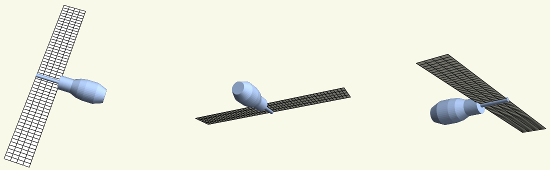
Recreating *in situ* measurements of potentially hazardous meteoroids

Althea Moorhead
NASA Meteoroid Environment Office, MSFC



Outline

- Damage equations/BLEs
- Meteoroid model: MEM 3
- *In situ* experiments
  - Pegasus
  - LDEF
- *In situ* constraints on the speed distribution?

Ballistic limit equations (BLEs)

modified Cour-Palais BLE

BLEs describe the extent of damage caused by an impact.

modified Cour-Palais (CP) BLE:

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

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

Ballistic limit equations (BLEs)

modified Cour-Palais BLE

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

CP BLE is widely used because ...

- it's simple
- it's separable
- can compute in log-space
- it's invertible

Ballistic limit equations (BLEs)

Watts & Atkinson (WA)

BLEs can be **considerably** more complex ...

crater diameter:

$$d_0 = 1.3235\, d(c_t/c)^{2/7}(v_\perp/v_0)^{4/7}$$

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

$$d_t = f \cdot d_0$$

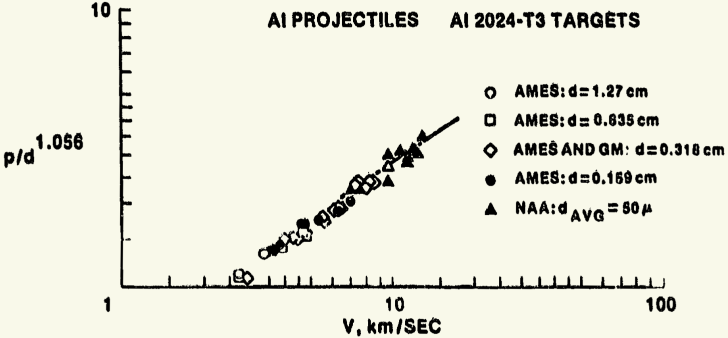
crater depth:

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

penetration thickness:

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

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?

Weighting to a constant limiting crater diameter

Meteoroid models are often mass-limited. A scaling relation is needed to adjust the flux level:

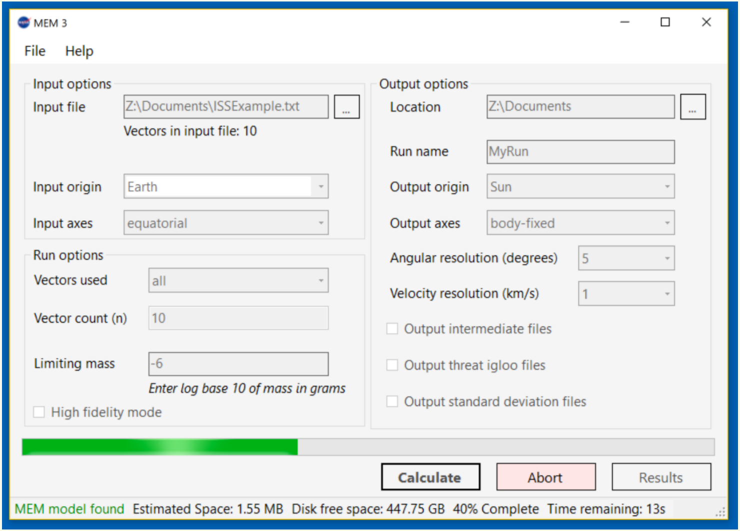
$$\text{flux}_{\text{effect}} = \sum_{i,j,k,n} \text{flux}_{i,j,k,n}(m_{\text{run}}) \times \frac{g(m_{\text{effect}}(\phi_i, \theta_j, v_k, \rho_n))}{g(m_{\text{run}})}$$

m_{effect} comes from your BLE:

$$\frac{d}{1\ \text{cm}} = \left[\frac{p_t}{5.24\ \text{cm}} h^{1/4} \left(\frac{\rho}{\rho_t}\right)^{-1/2} \left(\frac{v_\perp}{c_t}\right)^{-2/3}\right]^{18/19}$$

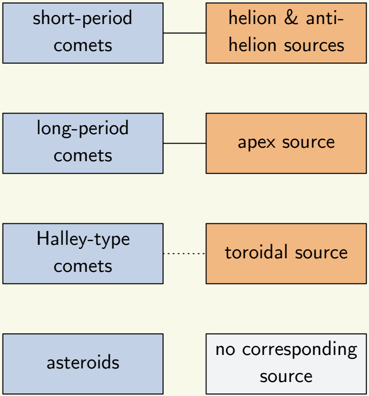
$$m = \pi \rho\, d^3/6$$

NASA Meteoroid Engineering Model (MEM), version 3

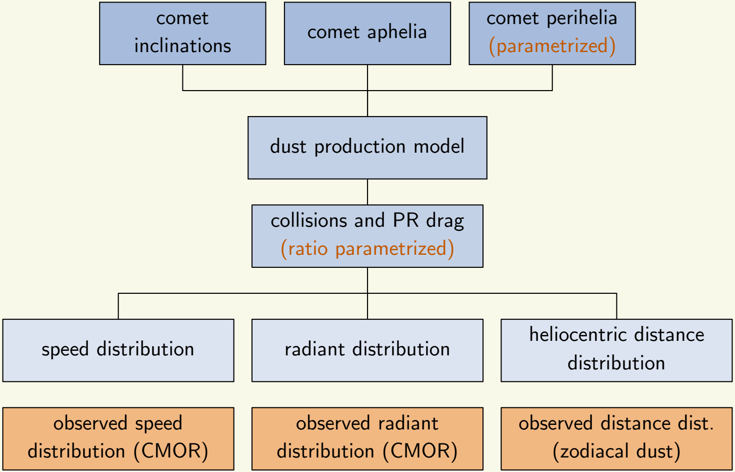


Jones (2004)

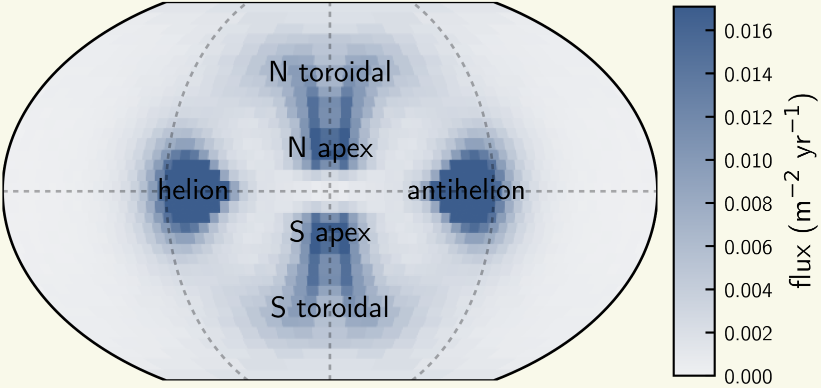
- MEM ...
  - is *not* purely empirical
  - is *not* an N-body simulation
  - *is* an analytic, physics-based model calibrated to match observations
- Jones (2004) linked parent populations to observed distributions, taking radiative forces and collisions into account
- Physical model mostly the same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



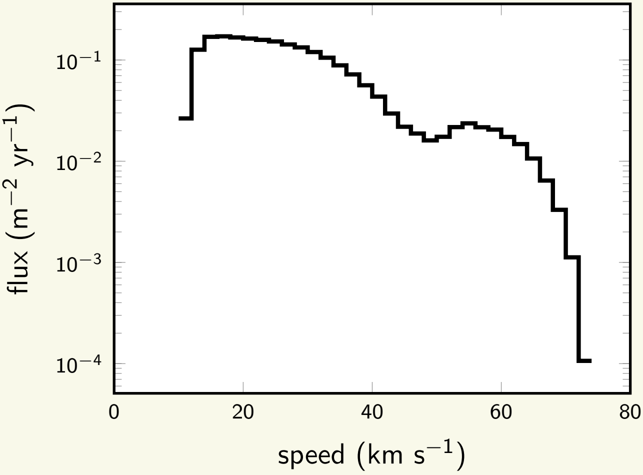
Jones (2004)


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)

Radiant distribution

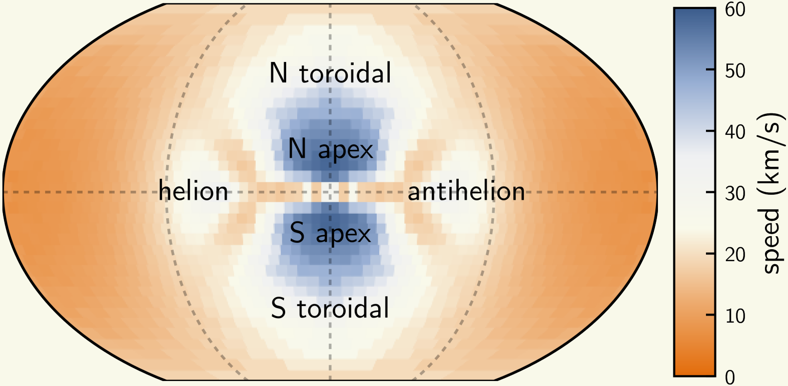


Speed distribution

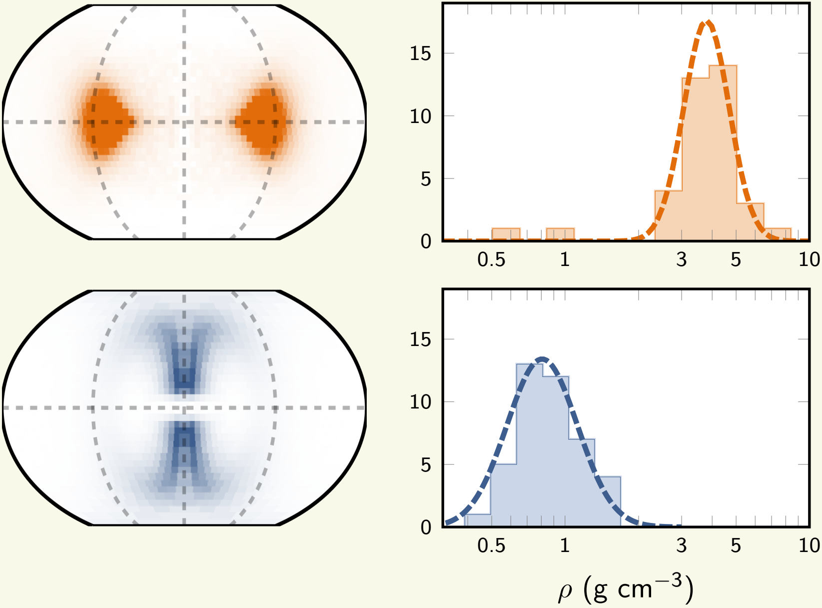


Velocity distribution

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

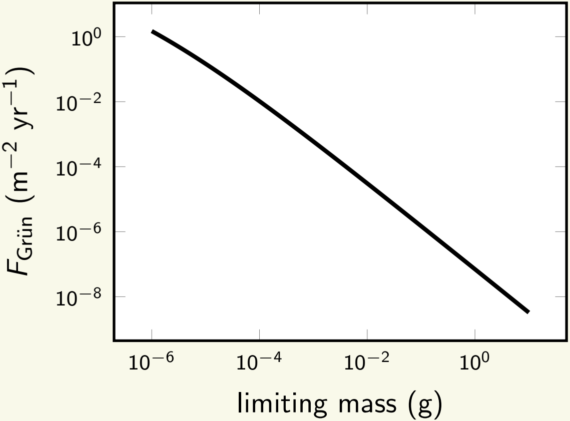


Density distribution



Mass scaling

MEM uses Grün et al. (1985) flux equation to scale to arbitrary limiting mass:



Ready to calculate damaging flux!

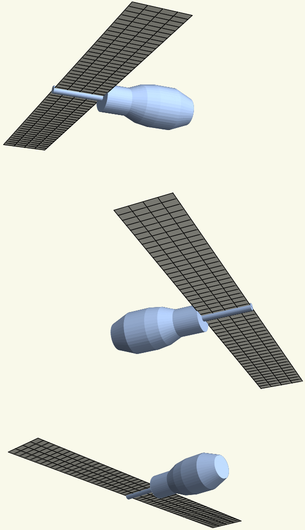
At this point, we have all needed elements to calculate damage-limited flux:

$$m_{\text{effect}} = \frac{\pi \rho_n}{6} \left[\frac{p_t}{5.24} h^{1/4} \left(\frac{\rho_n}{\rho_t} \right)^{-1/2} \left(\frac{v_\perp(v_k, \phi_i, \theta_j)}{c_t} \right)^{-2/3} \right]^{54/19}$$

$$\text{flux}_{\text{effect}} = \sum_{i,j,k,n} \text{flux}_{i,j,k,n}(m_{\text{run}}) \times \frac{g(m_{\text{effect}}(\phi_i, \theta_j, v_k, \rho_n))}{g(m_{\text{run}})}$$

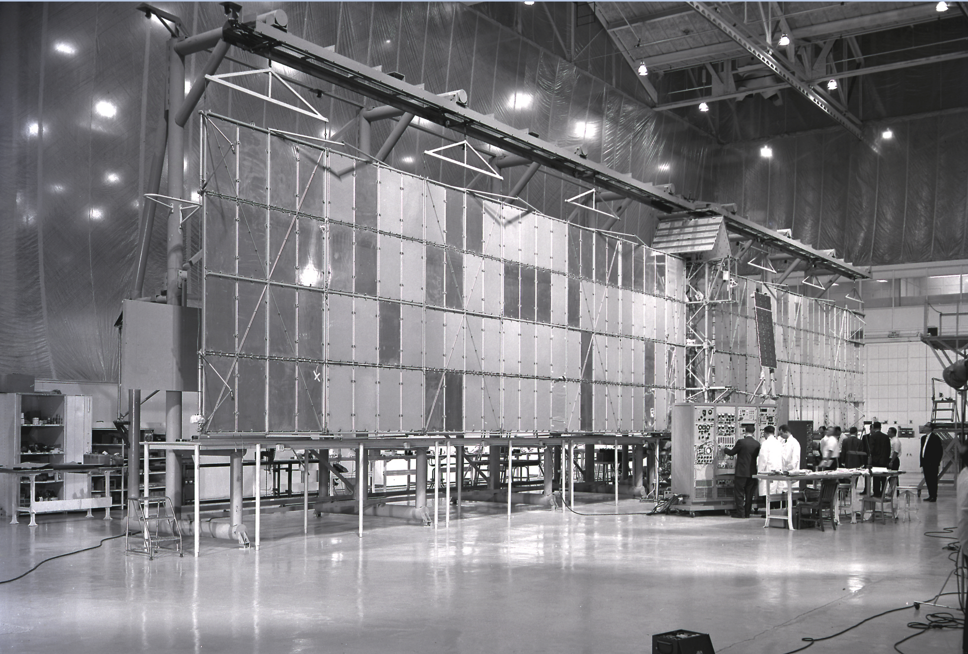
- Orange quantities provided by MEM
- Blue quantities depend on spacecraft surface
- Green quantity is determined by effect

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

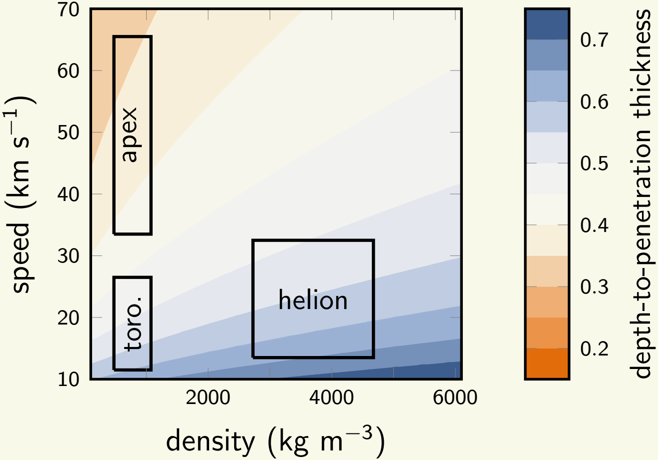
Pegasus



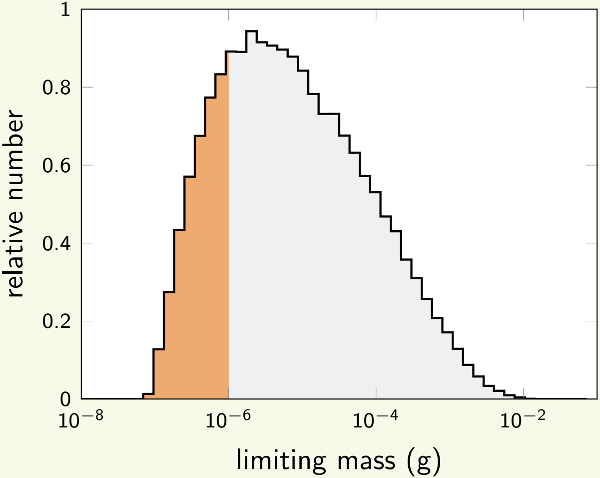
Pegasus: limiting penetration thickness

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

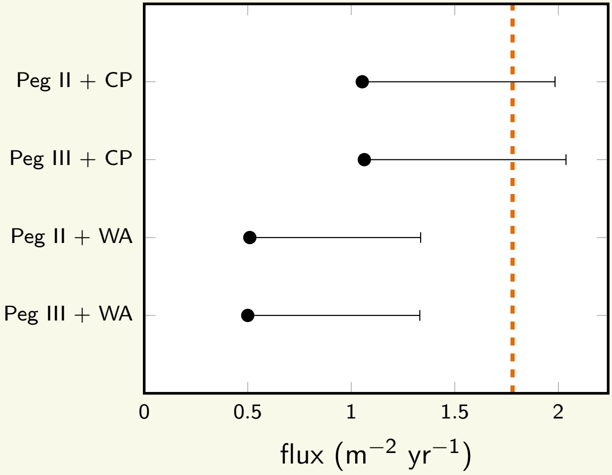
Watts & Atkinson:



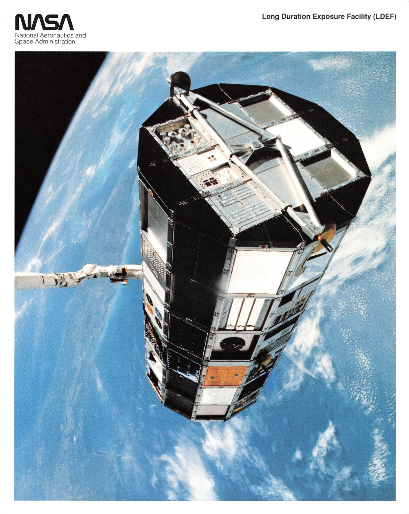
Pegasus: limiting masses



Pegasus results

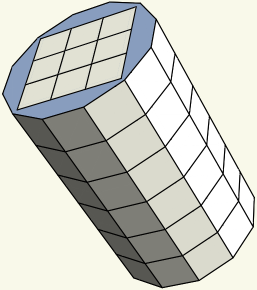


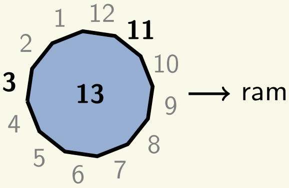
Long Duration Exposure Facility (LDEF)



- **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)



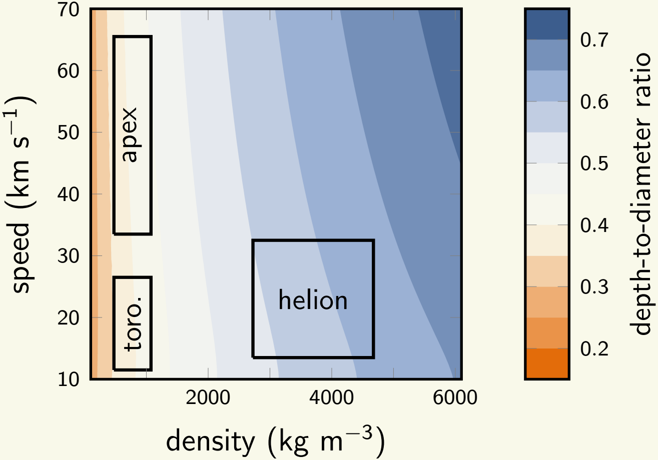


- Interested in largest craters (100 μm)
- Significant orbital debris present
- Orbital debris estimate available on three sides from smaller craters on CME

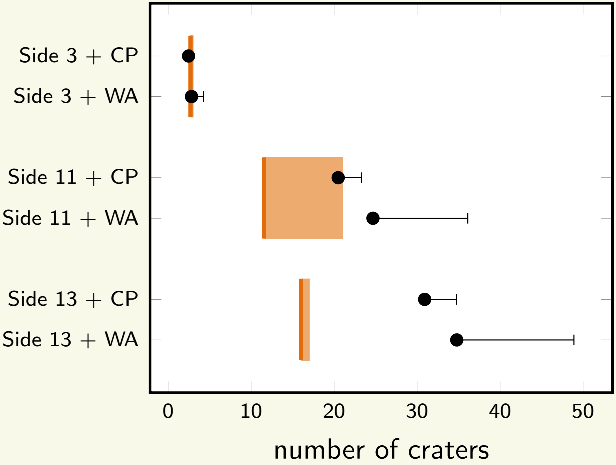
LDEF: depth-to-diameter ratio

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

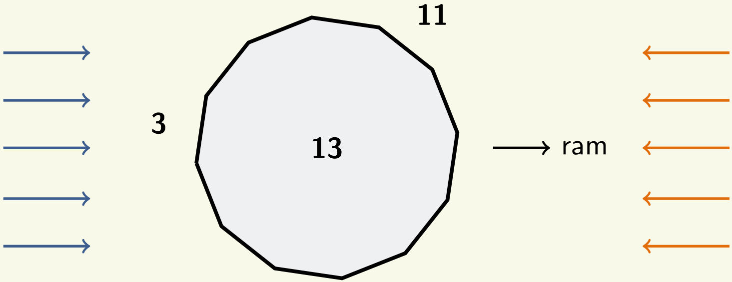
Watts & Atkinson:



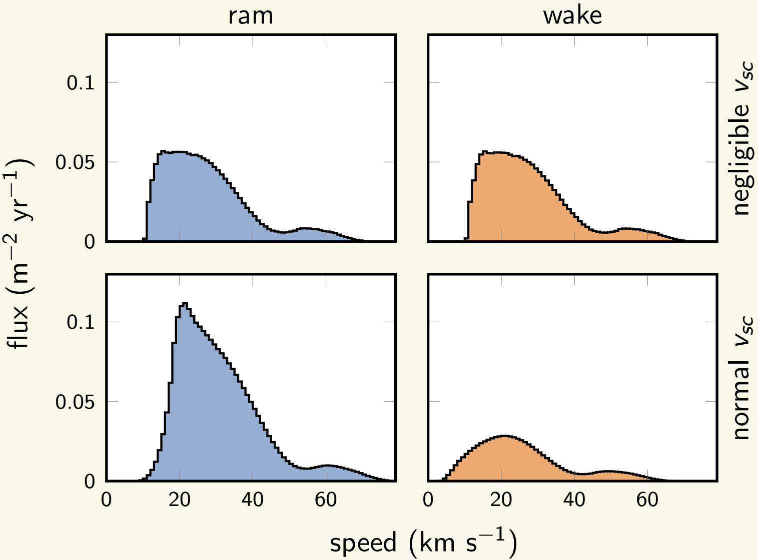
LDEF results



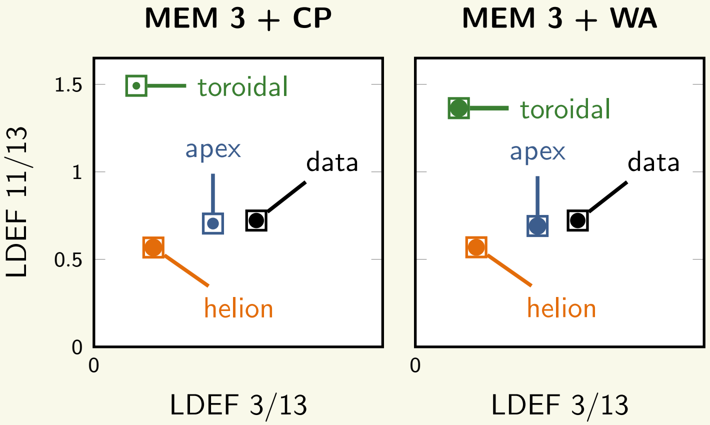
Constraints on speed distribution?



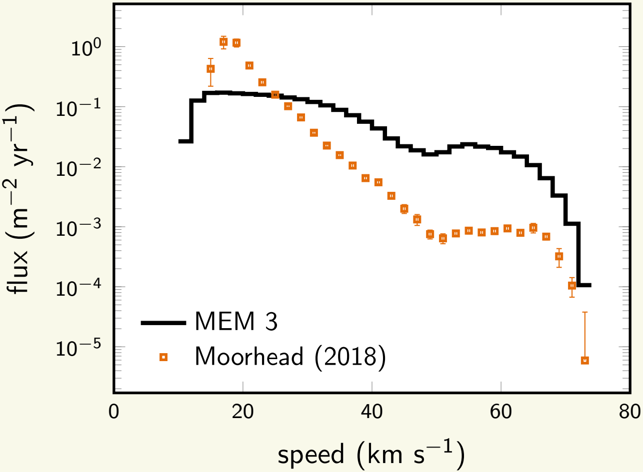
Effect of spacecraft velocity on flux



Crater ratios



Speed distribution measurements



Summary

- BLEs relate impact parameters to damage
- BLEs can be combined with meteoroid model to predict damage/risk
- We have combined MEM 3 with two BLEs (Cour-Palais, Watts & Atkinson) for:
  - Pegasus: predictions too low
  - LDEF: predictions too high
- Comparing the crater counts on different sides of LDEF constrains the speed distribution in theory, but the results are in conflict with meteor observations