Modeling Meteor Flares for Spacecraft Safety

Steven Ehlert

Qualis Corporation/Jacobs ESSSA Group
NASA Meteoroid Environment Office

February 28, 2017

Overview

- NASA's Meteoroid Environment Office
- A brief primer on the meteoroid environment
- Spacecraft effects
- Measuring meteoroid masses with video observations
- Observations of fragmenting meteors
- Future work

Part I: The MEO

NASA’s Meteoroid Environment Office

Program managed by NASA’s Office of Safety and Mission Assurance (OSMA)

NASA’s Meteoroid Environment Office (MEO) is the NASA organization responsible for meteoroid environments pertaining to spacecraft engineering and operations.

Spacecraft Risk!

JACOBS ESSSA Group

Primary Products

- Annual Meteor Shower Forecast
  - Predict flux as a function of time for various meteor showers in different mass regimes
  - Small fraction of overall risk ($\sim 10\%$), best managed by planning and operations
- Meteoroid Engineering Model (MEM)
  - Model sporadic meteoroid flux along spacecraft trajectory
  - Majority of overall risk ($\sim 90\%$), best managed by spacecraft design

JACOBS
ESSSA Group

In Short:

$$\Phi(r, \theta, \phi, m, \rho_{\mathrm{m}}, v, t)$$

In Short:

$$\Phi(r, \theta, \phi, m, \rho_{\mathrm{m}}, v, t)$$

This talk will focus on measuring m

Part 2: The Meteoroid Environment

In a nutshell

- Neither showers nor sporadic meteoroids are isotropic
- $v \sim 10 - 72\,\mathrm{km\,s^{-1}}$
- $\rho_\mathrm{m} \sim 0.1 - 8\,\mathrm{g\,cm^{-3}}$
- $dN = m^{-s} dm$, $s \in [1.5, 2.5]$
- Threat regime: $m \sim 10^{-6} - 1\,\mathrm{g}$

JACOBS ESSSA Group

Part 3: Spacecraft Effects

JACOBS ESSSA Group

A Useful Comparison

An impact from a $1\,\mathrm{mg}$ meteoroid at $\sim 20\,\mathrm{km\,s^{-1}}$ has the same kinetic energy as a Magnum .357 bullet

JACOBS ESSSA Group

A Hypervelocity Impact Test

Target: A Navy Transit Satellite

Impactor: A $5\,\mathrm{cm}$ Al sphere moving at $6\,\mathrm{km\,s^{-1}}$

Before Impact

After Impact

Recorded Spacecraft Impacts

Which spacecraft have been struck by meteoroids? And what happened to them?

Here are three spacecraft anomalies where meteoroid impacts were identified as the most likely culprit…

Chandra X-ray Observatory

- On 15 November 2003 Chandra showed an sudden change in attitude
- Attributed either to an impact from a $\sim 1\,\mathrm{mm}$ sporadic meteoroid or Leonid

XMM-Newton X-Ray Observatory

- XMM-Newton has four recorded impacts
- A 2001 impact created 27 bad pixels in the camera
- A 2005 impact destroyed CCD #6 in the MOS1 camera

Olympus Communication Satellite

- Solar array struck by a Perseid during the outburst of 1993
- Recovery exhausted fuel supply, now in disposal orbit
- Plasma produced by impact $\propto v^{3.5}$

Take-away messages

- Meteoroid impacts on spacecraft are infrequent, but do happen
- Effects may be small, serious, or catastrophic
- Important contribution to overall risk of spacecraft missions

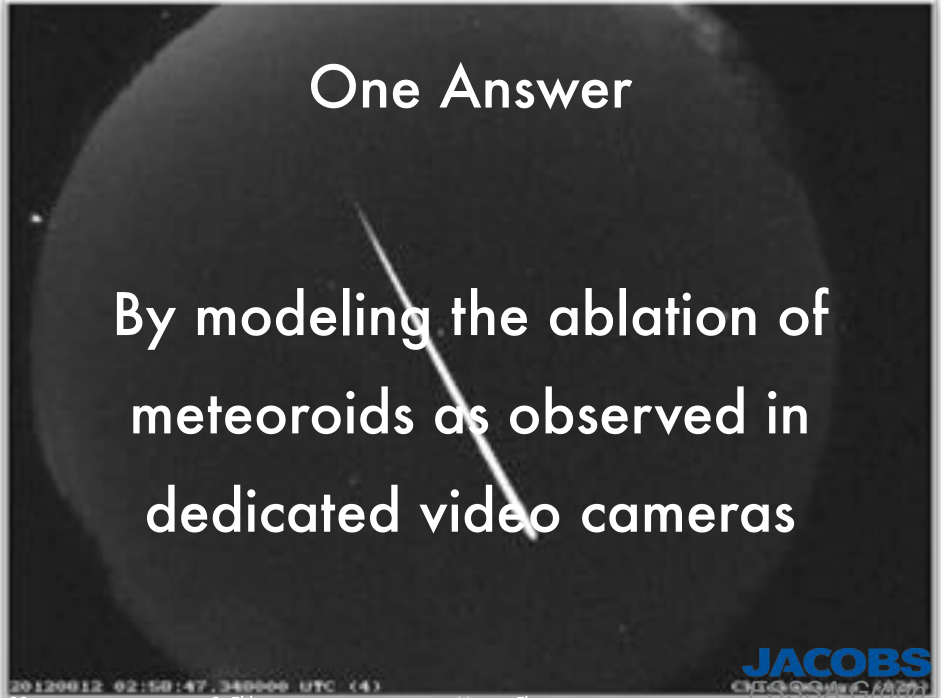
JACOBS ESSSA Group

Part 4: Meteor Masses

Question

How are the masses of individual meteoroids estimated?

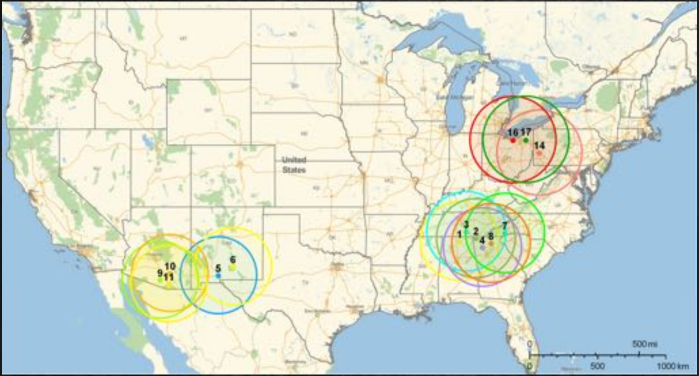
One Answer



By modeling the ablation of meteoroids as observed in dedicated video cameras

An All-sky Camera

NASA's All-sky Camera Network



Camera Data

Video camera data immediately provide

- Time of event
- Alt-Az of meteor at given time
- Photometry

Camera Data Part II

With 2+ cameras, we also get

- Trajectory: Height, Velocity, Range, etc...
- Orbital elements
- Absolute magnitude

More Camera Data

Trajectory + light curve enable meteoroid masses and densities to be estimated:

$v(t),\ h(t),\ \&\ \mathcal{L}(t)$ are measured

$m(t),\ \rho_{\mathrm{m}}$ can be calculated from assumed ablation model and atmospheric profile

Part 5: Ablation

The Classical Ablation Model

Meteoroid has mass m, density ρ_{m}, and velocity v at zenith angle η

$$\text{Deceleration:}\quad \frac{dv}{dt} = \frac{-\Gamma A}{m^{1/3}\rho_{\mathrm{m}}^{2/3}}\rho_{\mathrm{a}} v^2$$

$$\text{Ablation:}\quad \frac{dm}{dt} = -\Gamma A \sigma \left(\frac{m}{\rho_{\mathrm{m}}}\right)^{2/3} \rho_{\mathrm{a}} v^3$$

$$\text{Height:}\quad \frac{dh}{dt} = -v\cos\eta$$

$$\text{Atmosphere:}\quad \rho_{\mathrm{a}}(h) = \rho_0 e^{-\frac{h}{H^\star}}$$

$$\text{Luminosity:}\quad \mathcal{L}' = -\tau \times \frac{dK}{dt} = -\tau(v) \times \frac{1}{2} v^2 \frac{dm}{dt}$$

JACOBS ESSSA Group

The Classical Ablation Model

Meteoroid has mass m, density $\rho_{\rm m}$, and velocity v at zenith angle η

Deceleration: $$\frac{dv}{dt} = \frac{-\Gamma A}{m^{1/3}\rho_{\rm m}^{2/3}}\rho_{\rm a} v^2$$

Ablation: $$\frac{dm}{dt} = -\Gamma A \sigma \left(\frac{m}{\rho_{\rm m}}\right)^{2/3} \rho_{\rm a} v^3$$

Height: $$\frac{dh}{dt} = -v\cos\eta$$

Atmosphere: $$\rho_{\rm a}(h) = \rho_0 e^{-\frac{h}{H^\star}}$$

Luminosity: $$\mathcal{L}' = -\tau \times \frac{dK}{dt} = -\tau(v) \times \frac{1}{2} v^2 \frac{dm}{dt}$$

Γ: Drag Coefficient

The Classical Ablation Model

Meteoroid has mass m, density ρ_{m}, and velocity v at zenith angle η

Deceleration: $$\frac{dv}{dt} = \frac{-\Gamma A}{m^{1/3}\rho_{\mathrm{m}}^{2/3}}\rho_{\mathrm{a}} v^2$$

Ablation: $$\frac{dm}{dt} = -\Gamma A \sigma \left(\frac{m}{\rho_{\mathrm{m}}}\right)^{2/3} \rho_{\mathrm{a}} v^3$$

Height: $$\frac{dh}{dt} = -v\cos\eta$$

Atmosphere: $$\rho_{\mathrm{a}}(h) = \rho_0 e^{-\frac{h}{H^\star}}$$

Luminosity: $$\mathcal{L}' = -\tau \times \frac{dK}{dt} = -\tau(v) \times \frac{1}{2}v^2\frac{dm}{dt}$$

A: Shape Coefficient

JACOBS ESSSA Group

The Classical Ablation Model

Meteoroid has mass m, density ρ_{m}, and velocity v at zenith angle η

Deceleration: $$\frac{dv}{dt} = \frac{-\Gamma A}{m^{1/3}\rho_{\mathrm{m}}^{2/3}}\rho_{\mathrm{a}} v^2$$

Ablation: $$\frac{dm}{dt} = -\Gamma A \sigma \left(\frac{m}{\rho_{\mathrm{m}}}\right)^{2/3} \rho_{\mathrm{a}} v^3$$

Height: $$\frac{dh}{dt} = -v\cos\eta$$

Atmosphere: $$\rho_{\mathrm{a}}(h) = \rho_0 e^{-\frac{h}{H^\star}}$$

Luminosity: $$\mathcal{L}' = -\tau \times \frac{dK}{dt} = -\tau(v) \times \frac{1}{2} v^2 \frac{dm}{dt}$$

σ: Ablation Coefficient

JACOBS ESSSA Group

The Classical Ablation Model

Meteoroid has mass m, density ρ_{m}, and velocity v at zenith angle η

$$\text{Deceleration:}\quad \frac{dv}{dt} = \frac{-\Gamma A}{m^{1/3}\rho_{\mathrm{m}}^{2/3}}\rho_{\mathrm{a}}v^2$$

$$\text{Ablation:}\quad \frac{dm}{dt} = -\Gamma A\sigma\left(\frac{m}{\rho_{\mathrm{m}}}\right)^{2/3}\rho_{\mathrm{a}}v^3$$

$$\text{Height:}\quad \frac{dh}{dt} = -v\cos\eta$$

$$\text{Atmosphere:}\quad \rho_{\mathrm{a}}(h) = \rho_0 e^{-\frac{h}{H^\star}}$$

$$\text{Luminosity:}\quad \mathcal{L}' = -\tau \times \frac{dK}{dt} = -\tau(v) \times \frac{1}{2}v^2\frac{dm}{dt}$$

$H^\star$: Scale Height of Atmosphere

JACOBS
ESSSA Group

The Classical Ablation Model

Meteoroid has mass m, density ρ_{m}, and velocity v at zenith angle η

$$\text{Deceleration: } \frac{dv}{dt} = \frac{-\Gamma A}{m^{1/3}\rho_{\mathrm{m}}^{2/3}}\rho_{\mathrm{a}} v^2$$

$$\text{Ablation: } \frac{dm}{dt} = -\Gamma A \sigma \left(\frac{m}{\rho_{\mathrm{m}}}\right)^{2/3} \rho_{\mathrm{a}} v^3$$

$$\text{Height: } \frac{dh}{dt} = -v\cos\eta$$

$$\text{Atmosphere: } \rho_{\mathrm{a}}(h) = \rho_0 e^{-\frac{h}{H^\star}}$$

$$\text{Luminosity: } \mathcal{L} = -\tau \times \frac{dK}{dt} = -\tau(v) \times \frac{1}{2} v^2 \frac{dm}{dt}$$

τ: Luminous Efficiency

Measuring Masses

If you measure deceleration and you assume a solid body, you can measure the mass two ways:

Dynamic: $$m_{\mathrm{d}} = \frac{\Gamma^3 \rho_{\mathrm{a}}^3 v^6 A^3}{\rho_{\mathrm{m}}^2 \left(\frac{dv}{dt}\right)^3}$$

Photometric: $$m_{\mathrm{p}} = \int \frac{2\mathcal{L}(t)}{\tau v^2} dt$$

Practical Challenges

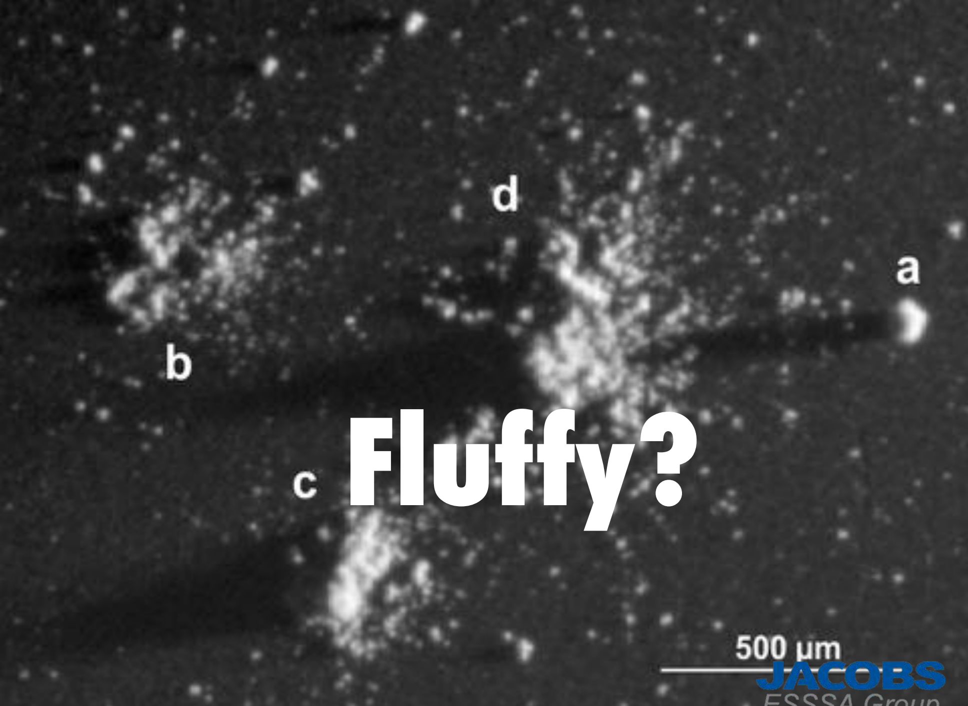
Challenges with Dynamic Masses

- Deceleration frequently not observed
- Uncertainties compound quickly
- What is ρ_m?

Challenges with Model Assumptions

- What is τ?
- Critical scale-dependent physics not included
- Fragmentation commonly observed
- Lots of evidence that meteoroids are "fluffy", not solid bodies

JACOBS
ESSSA Group



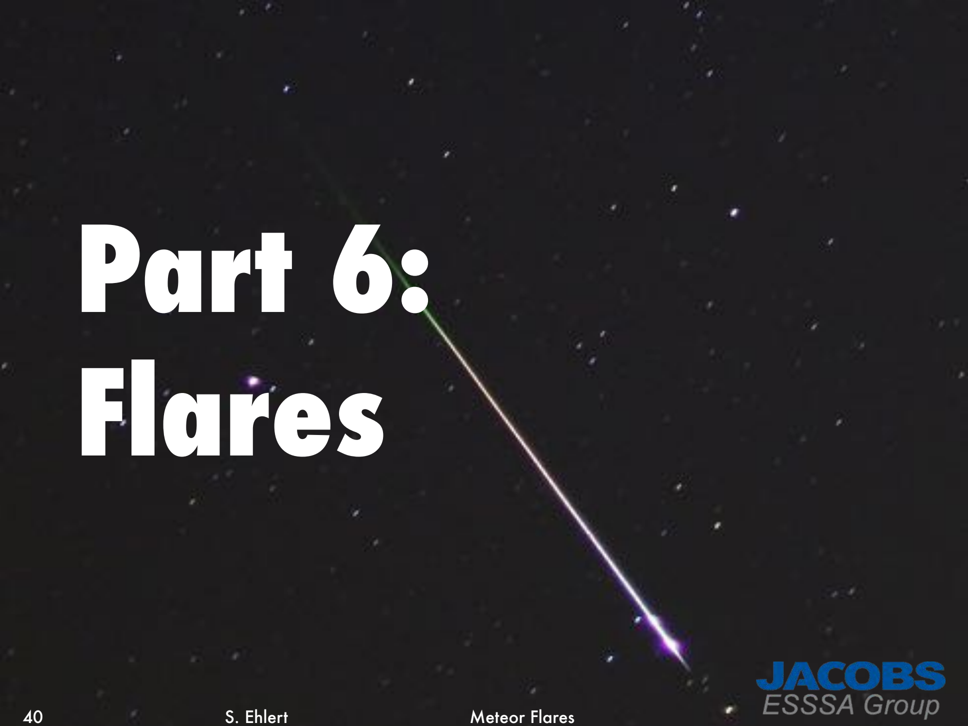
JACOBS
ESSSA Group

Proposed Model Complexities

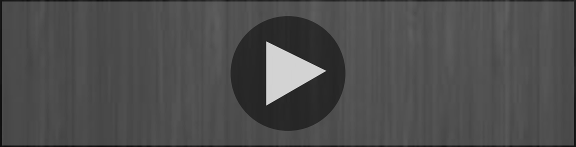
- “Dust-ball ” structure
- Thermal stresses within the meteoroid
- Fragmentation

Still no definitive model for meteoroid structure!

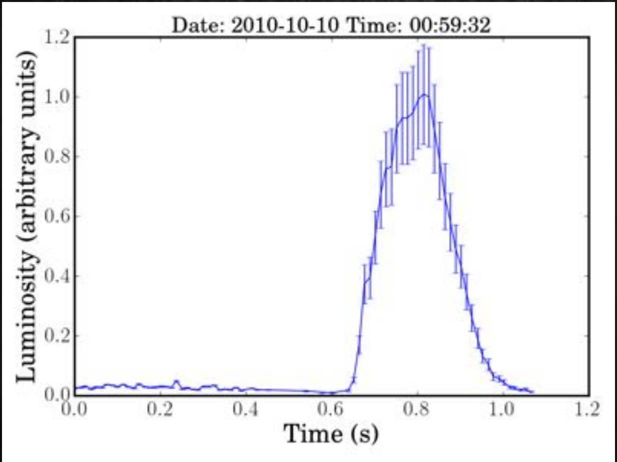
Part 6: Flares



A Flaring Meteor



A Flaring Meteor



JACOBS ESSSA Group

What use are flaring meteors?

Assuming we have double station video observations

- Trajectory $\rightarrow$ conditions of atmosphere at onset of ablation and flare
- Light curve $\rightarrow$ lifetime of fragment ablation, luminous efficiency

Much safer to assume that the fragments are solid bodies!

JACOBS ESSSA Group

A flare model

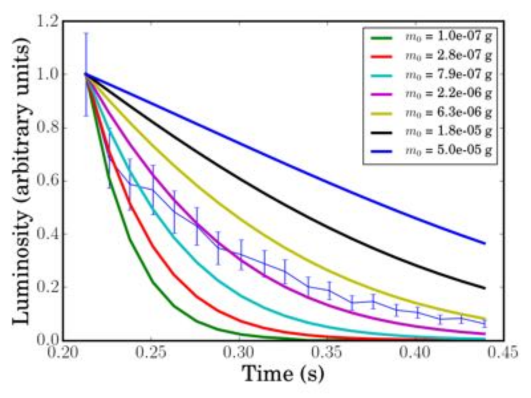
- Flare light curve is a superposition of self-similar classical ablations
- Further assume $\rho_\mathrm{m} = 3.5\,\mathrm{g\,cm^{-3}}$, $\sigma = 2 \times 10^{-12}\,\mathrm{s^2\,cm^{-2}}$
- Fragment masses distributed as a power-law $dN = N_0 \times m^{-q} dm$
- Luminous efficiency $\tau(v) = \tau_0 \times v$, $\tau_0 = 5.25 \times 10^{-10}\,\mathrm{s\,cm^{-1}}$
- Only fitting "decaying" edge of the flare

JACOBS
ESSSA Group

Camera Data

- Southern Ontario Meteor Network video data
- 640×480 pixel video cameras provide $25.8^\circ \times 19.2^\circ$ FOV
- Video is at ~ 75 frames per second
- Limiting meteor magnitude of $R \sim 5$

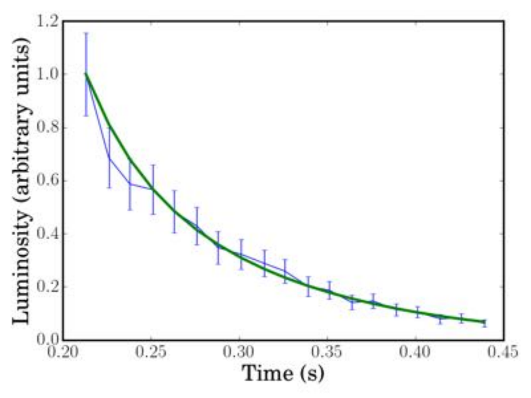
Individual Fragment Light Curves



JACOBS
ESSSA Group

The Superposition Model with

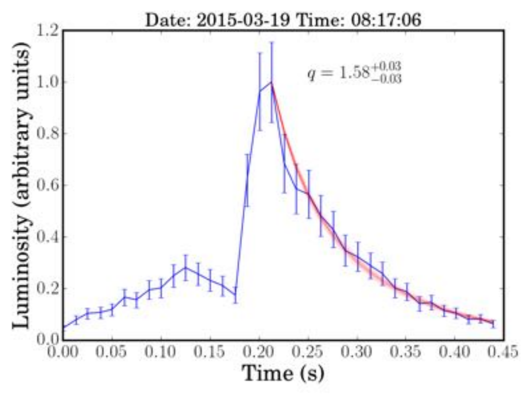
$$q = 1.58$$



Results for Eleven Flares

Date (UTC)	Time (UTC)	q
2010-09-20	08:46:08	$2.27^{+0.13}_{-0.11}$
2010-10-10	00:59:32	$2.56^{+0.08}_{-0.07}$
2011-07-06	05:42:34	$2.22^{+0.05}_{-0.04}$
2011-08-30	07:15:19	$2.29^{+0.10}_{-0.10}$
2011-10-05	08:47:34	$2.09^{+0.06}_{-0.05}$
2012-05-21	06:18:37	$2.58^{+0.14}_{-0.12}$
2015-03-19	04:42:03	$2.35^{+0.14}_{-0.12}$
2015-03-19	08:17:06	$1.58^{+0.03}_{-0.03}$
2015-03-23	03:56:32	$1.44^{+0.08}_{-0.10}$
2015-03-29	09:44:30	$1.44^{+0.08}_{-0.08}$
2015-04-12	02:27:06	$1.24^{+0.09}_{-0.09}$

One Fit Result

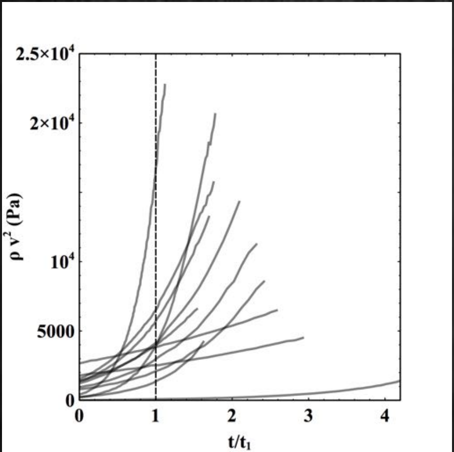


JACOBS ESSSA Group

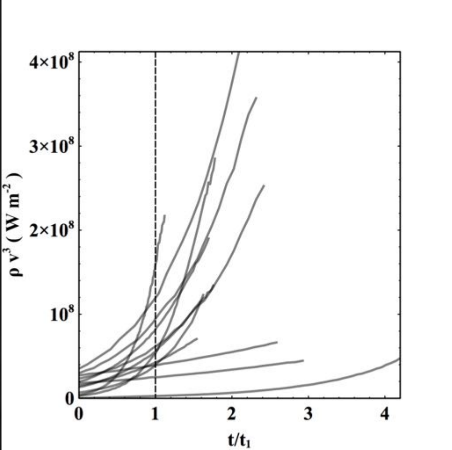
Dynamical State at Fragmentation

Do these particular flares all occur at a critical pressure or energy flux?
Short Answer - NO

Pressure



Energy Flux



JACOBS ESSSA Group

Future Considerations

- Degeneracy between model parameters - especially mass index q and ablation coefficient σ
- Start investigating conditions at onset of flare to ascertain origin
- Find more flaring meteors in video archives
- Confront models of meteoroid structure with these data

JACOBS ESSSA Group

Conclusions

- Meteoroids are NOT Spherical Rocks!
- Meteoroid structure and material properties play a major role in understanding spacecraft risk
- Flares are useful for gaining some insights into meteoroid structure
- Flares can be reasonably modeled as a superposition of classically ablating meteoroids
- Many assumptions about meteoroid structure still required, and many questions still persist

JACOBS ESSSA Group