Meteoroid Structure and Fragmentation

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Structure of meteoroids: why?

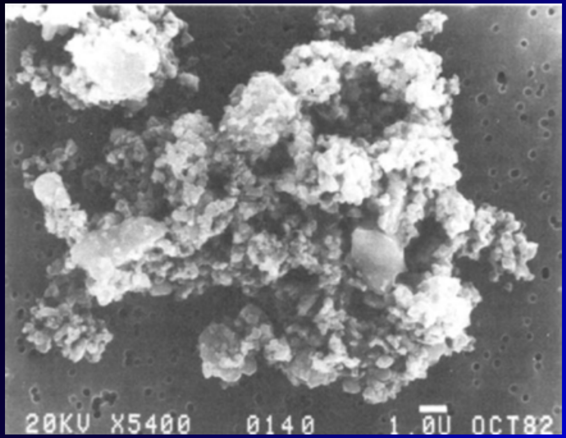
- Links to structure of parent bodies: comet/asteroid differences
- Modifications in space (e.g. low *q*)
- Meteoroid modelling, densities, luminous efficiency
- Particle strength for spacecraft impacts

Structure of meteoroids: how?

- Meteorites
  - Only large, strong, refractory, slow material survives.
- IDPs/comet dust
  - Only small, slow meteoroids survive.
  - Only a few in-situ structures measured
- Meteoroids 100 μm to 1 m:
  - Optical observations
  - Radar observations

Structure of meteoroids

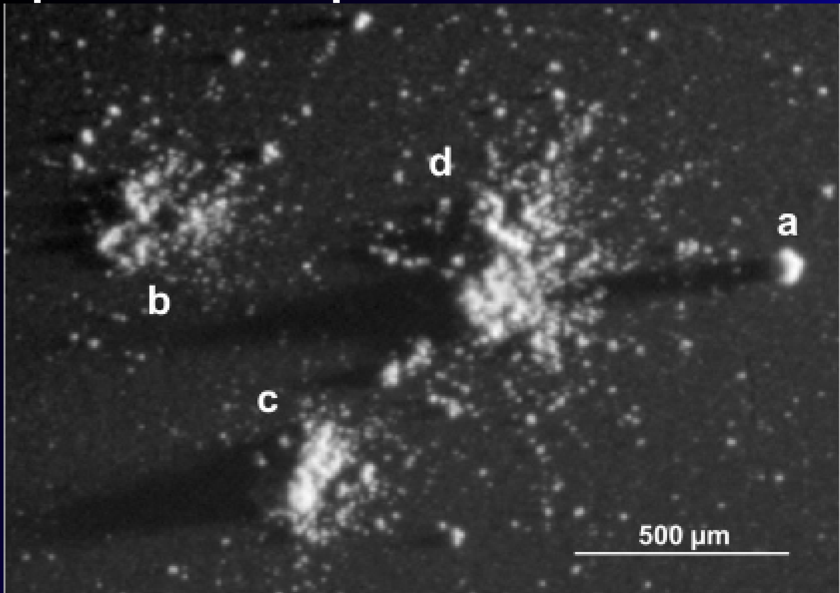
- Asteroids
  - Regolith/rubble piles prevalent: contact forces important
- Meteorites
  - Some are very inhomogeneous (Almahatta Sitta, Benešov)
  - Observed falls provide constraints
- IDPs
  - Some very fragile and some strong
  - Cometary particles from Stardust range from aggregates to CAI and chondrule-like particles



Brownlee, 1985

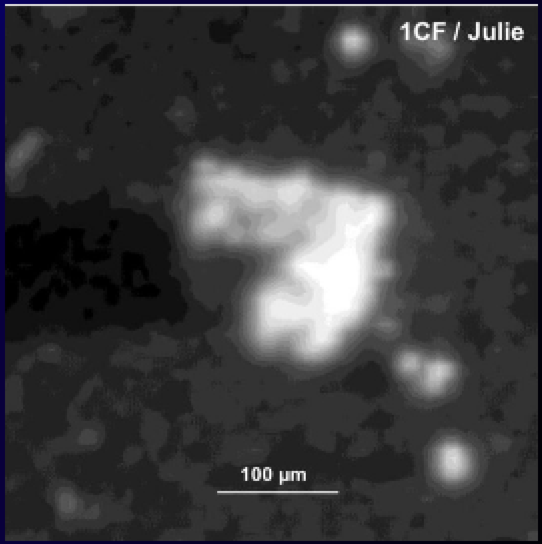
Comet Dust

- Rosetta's COSISCOPE has imaged more than 10,000 dust particles with a resolution of 14 μm.
- More than 100 particles have sizes greater than 100 μm.
- Evidence for a population of very fluffy cluster particles from dust mantle, plus compact particles.
- Many cluster particles part of mm-sized objects which fragmented near collection.

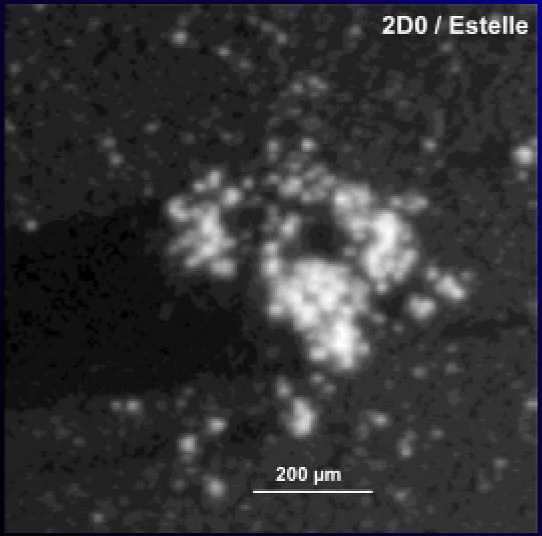


Langevin et al., 2016

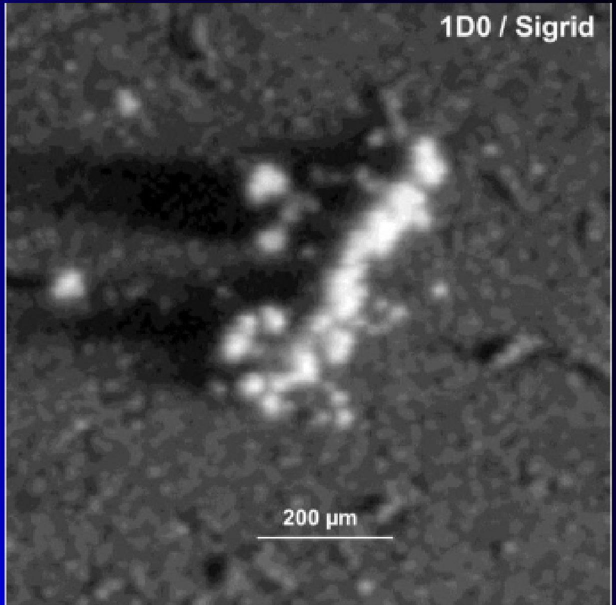
Comet Dust



Compact particle
~15% (>100µm)

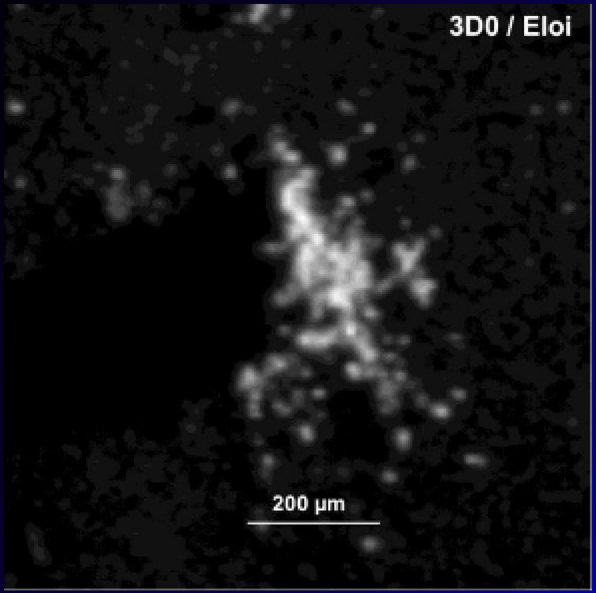


Shattered cluster



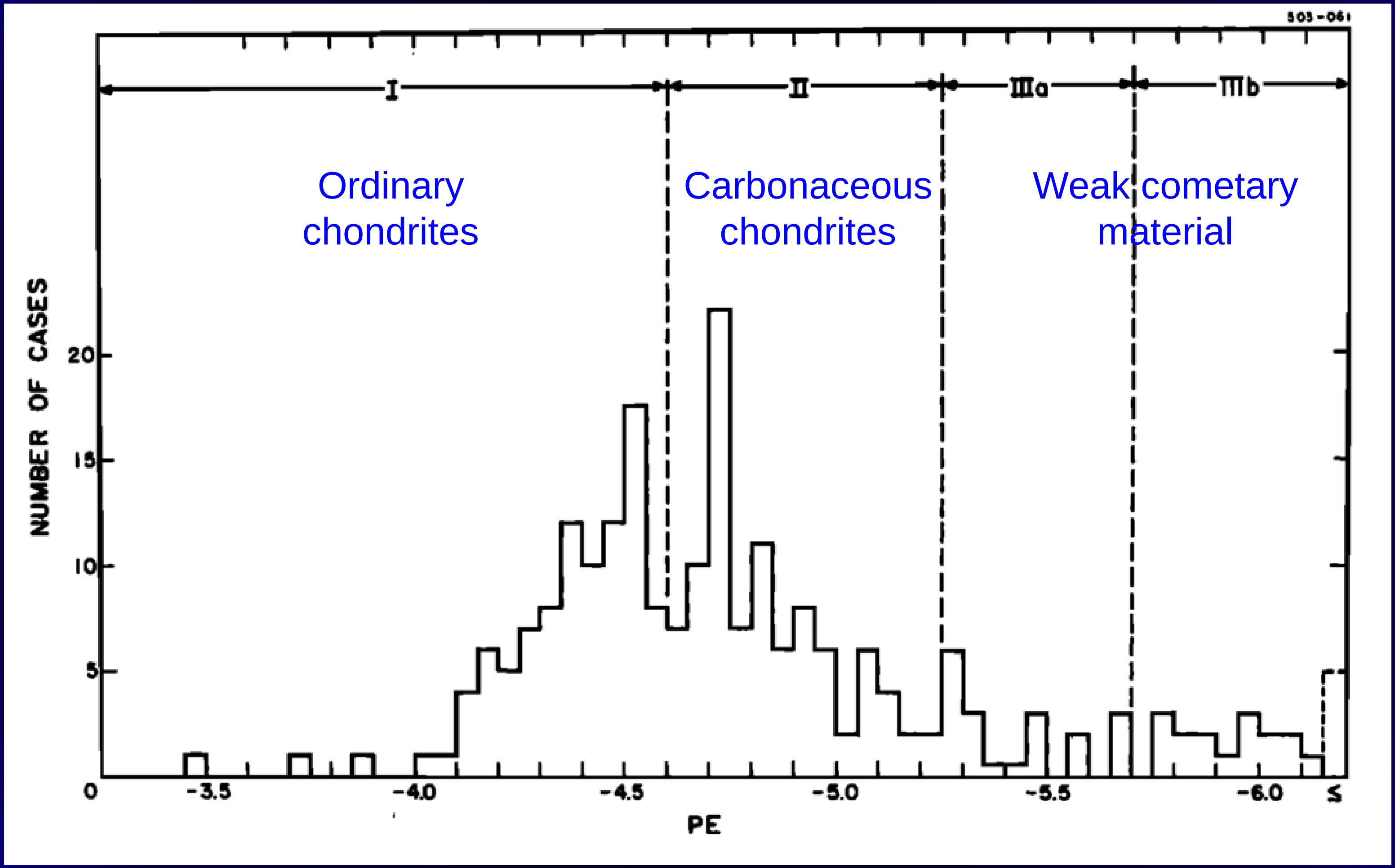
Glued cluster

Rubble Pile



Langevin et al., 2016

Fireballs: end height and PE criterion



Ceplecha & McCrosky, 1976

Weaker material ablates faster and ends sooner

Fireballs: other criteria

- PE: depends on end height, initial mass, speed and entry angle

$$\mathbf{PE} = \log \rho_e + \boldsymbol{A} \log m_\infty + \boldsymbol{B} \log v_\infty + \boldsymbol{C} \log(\cos z)$$

- SD: depends on geometry of particle and ablation coefficient, requires precise measurements

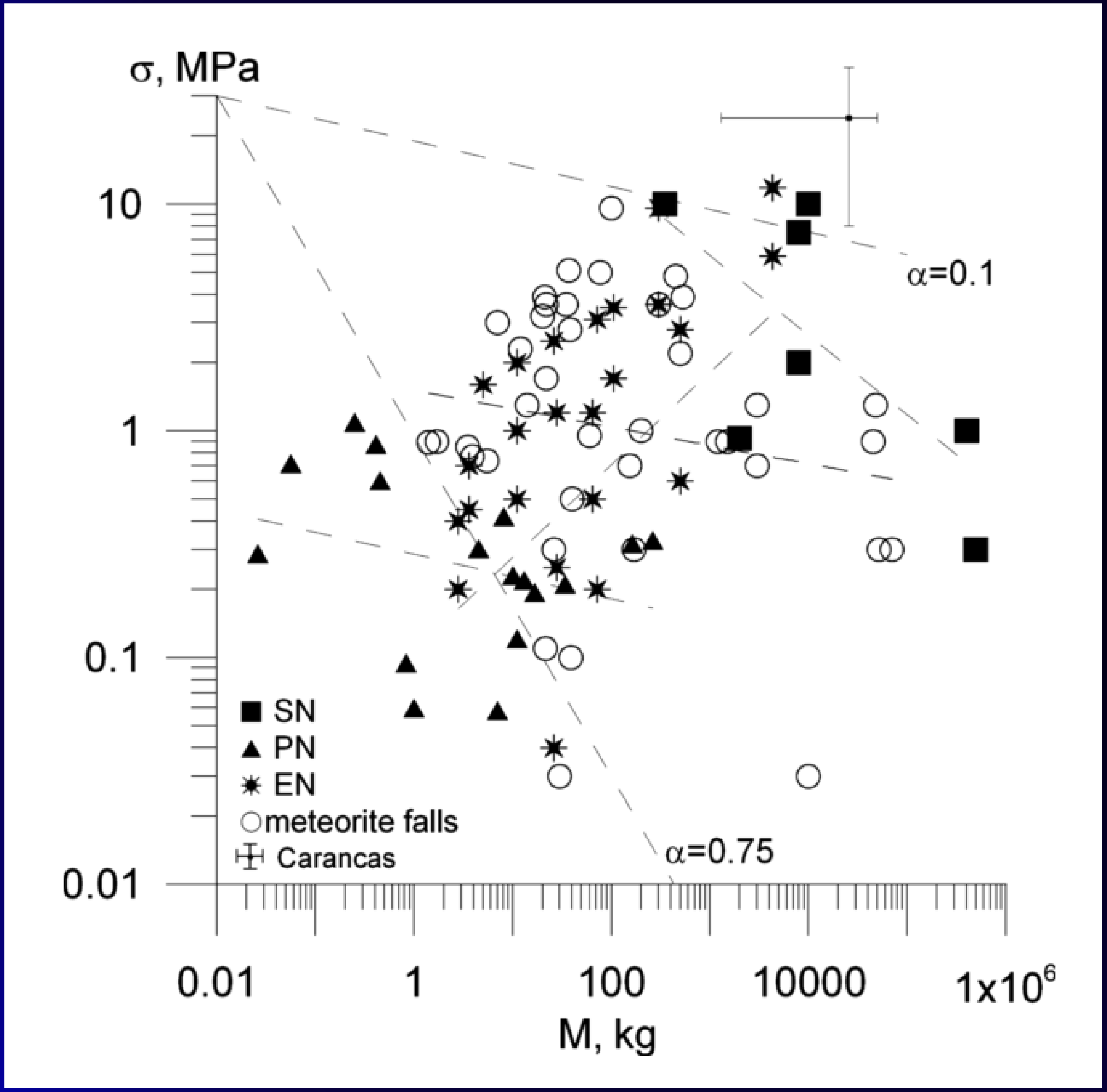
$$\boldsymbol{SD} = \log\left(\Gamma A {\rho_m}^{-2/3}\right) + \log\left(\frac{\Lambda}{2\Gamma\zeta}\right)$$

- AL: depends only on ablation and light produced

$$\boldsymbol{AL} = \mathbf{5} \log \boldsymbol{v}_\infty + \mathbf{2} \log\left(\frac{\rho_e}{\cos z}\right) - \mathbf{0.83} \log\left(\int_{t_B}^{t_e} I dt\right)$$

- The ablation coefficient alone also gives a measure of the strength/friability $\boldsymbol{\sigma} = \dfrac{\Lambda}{2\Gamma\zeta}$

Fireballs: Fragmentation pressure



Popova et al., 2011

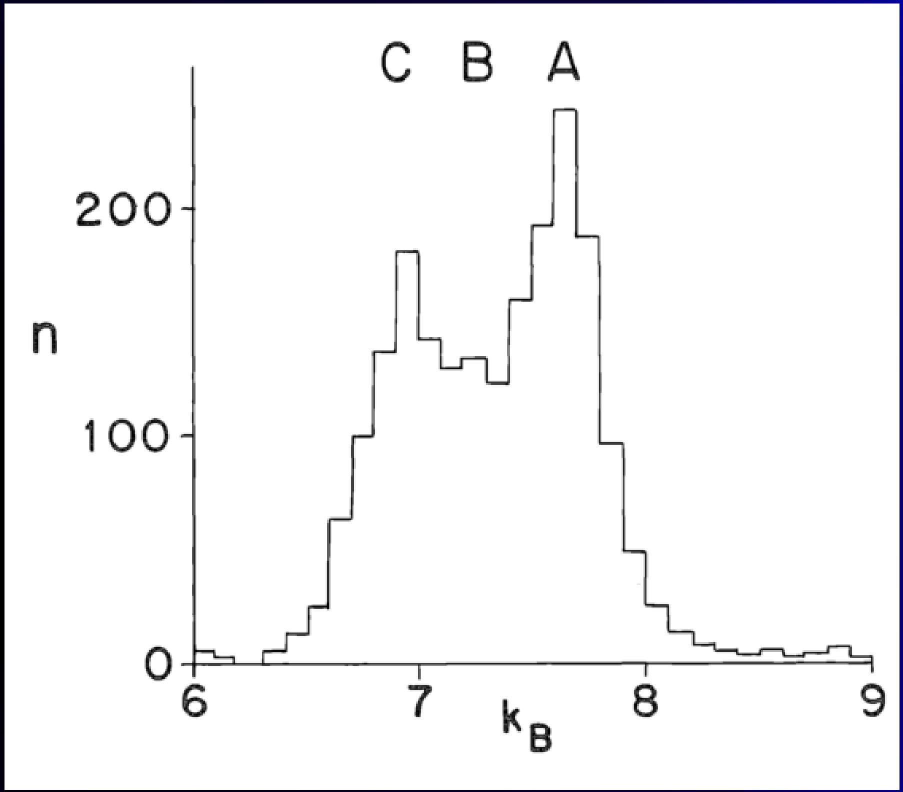
Most asteroidal meteoroids are much weaker than meteorites; evidence for highly fractured or rubble-pile objects.

Faint meteors: k_B, k_C parameter

k_B is calculated from the begin height, speed and zenith angle

It depends on the heat conductivity, density and specific heat

kC is a different formulation with similar properties (Jenniskens et al., 2016)

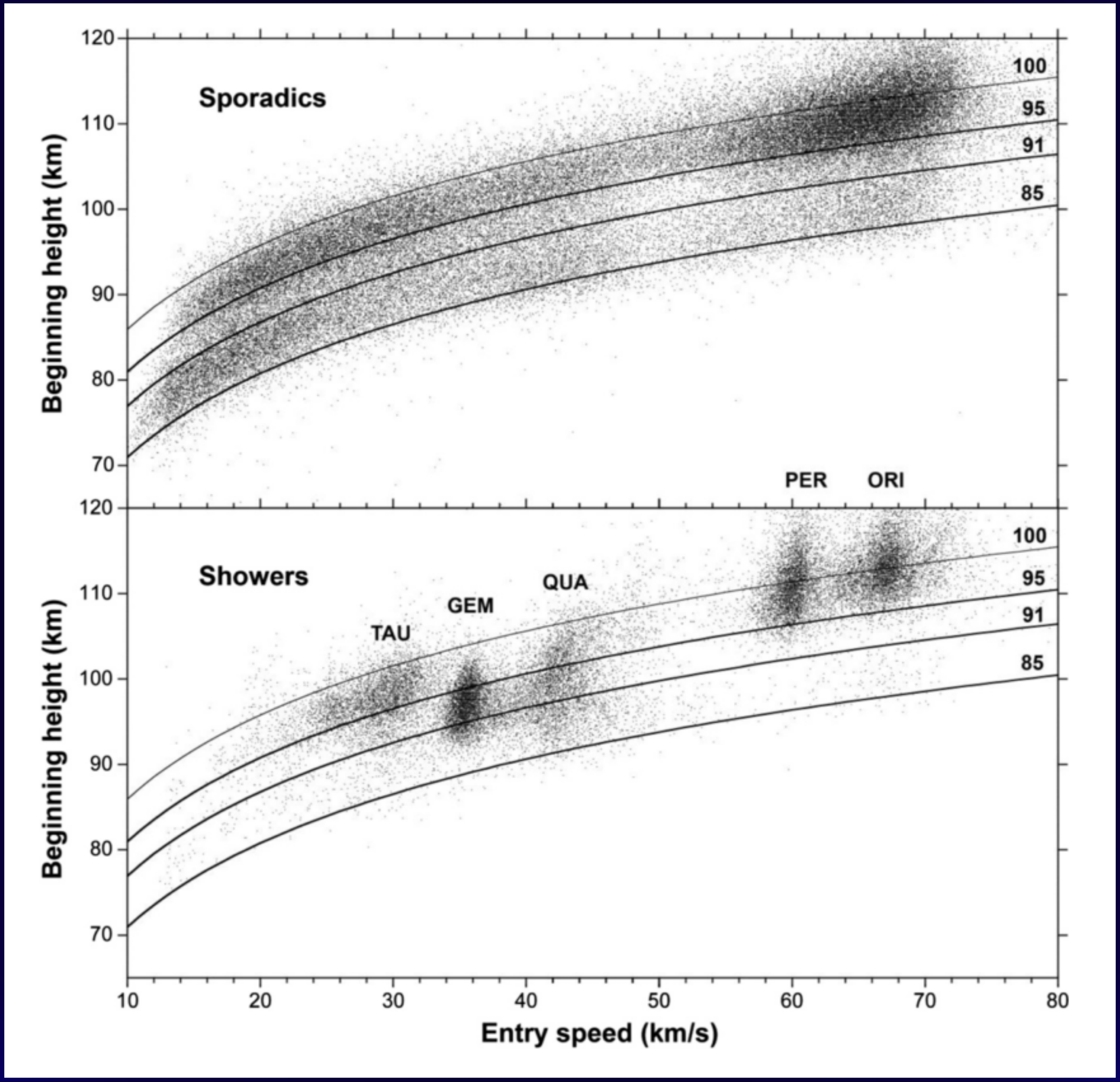


Ceplecha 1967

$$\boldsymbol{k_B} = \log \rho_\infty + \mathbf{2.5} \log v_\infty - \mathbf{0.5} \log(\cos z)$$

$$\boldsymbol{k_C} = \boldsymbol{h_B} + \frac{\mathbf{2.86} - \mathbf{2.00} \log v_\infty}{\mathbf{0.0612}}$$

Faint meteors: Begin height

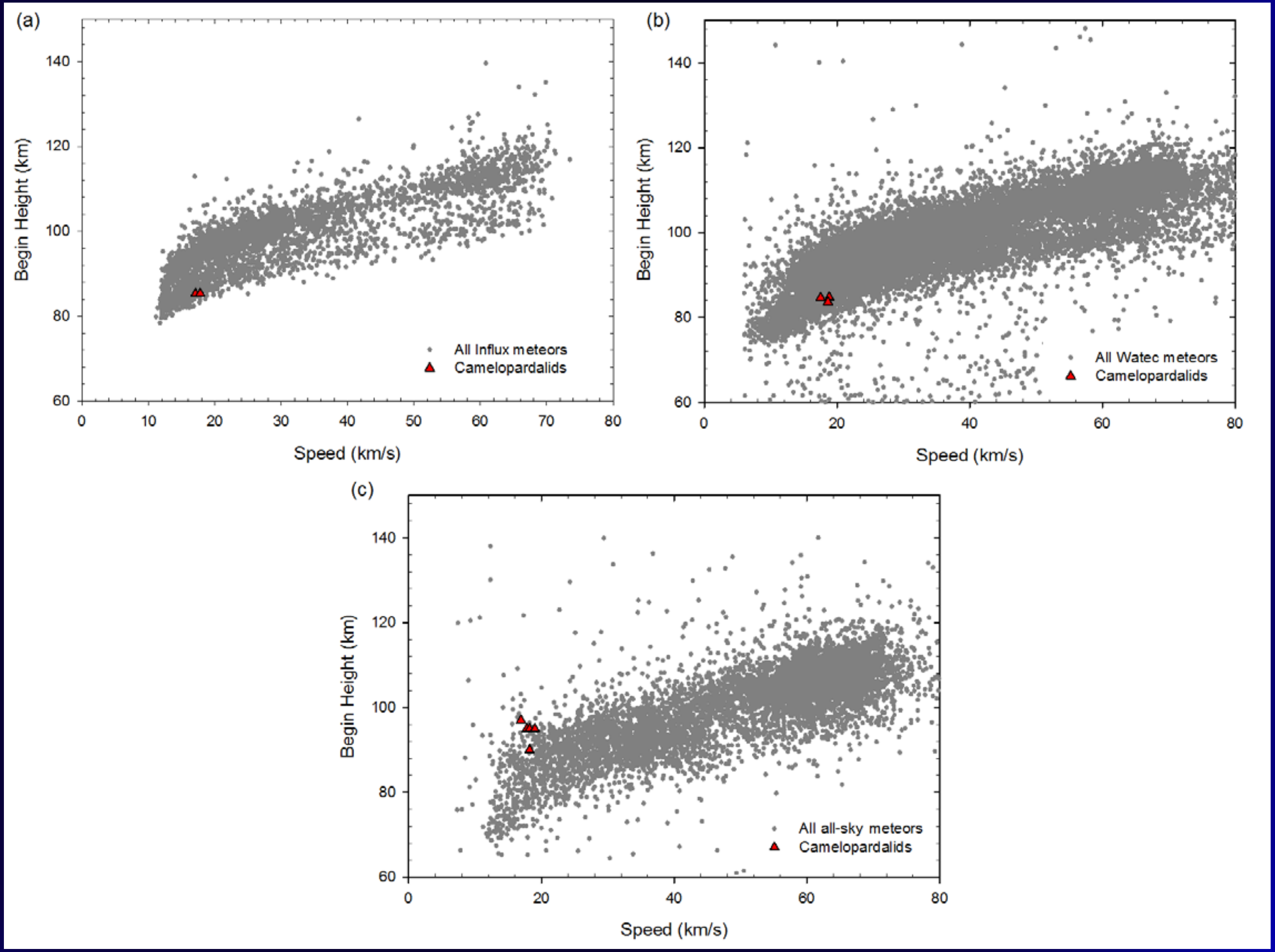


Jenniskens et al., 2016

2014 Camelopardalids

m = 1 → 10 mg

m = 1 → 10 g

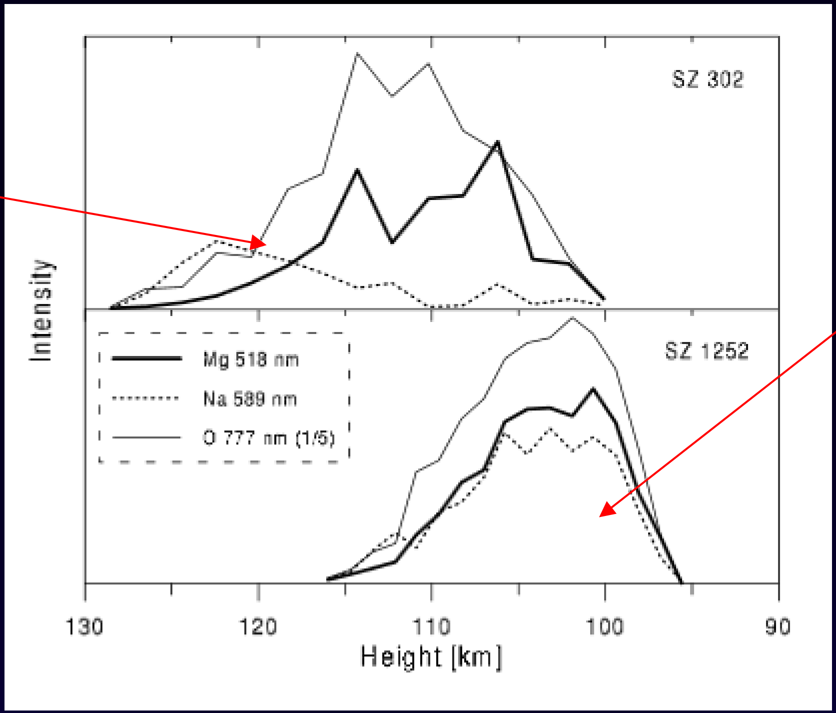


Campbell-Brown et al., 2016

Faint meteors: spectra

Early release of sodium may indicate meteoroid disruption

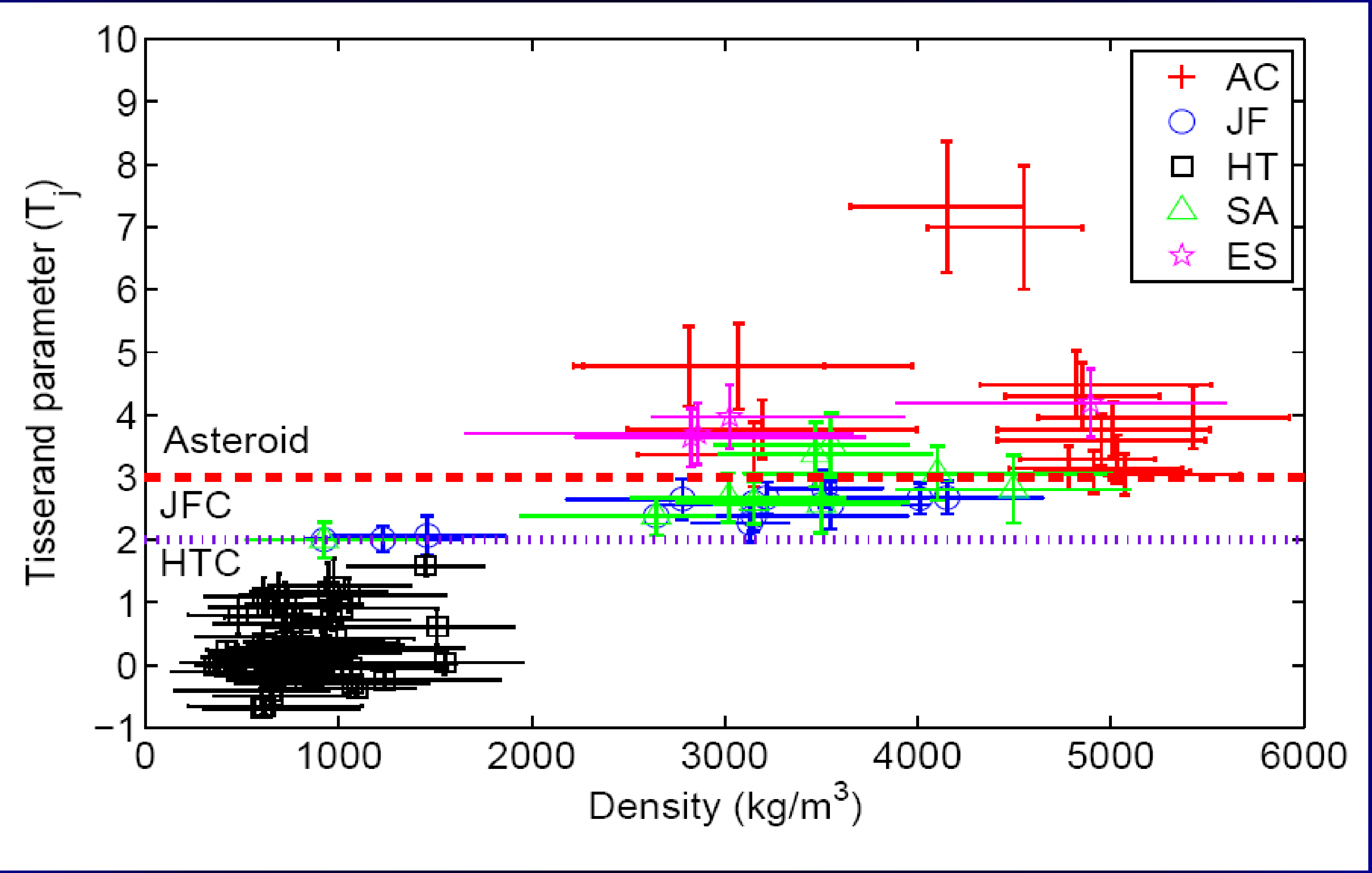
Sodium released early; breakup into small grains where Na can escape



Sodium released with other elements

Borovička 2006

Faint meteors - densities



Requires an ablation/fragmentation model

Kikwaya et al., 2011

Light curve and structure

Jacchia (1955) suggested that

- The disagreement between photometric and dynamic mass in faint meteors
- The short trail length of faint meteors
- Terminal blending of shutter breaks
- The symmetric shapes of light curves

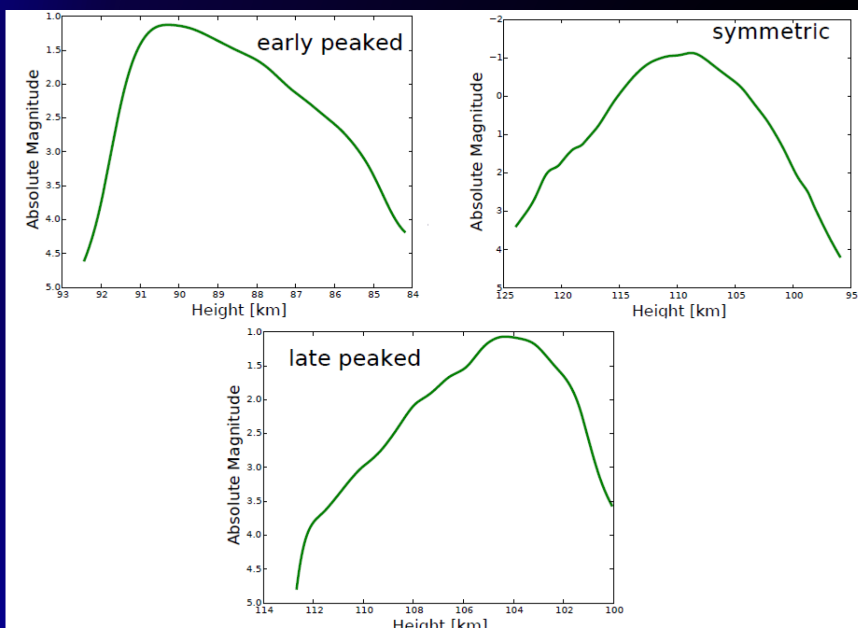
Could be explained if most meteors underwent progressive fragmentation.

Hawkes & Jones (1975) developed a quantitative model of dustball meteors.

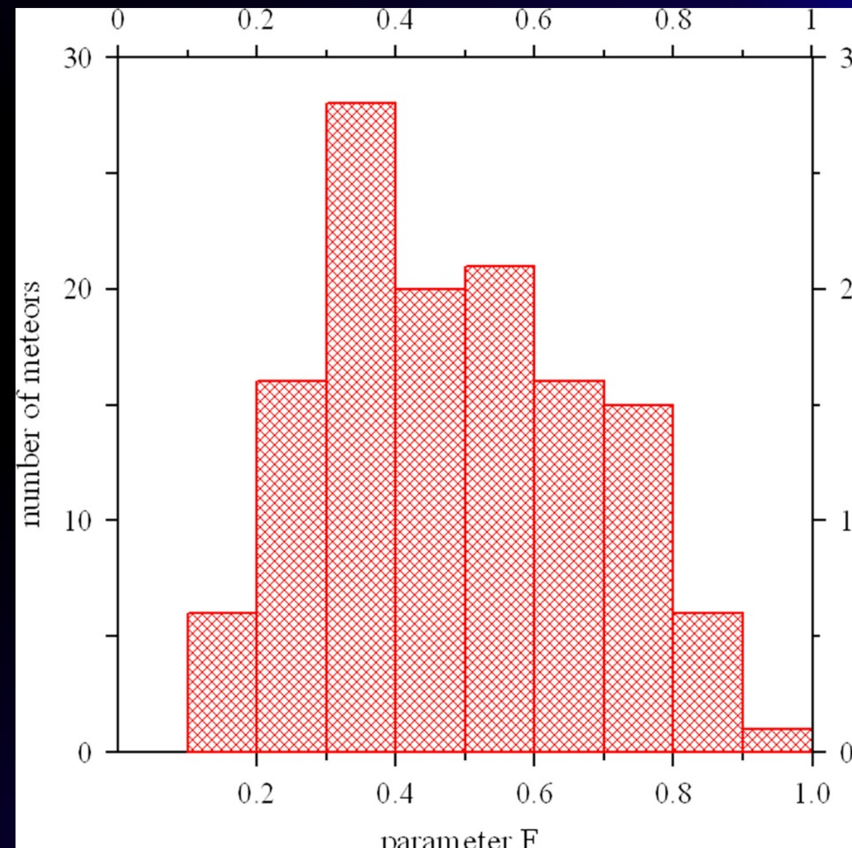
Light curves: F parameter

F < 0.5

F ≈ 0.5

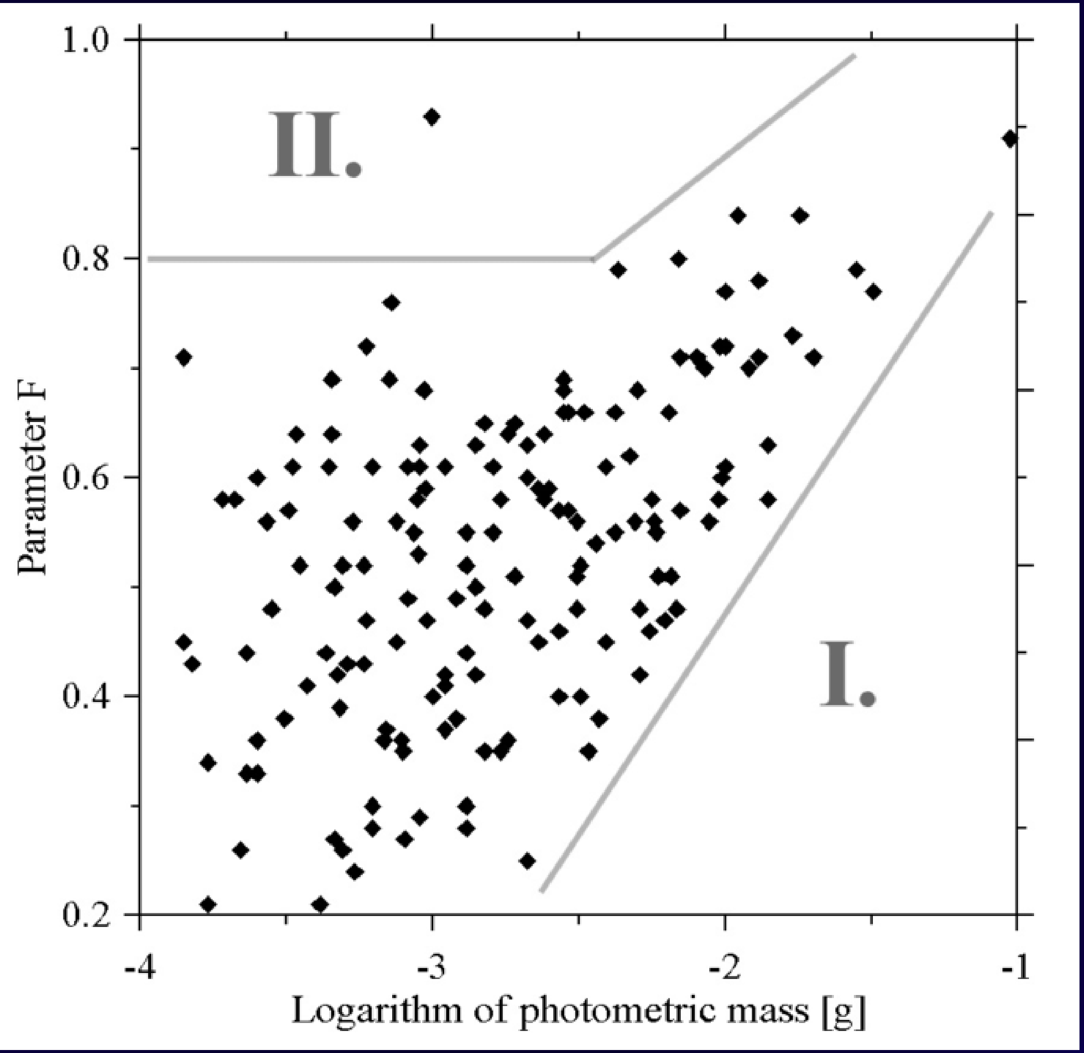


F > 0.5



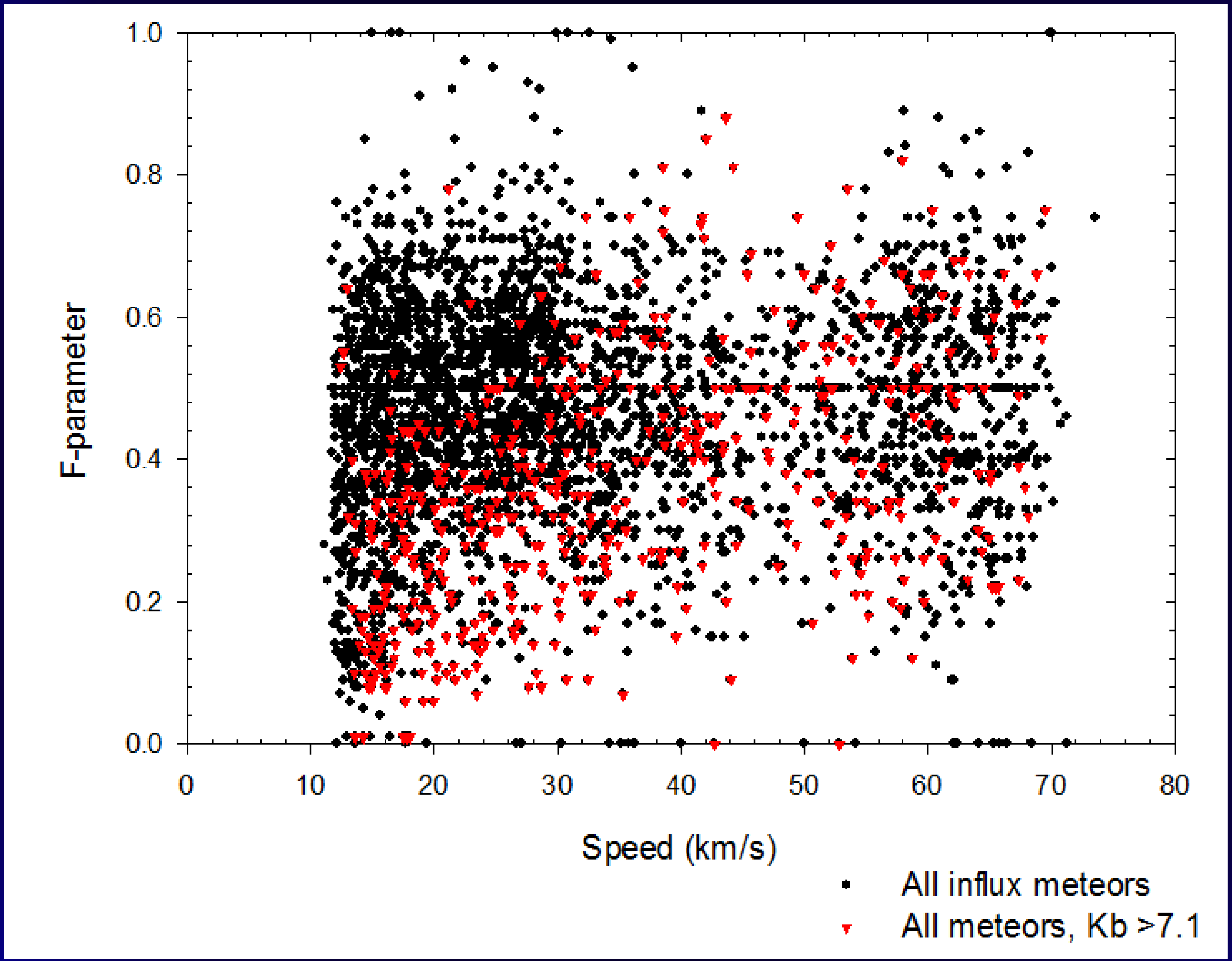
2011 Draconids, Koten et al. 2015

Light curve shape and mass

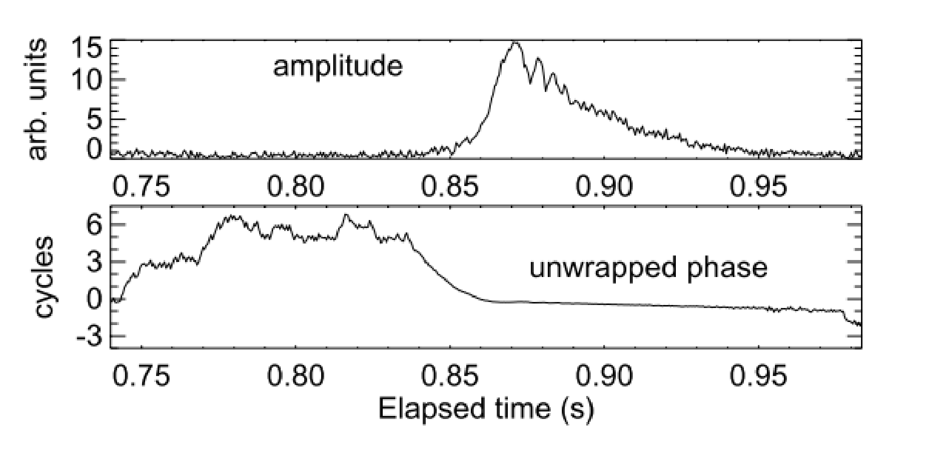


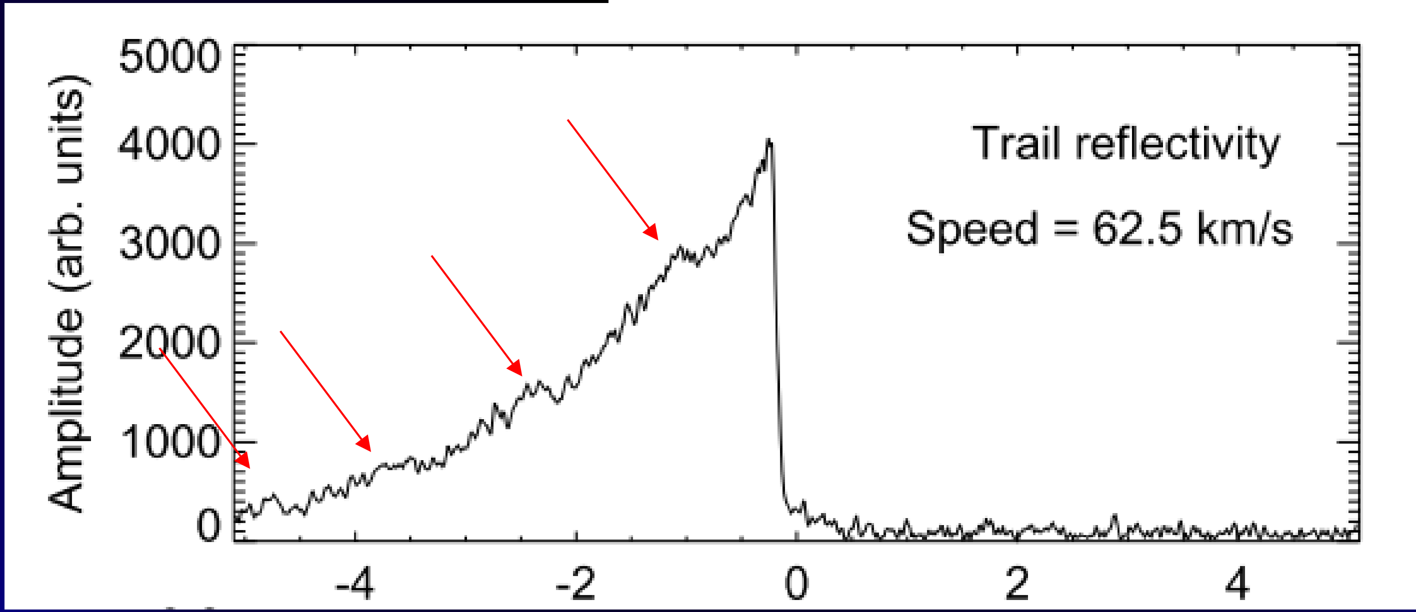
Perseid meteors Koten et al., 2004

Light curve shape and strength



Direct measurement: Fresnel Holography in trail scatter echoes

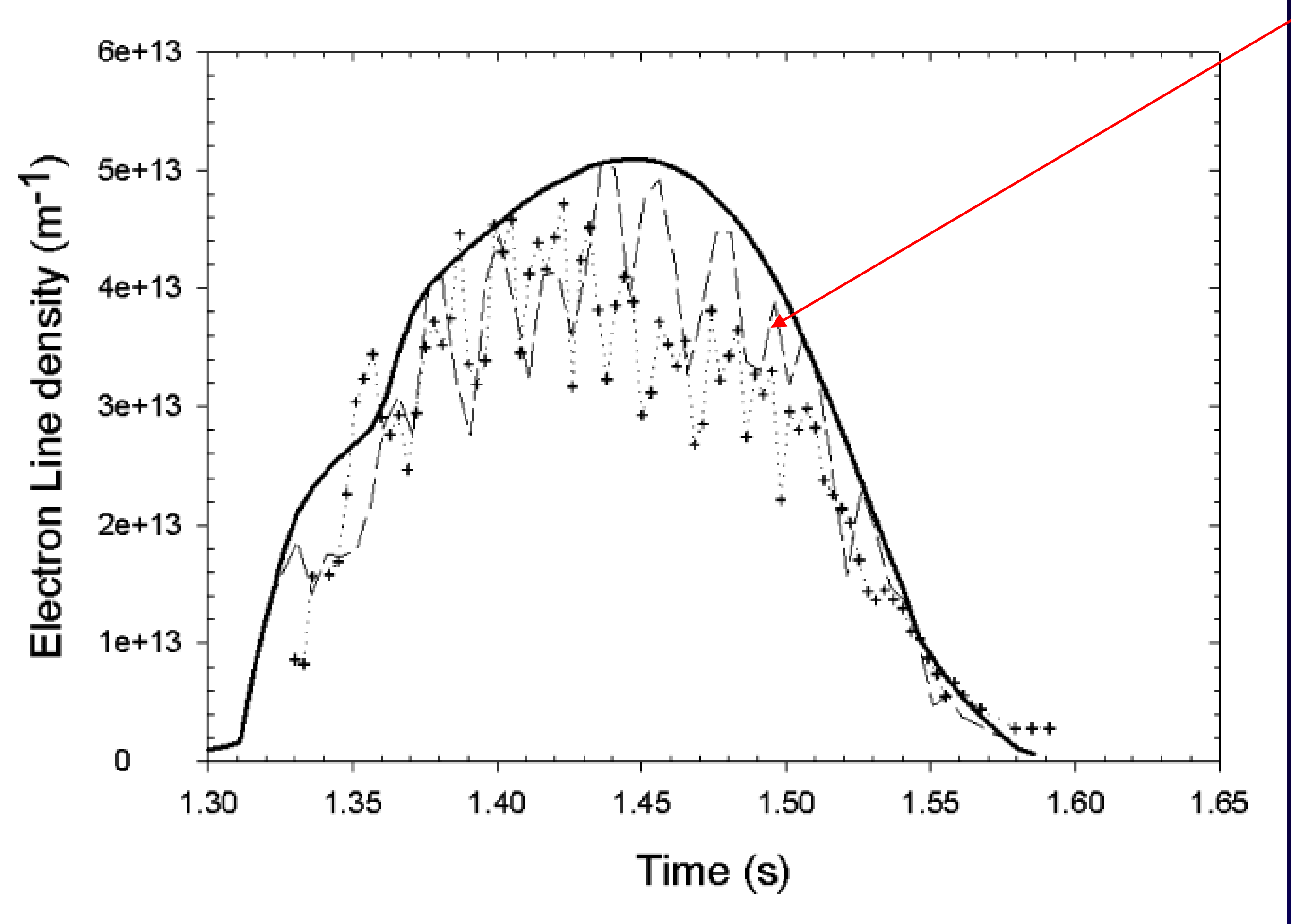




Elford, 2004

Head echoes

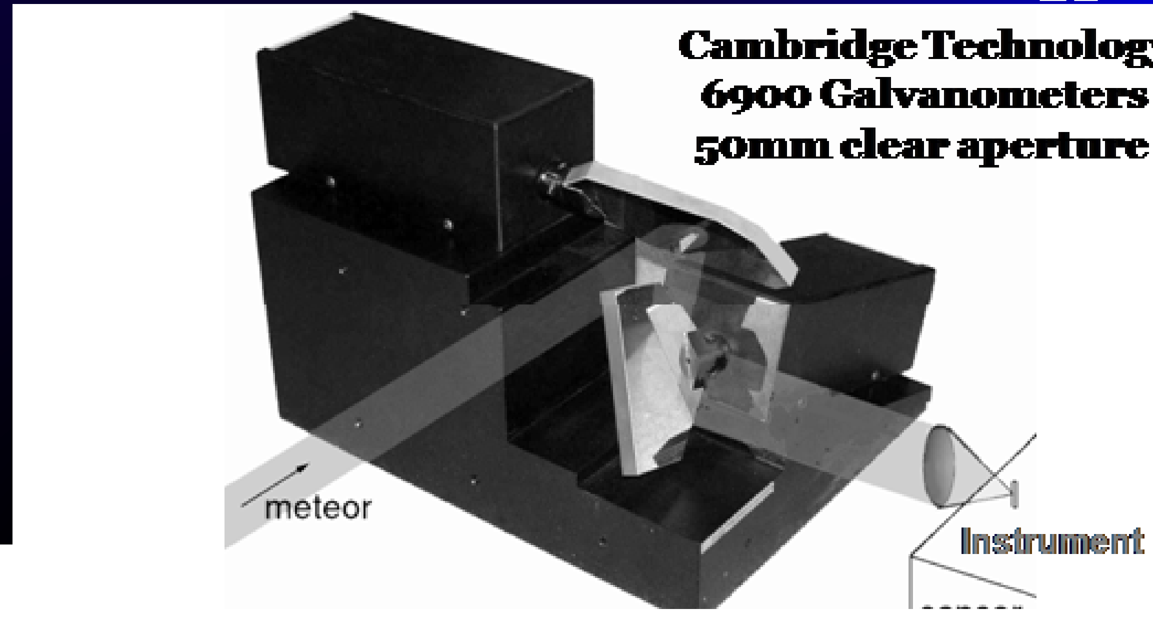
Oscillations in signal not necessarily due to scattering strength

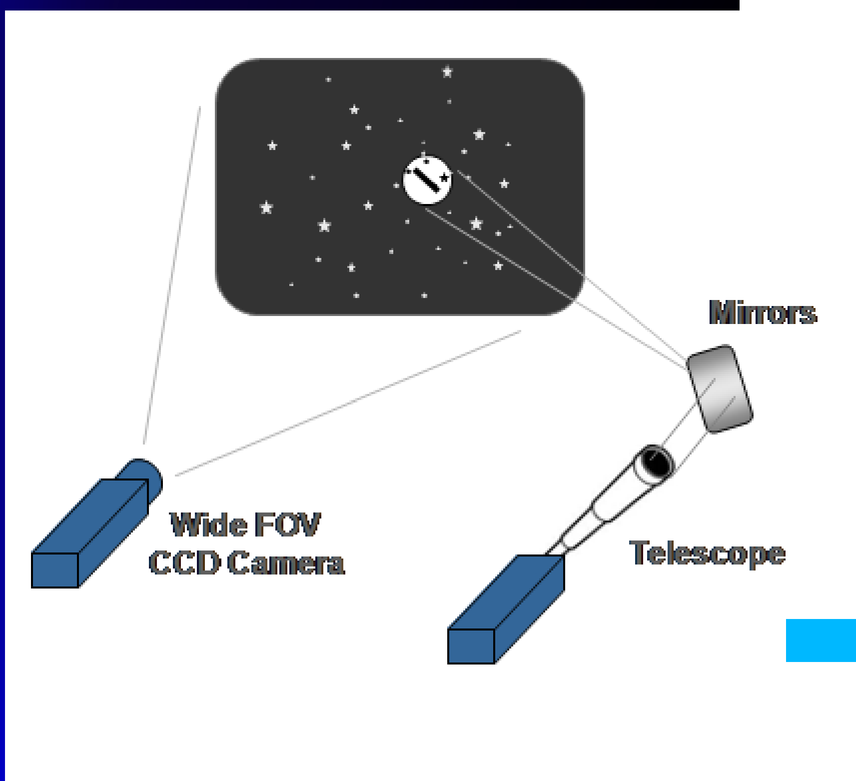


Altair head echo and model

Campbell-Brown & Close, 2007

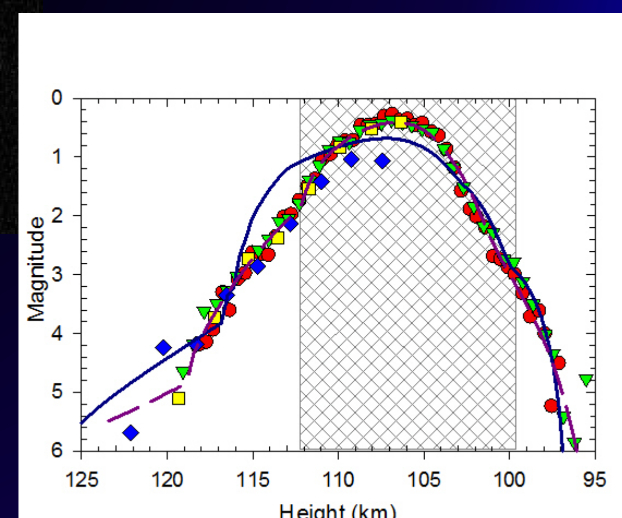
CAMO tracking system





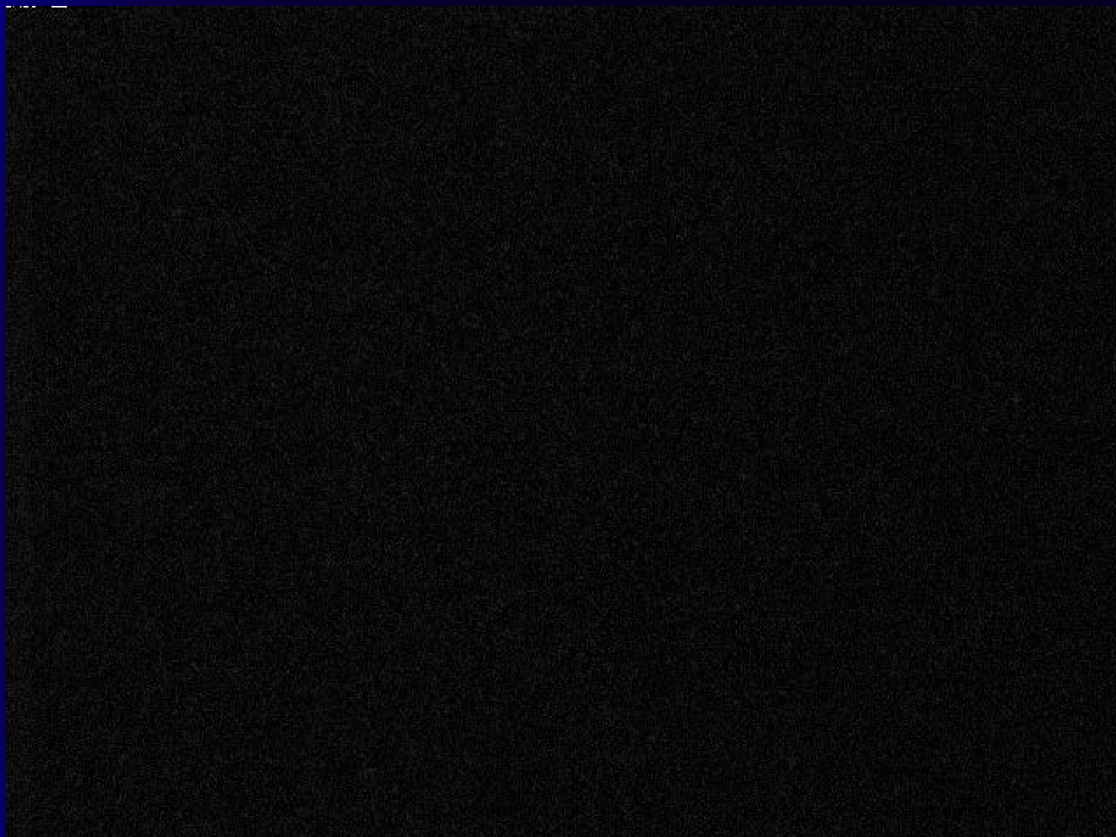
Narrow field morphologies

Light curves typically symmetric (as expected)

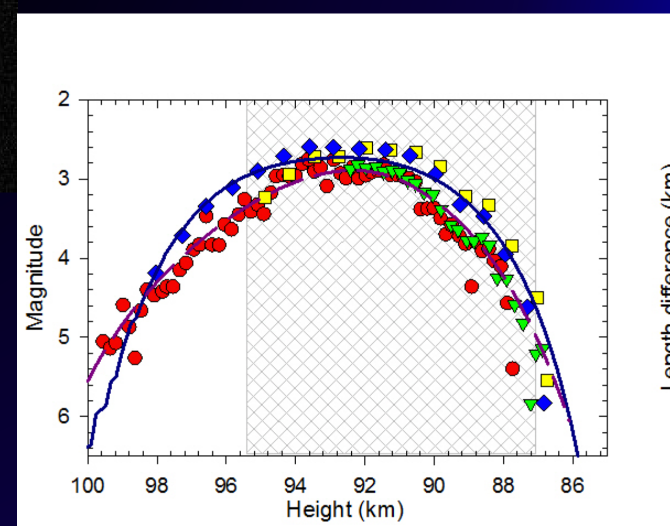


Long wake (~85%)
Crumbling fragmentation

Narrow field morphologies



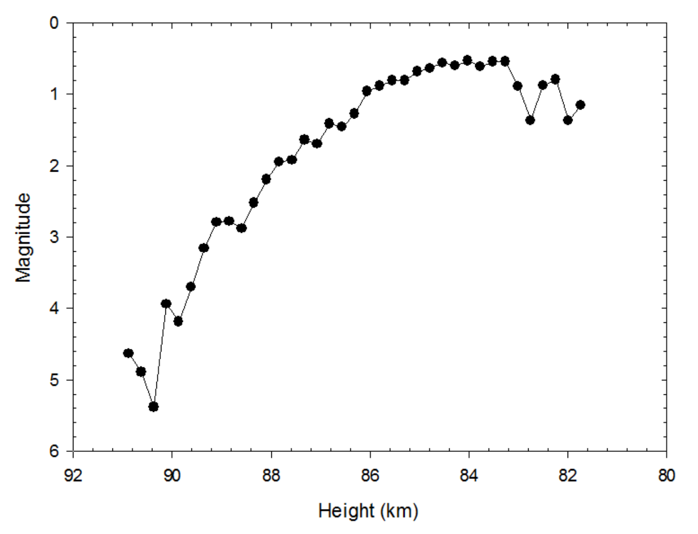
Light curves typically symmetric (not as expected)



Little wake (~9%)
Little fragmentation

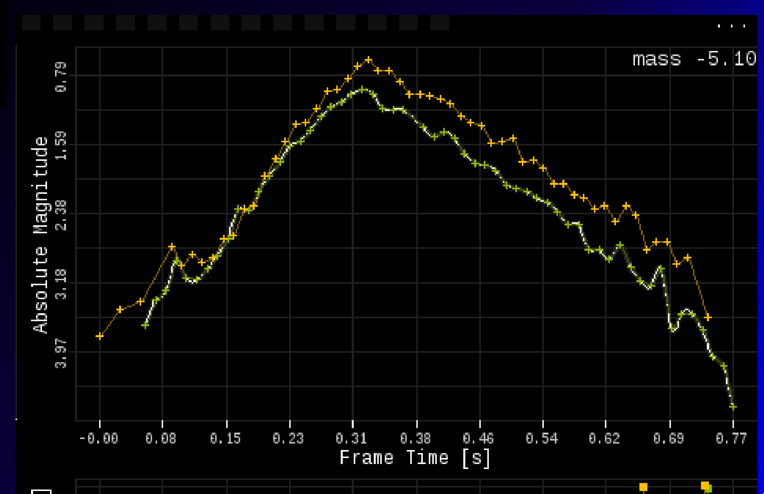
Narrow field morphologies

Distinct fragments (~5%)
Gross fragmentation



Narrow field morphologies

Also seen in wide field data (eg Borovička & Jenniskens 2000)



Terminal fragment
Refractory inclusion

Summary

- Meteoroids display a wide range of behaviours, consistent with differences among and within their parent bodies

- Increasing constraints on meteoroid structure will help improve meteoroid ablation models

- Combinations of observing techniques will give the best characterization of meteoroid structure.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