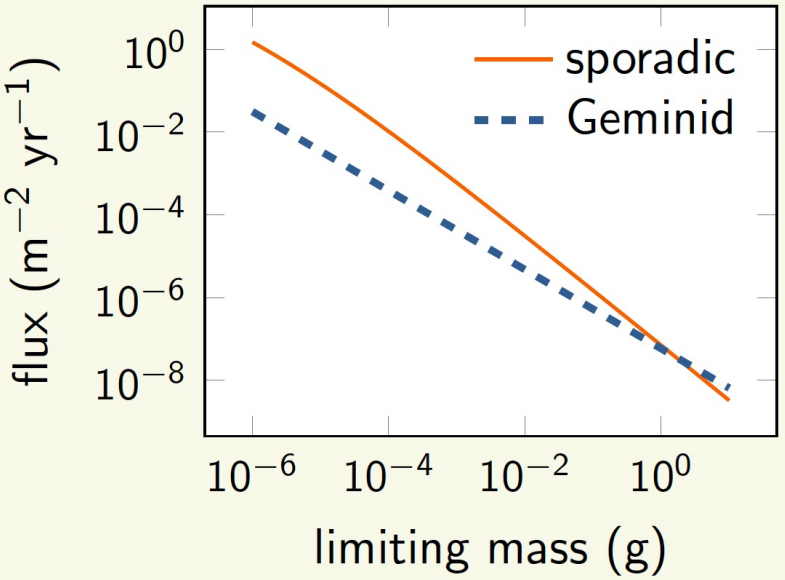
Shower and sporadic meteoroids



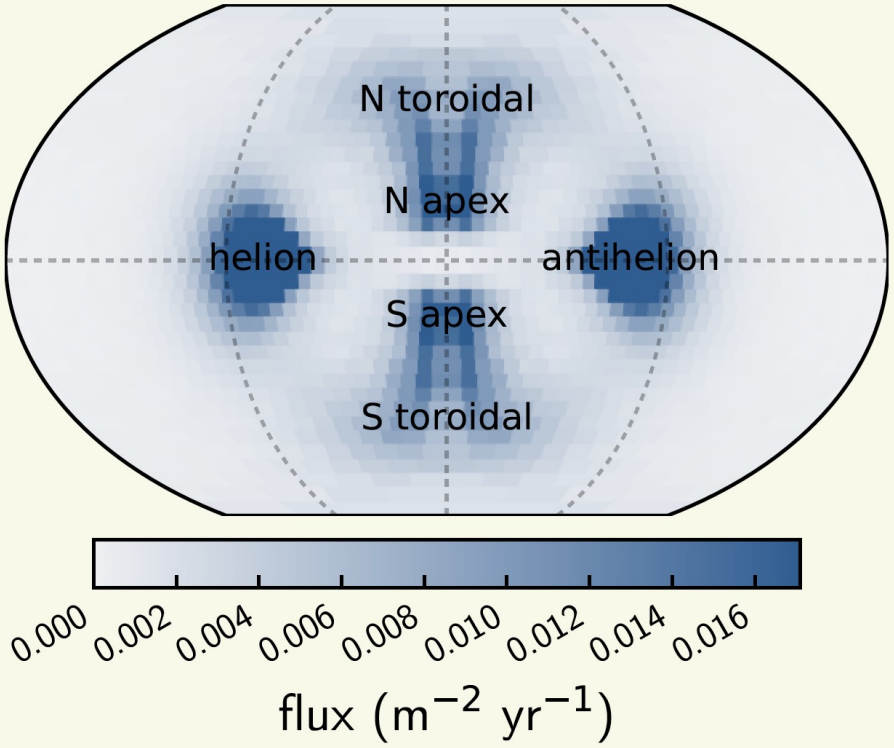
Photographs by David Kingham

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

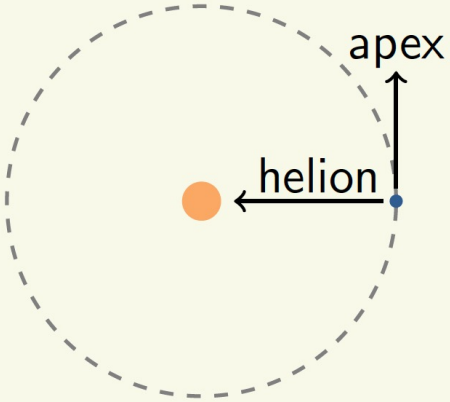
Sporadic meteors occur at any time, have varied orbits, and pose more risk.



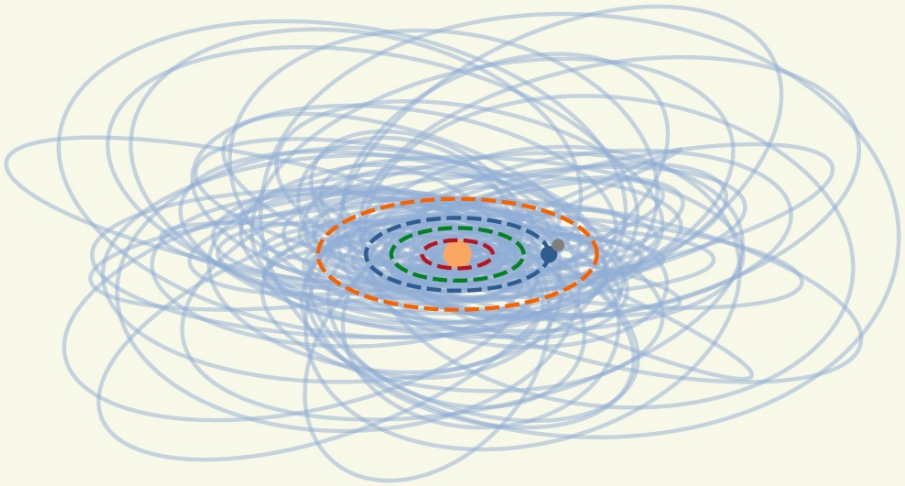
Meteoroid directionality is not isotropic.



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

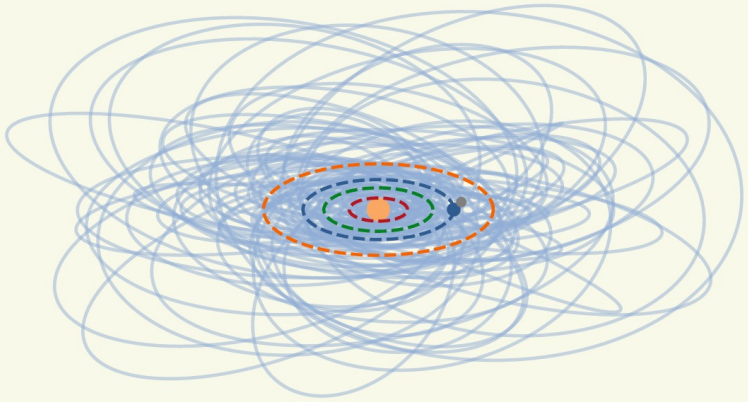


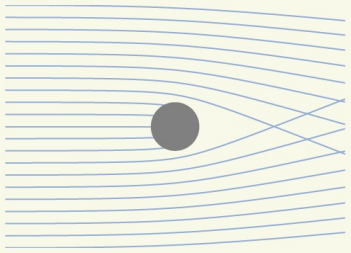
Sporadic directionality is dynamically linked to specific classes of objects

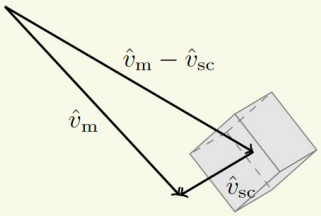


short-period comets	helion & anti-helion sources
long-period comets	apex source
Halley-type comets	toroidal source
asteroids	no corresponding source

The Meteoroid Engineering Model



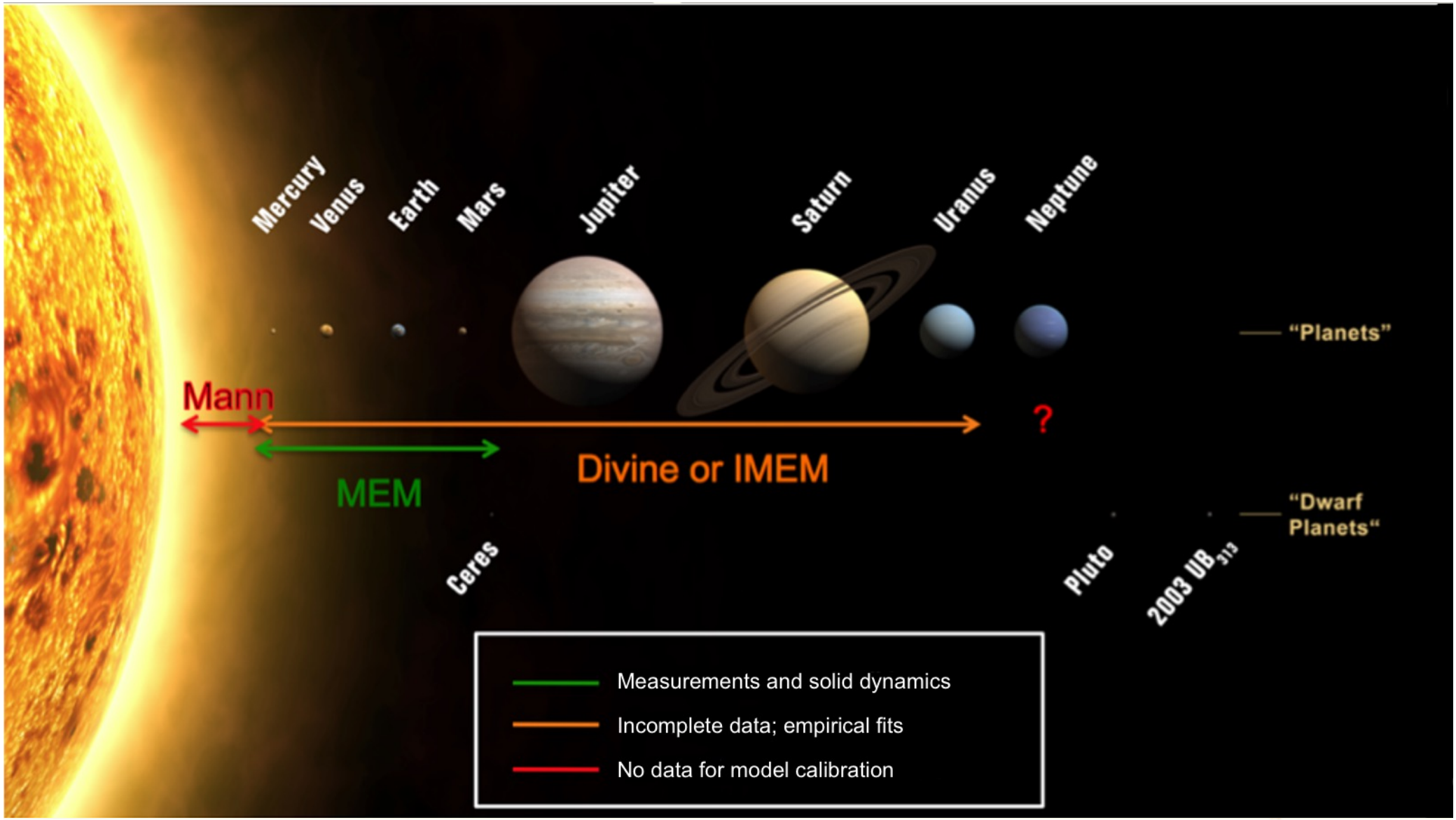




Meteoroid models primarily consist of populations of meteoroid orbits. The environment varies across interplanetary distances, not km, which allows us to extrapolate from Earth-based observations.

The gravity and size of the Earth and Moon affect the local environment, and the spacecraft's motion factors in to the apparent velocity of the meteoroids it encounters.

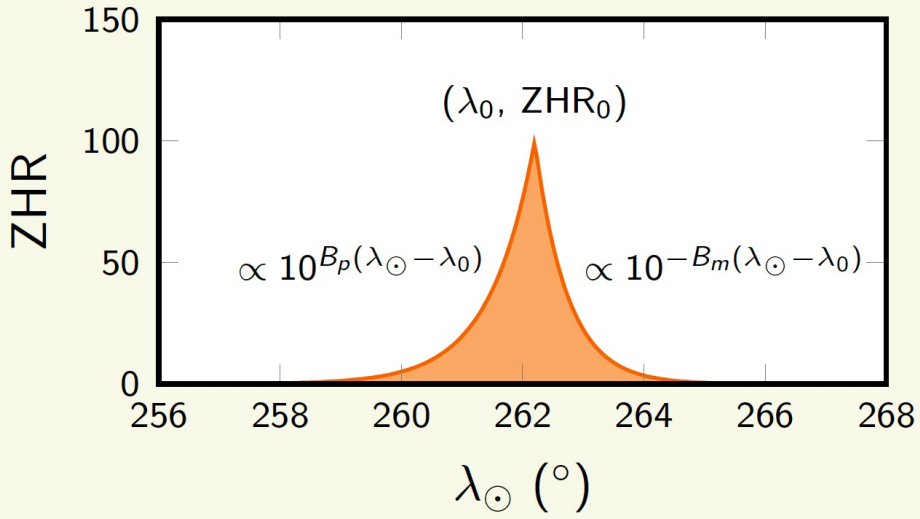
MEM then describes the resulting environment relative to a given spacecraft trajectory [ref, ref, ref, ref, ref].

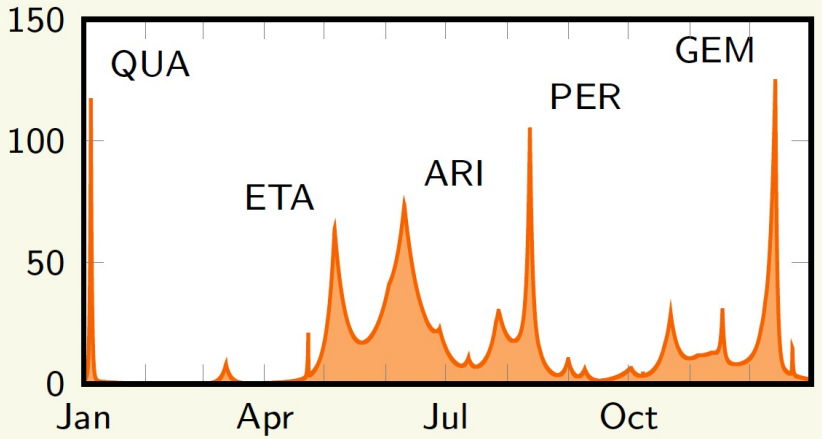

Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
"Planets"
Mann
?
Divine or IMEM
MEM
"Dwarf Planets"
Ceres
Pluto
2003 UB313
Measurements and solid dynamics
Incomplete data; empirical fits
No data for model calibration

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

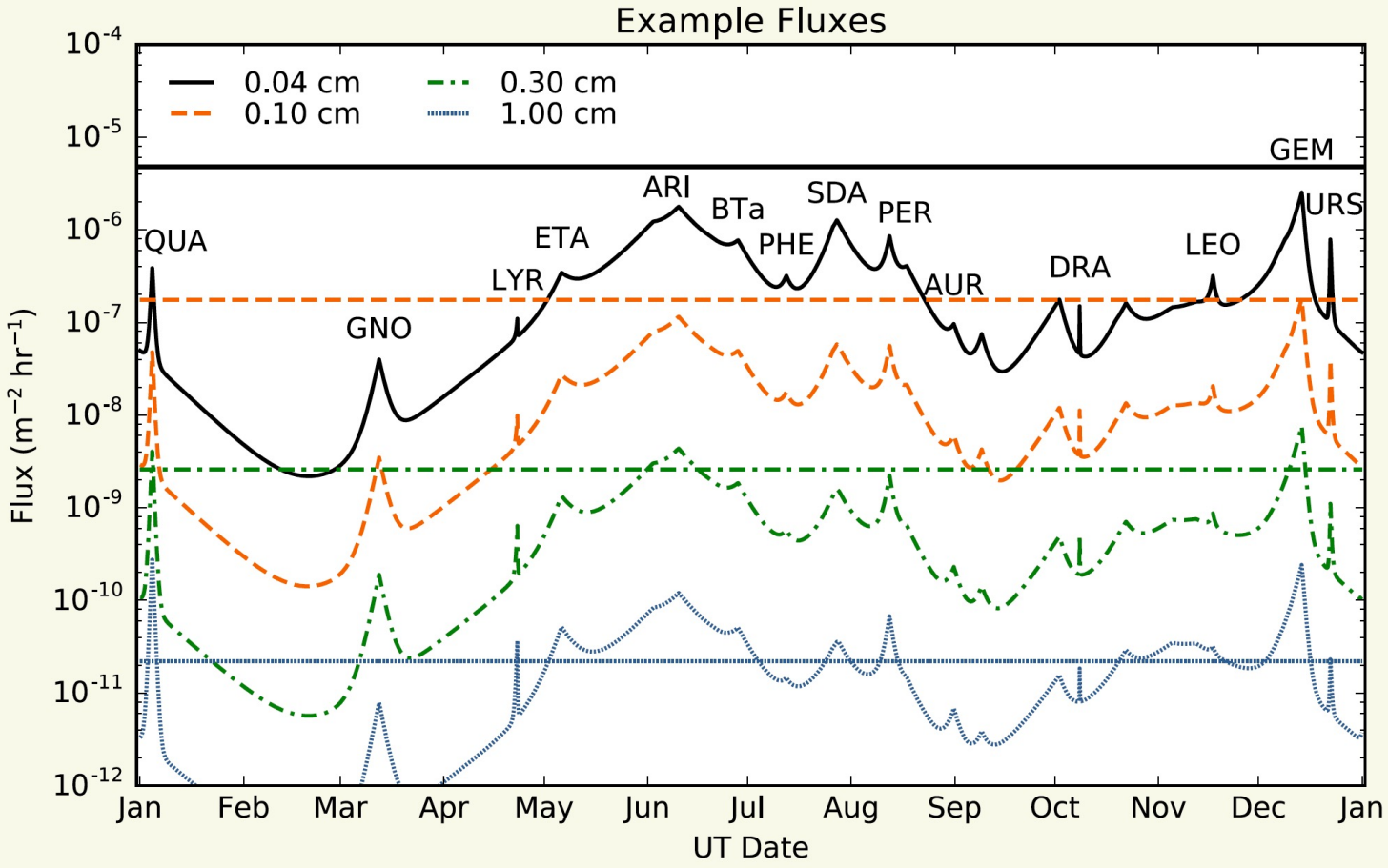




hi

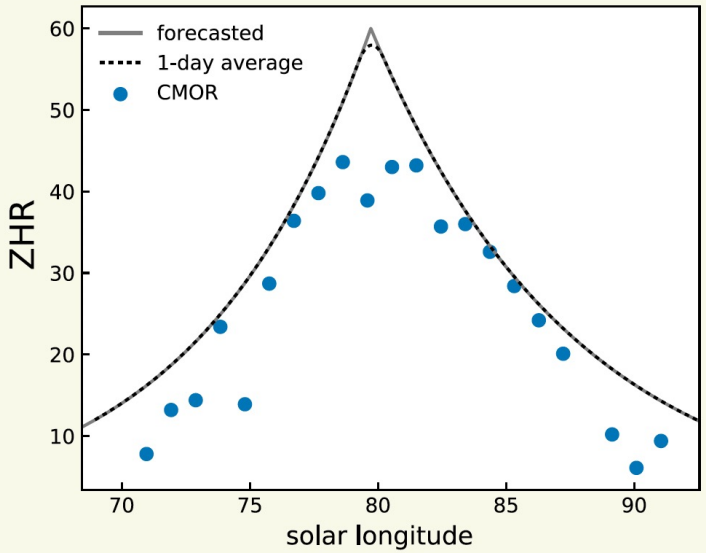
Can do custom forecasts for spacecraft in Earth/lunar orbit

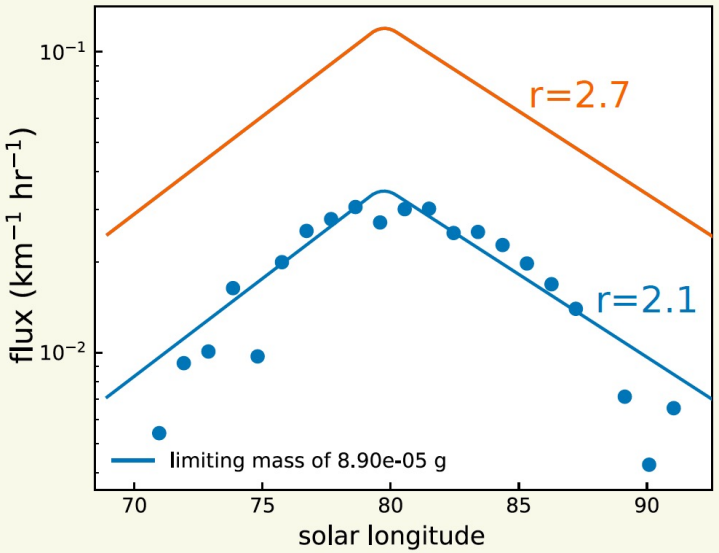
Can also generate for specific locations on lunar surface



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).

Meteoroids are not rocks

The overwhelming majority of meteoroids are relatively fragile, porous conglomerates of particles held together by ”organic glue”

They have extremely low RCS and albedo – no public confirmation of any in-space meteoroid detection by a ground-based sensor (JPL has been looking with Goldstone for the past 2 years and found nothing)

We study meteoroids through proxies – the light/ionization they produce when ablating in planetary atmospheres or the damage caused by impacts with surfaces

Hughes, 1976

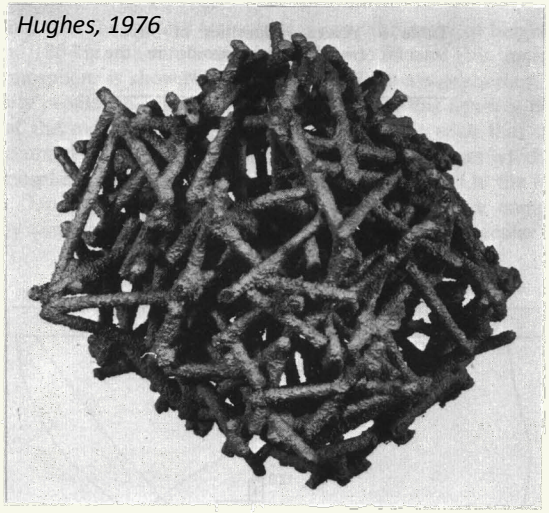
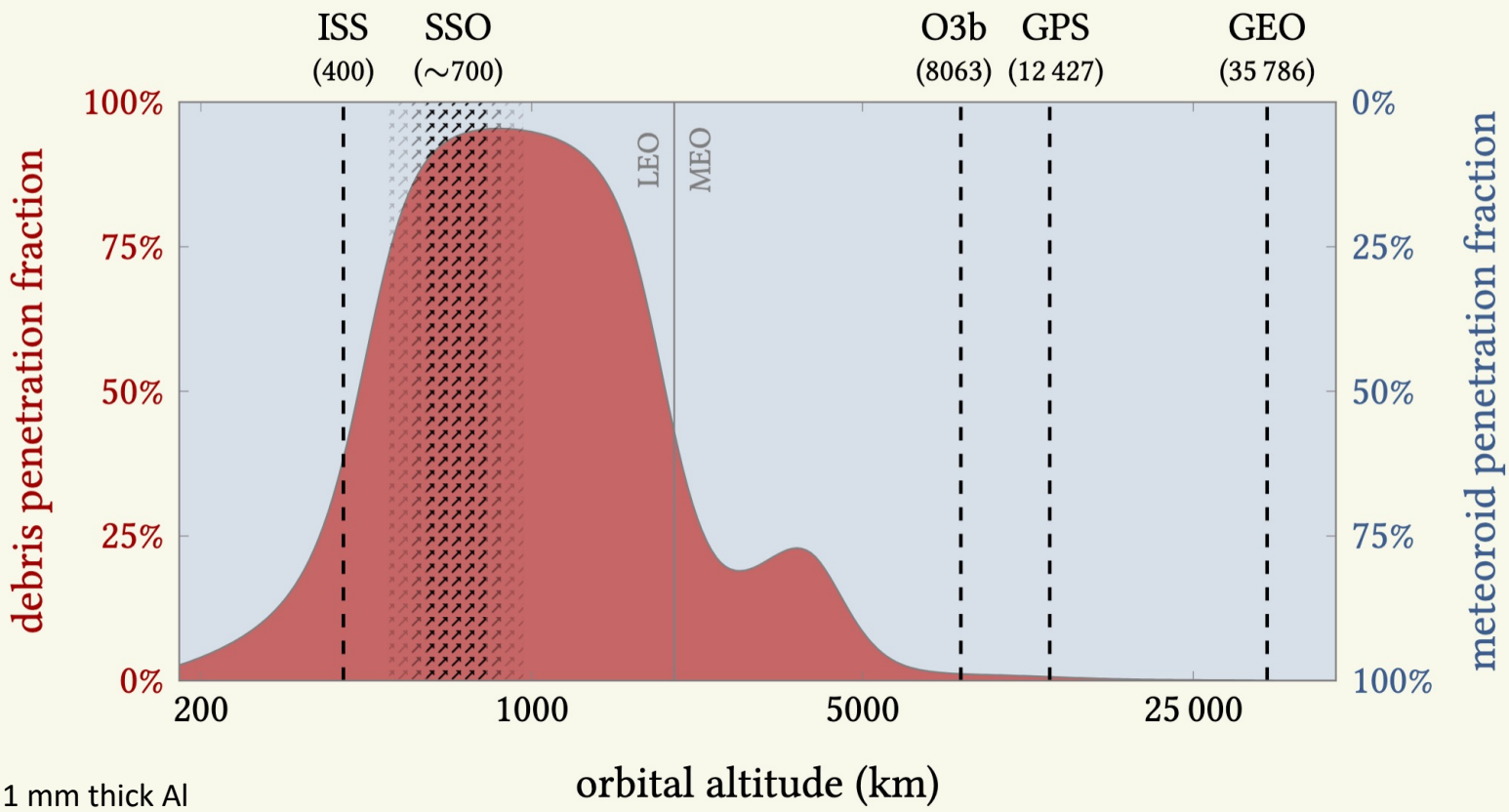


Figure 23 The possible form of a meteoroid responsible for a +3 magnitude visual meteor. Mass 0·1 g, diameter 0·9 cm, density 0·3 g cm^{-3}

Meteoroids dominate the MMOD environment above 5000 km altitude



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

Take away points

1. The ever-present sporadic meteoroid background accounts for ~95% of the risk to space vehicles. It is the “design to” environment
2. Meteor showers, while visually spectacular for short periods, are a small percentage (< 5%) of the total threat. Usually mitigated though operational procedures
3. We know the meteoroid environment in cis-lunar/lunar space with the same certainty as we know it at the top of the atmosphere – to within a factor of 2
4. Meteoroids are not rocks – their small RCS and albedos mean you cannot track them in space with current instruments. Unlike the situation with large orbital debris, collision avoidance is not possible
5. Orbital debris is an issue only in LEO/MEO. Meteoroids completely dominate above 5000 km

Overview of NASA Meteoroid Environment Office Products

	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 down-load and run	annual report and data files	individual emailed reports
what is it used for?	spacecraft design	operational mitigation	keeping the public informed