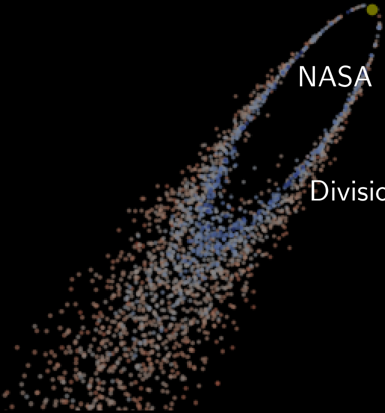
The formation and early evolution of meteoroid streams



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Division on Dynamical Astronomy Meeting
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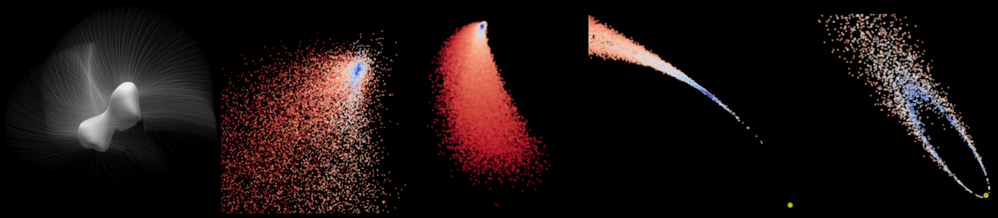
Stages of meteoroid stream evolution



- This talk covers the ejection of particles from comets to the initial formation of a meteoroid stream
- Presents new work on ejection velocity and unbound particles
- Recurring focus on dust-to-meteoroid transition

Stage 1: Ejection from a comet nucleus

- Sublimating volatiles carry solid particles away from the nucleus
- Ejection velocity depends on:
  - heliocentric distance
  - solar zenith angle
  - rotation
  - thermal properties of comet
  - geometry of comet
  - ejected particle properties
  - and more ...
- Most of the above information is usually unknown

Stage 1: Ejection from a comet nucleus

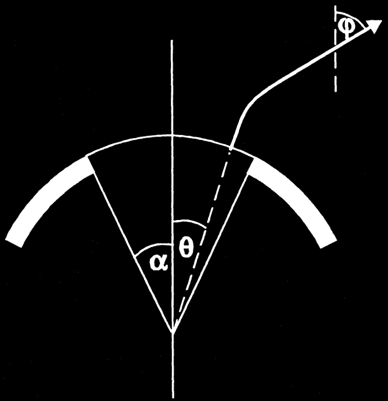


Figure 1. The geometry of the ejection of a dust grain from a polar spherical cap of semi-angle α. The black region surrounding the cap denotes the inert rubble mantle. The initial trajectory of the grain has a polar angle of θ. The polar angle of the trajectory when the grain has moved away from the comet is φ.

- We usually use a much simpler model
  - Spherical or azimuthal symmetry
  - Either even or localized heating of the nucleus

Stage 1: Ejection from a comet nucleus

Gas dynamics

The gas production at the surface of the nucleus is determined by the energy balance equation:

$$\frac{L_\odot}{r^2} \cos\theta = \sigma T^4 + H\, Z(T)$$

or, if we average over the sunward half of the nucleus ...

$$\frac{L_\odot}{r^2} = 2\sigma T^4 + 2H\, Z(T)$$

Z determined by pressure of saturated gas (known) at temperature T

Stage 1: Ejection from a comet nucleus

Gas dynamics

Once we have the temperature:

$$
\begin{aligned}
p_s &= \frac{1}{2} p_{sat} \\
n_s &= \frac{1}{2} n_{sat} \\
v_s &= \frac{\pi \bar{v}_{sat}}{4}
\end{aligned}
$$

Then, the ideal gas law and conservation of mass gives you the gas dynamics

Stage 1: Ejection from a comet nucleus

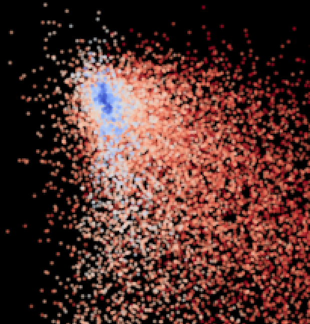
Dust dynamics

Solid particles feel gas drag (see Jones, 1995):

$$\frac{d^2x}{dt^2} = \frac{A\Gamma}{2} m^{-1/3} \rho_d^{-2/3} \rho_{gas}(x) \left[v_{gas}(x) - \frac{dx}{dt} \right]^2$$

Then:

$$\Delta v = \left. \frac{dx}{dt} \right|_{t \to \infty}$$



Stage 1: Ejection from a comet nucleus

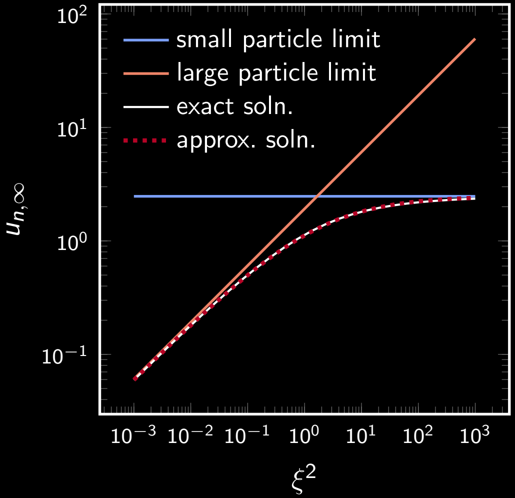
Dust dynamics

- Limiting cases:
  - Small particles: coupled to gas
  - Large particles: $v_{gas}(x) - \frac{dx}{dt} \simeq v_{gas}(x)$
- But Δv has no analytic form in the general case

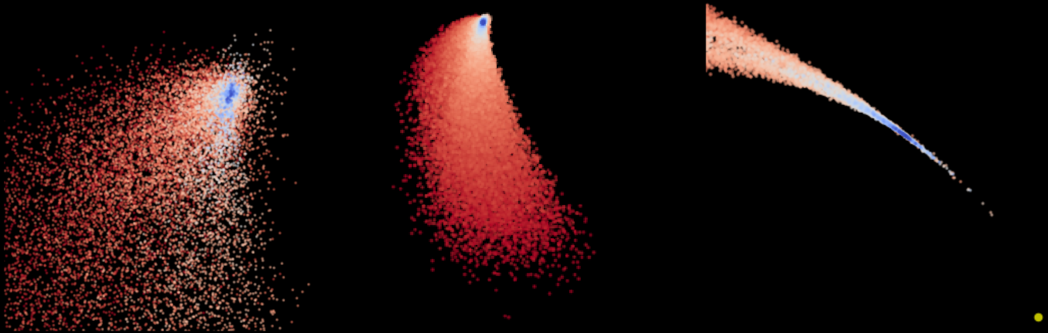
$$\Delta v \simeq v_{gas,0}\left(0.385 + 0.503 \cdot \xi^{-1.054}\right)^{-0.949}$$

$$\xi = \frac{A\Gamma}{2} m^{-1/3} \rho_d^{-2/3} \rho_{gas,0}\, x_c$$

Ugly but numerically cheap!



Stage 2: Dust trail formation



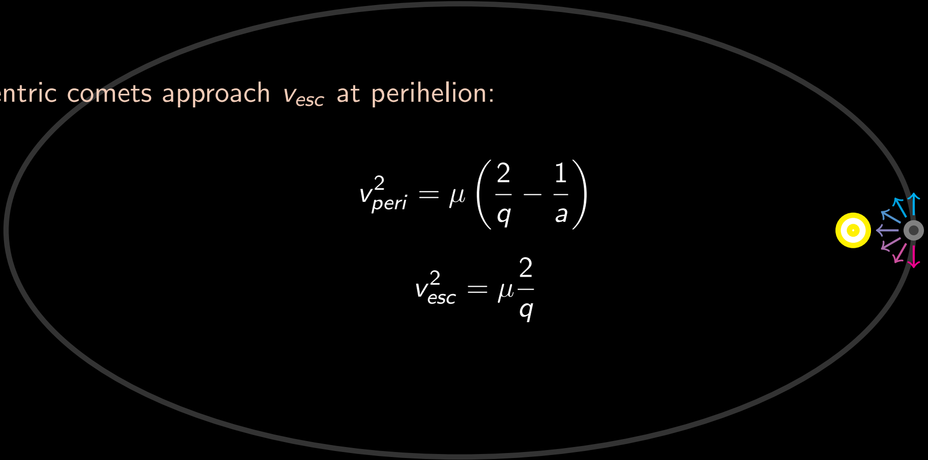
Stage 2: Dust trail formation

Escape velocity

Eccentric comets approach v_{esc} at perihelion:

$$v_{peri}^2 = \mu \left(\frac{2}{q} - \frac{1}{a} \right)$$

$$v_{esc}^2 = \mu \frac{2}{q}$$



Stage 2: Dust trail formation

Radiation pressure

- Radiation pressure follows inverse square law
- Reduces central potential by β:

$$\beta = \frac{F_r}{F_g} = 5.7 \times 10^{-4}\ \mathrm{kg\ m}^{-2} \times (Q_{pr}/\rho s)$$

- Effect is inversely proportional to size ... for large particles and “ideal” optics:

$$\beta \propto 1/s$$

Stage 2: Dust trail formation

Escape velocity and radiation pressure

$$v_{esc}^2 = \mu(1-\beta)\frac{2}{q}$$

- For $\beta \geq 1$, there are no bound orbits
- For $\beta < 1$, v_{esc} is reduced
- Comet's velocity alone exceeds v_{esc} for:

$$\beta > \frac{1-e}{2}$$

Burns, Lamy, & Soter (1979)

Stage 2: Dust trail formation

Escape velocity and ejection velocity

- Meteoroids ejected in the direction of the comet's motion get a boost; trailing particles the opposite.
- For large particles:

$$\Delta v = v_0 \sqrt{\beta}$$

- The value of β above which particles are unbound has an analytical solution. For leading particles:

$$y = \sin^{-1}\left(\frac{v_{peri}}{\sqrt{v_0^2 + v_{esc}^2}}\right) - \text{atan2}(v_{esc}, v_0)$$

$$\beta_L = \sin^2 y$$

- A similar equation exists for trailing particles

Stage 2: Dust trail formation

Calculating β for small particles and real materials

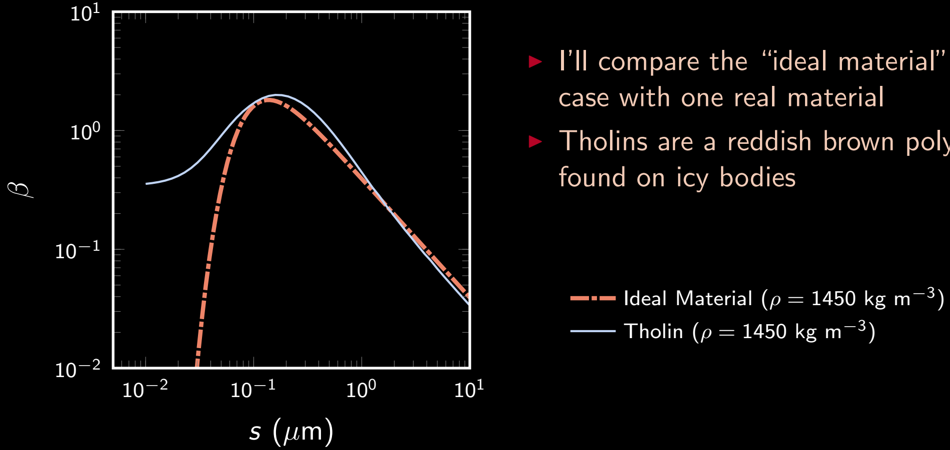
$$\beta = 5.7 \times 10^{-4} \text{ kg m}^{-2} \times (Q_{pr}/\rho s)$$

$$\Delta v \not\propto \sqrt{\beta}$$

- Geometric optics: $Q_{pr} = 1$
- "Ideal material": $Q_{pr} = 1$ for $\lambda < 2\pi s$, 0 otherwise
- Real materials: Calculate Q_{pr} using Mie theory (Python code available from Navarro & Werts, 2012)

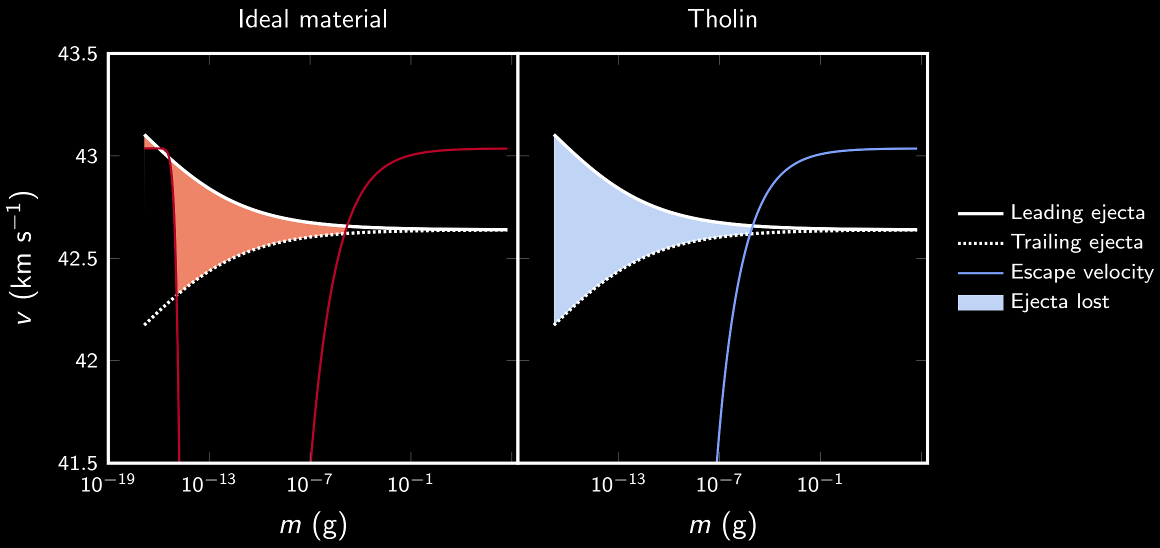
Stage 2: Dust trail formation

Calculating β for small particles and real materials

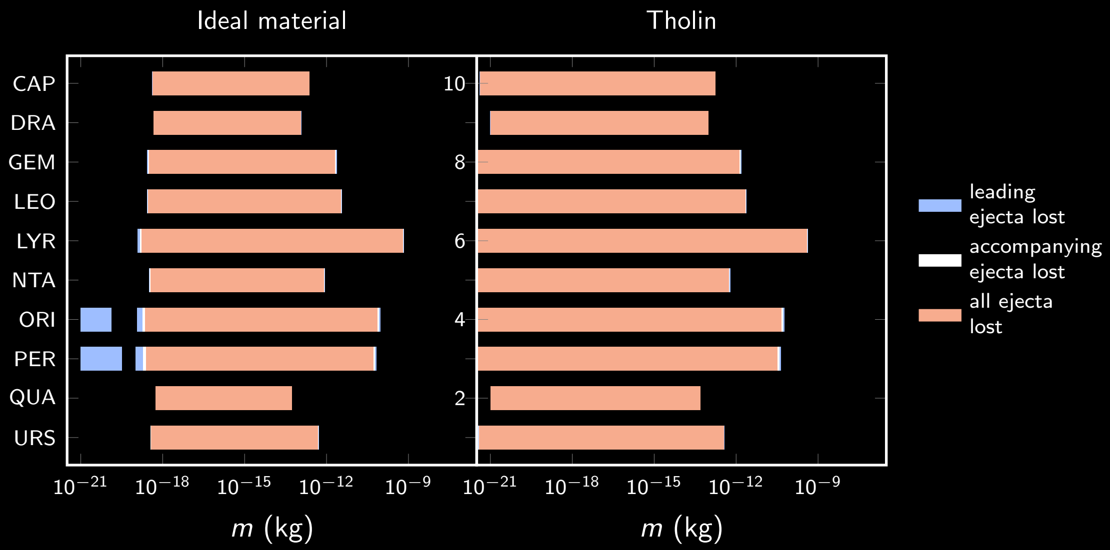


- I'll compare the "ideal material" case with one real material
- Tholins are a reddish brown polymer found on icy bodies

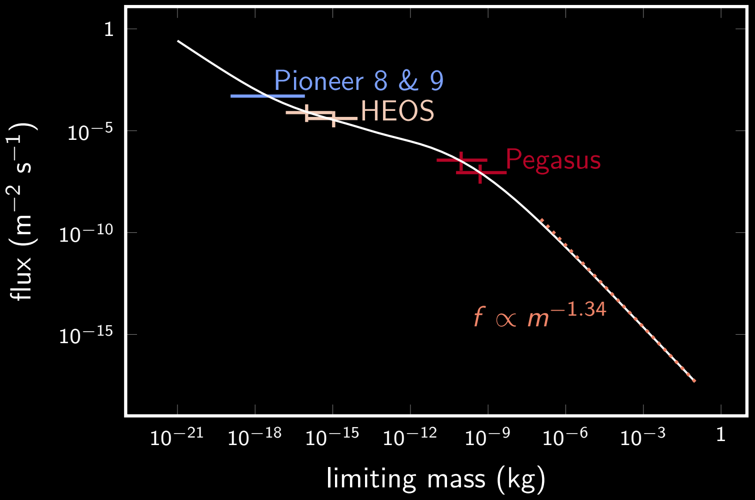
Stage 2: Forming the Perseids



Forbidden mass ranges for 10 major showers



Forbidden mass ranges compared to *in situ* data



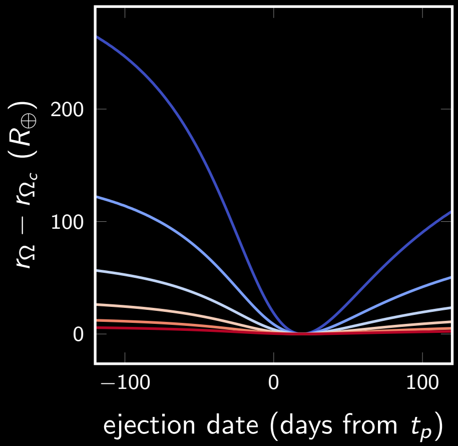
Grün et al. (1985)

Stage 3: Meteoroid stream formation

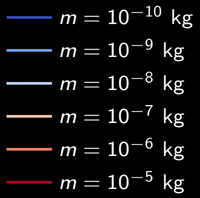
- After 1 rev, unbound particles leave the solar system
- After many revs, particles disperse along orbit
- In addition to spread in e values, there will be a range of distances at which meteoroids cross ecliptic plane, r_{Ω}

Stage 3: Meteoroid stream formation

Changes in nodal radius

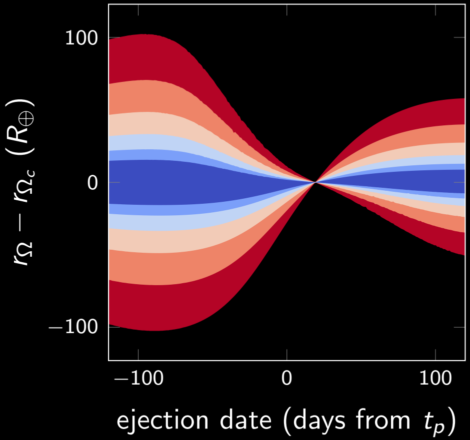


- Nodal radius will be affected by radiation pressure



Stage 3: Meteoroid stream formation

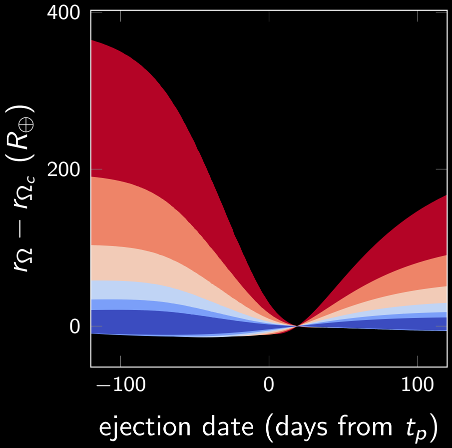
Changes in nodal radius



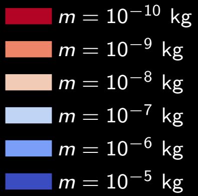
- Nodal radius will also be affected by ejection velocity vector

Stage 3: Meteoroid stream formation

Changes in nodal radius



- Nodal radius taking both ejection velocity and radiation pressure into account



Stage 4+: Continued evolution of meteoroid streams and formation of the sporadic complex

- Poynting-Robertson drag and solar wind will continue to modify orbits over thousands of years
- Collisions will grind larger particles into dust
- Planets will perturb orbits (some more than others)
- Continued exposure to Sun/vacuum may alter material properties of particles
- Eventually, meteoroid streams disperse into sporadic complex

Summary

- Meteoroid streams are formed when particles are carried off a comet nucleus by sublimating gases.
  - We've extended v formula to handle arbitrary particle size.
- Meteoroids may be on unbound orbits.
  - Analytic solution for β limit for large particles
  - Approximate solution for all particle sizes
  - Ideal material: very small particles may remain in stream
  - Tholins: small particles do not remain in stream
  - Eccentric comets: excluded range can be large: no Lyrids smaller than 4×10^{-7} g
- Particles may remain in stream but intersect ecliptic at modified heliocentric distance.