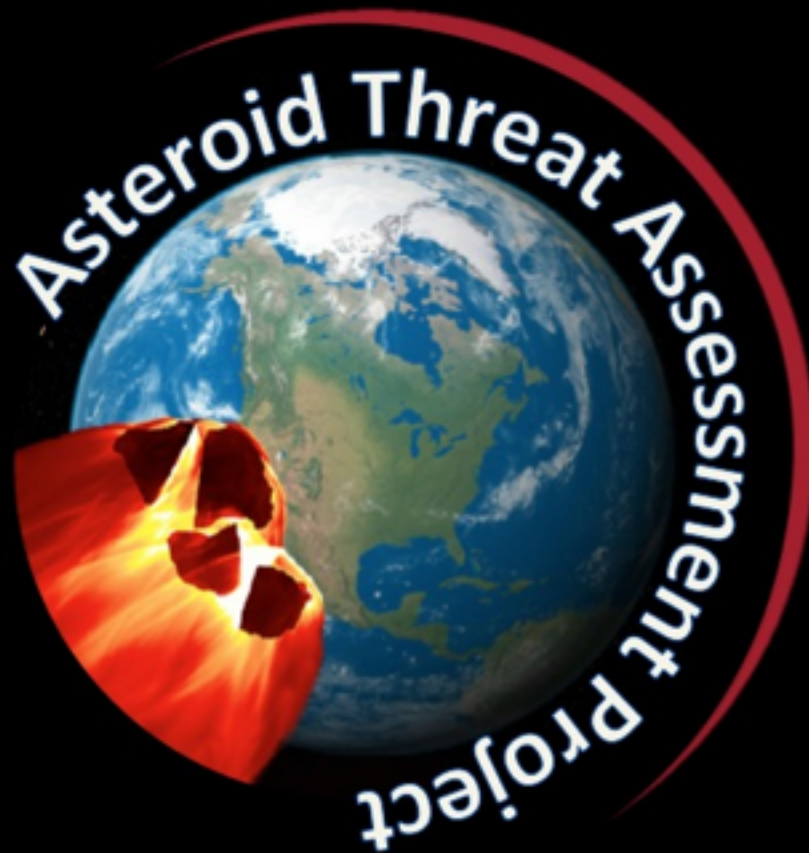




Radiant Heating Tests on Meteoritic Material

*Eric Stern
Susan White
Y-K. Chen
Dinesh Prabhu*

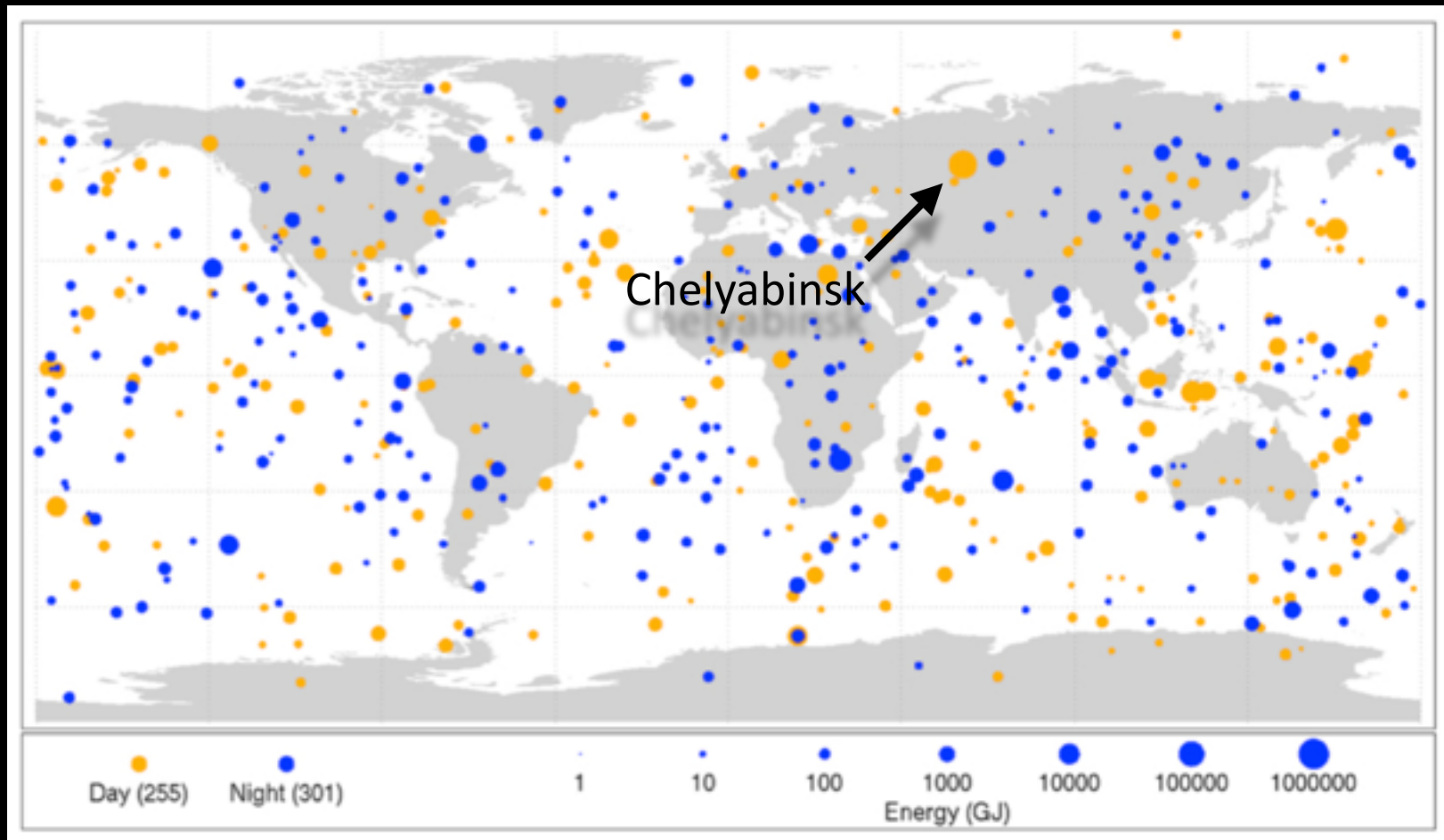
Threat from Small Asteroids



**Youtube*

- ~19m asteroid entered the atmosphere over Chelyabinsk, Russia on 2/15/2013
- Entry velocity ~19 km/s
- Resultant airburst with total yield approximately equivalent to 500 kilotons of TNT

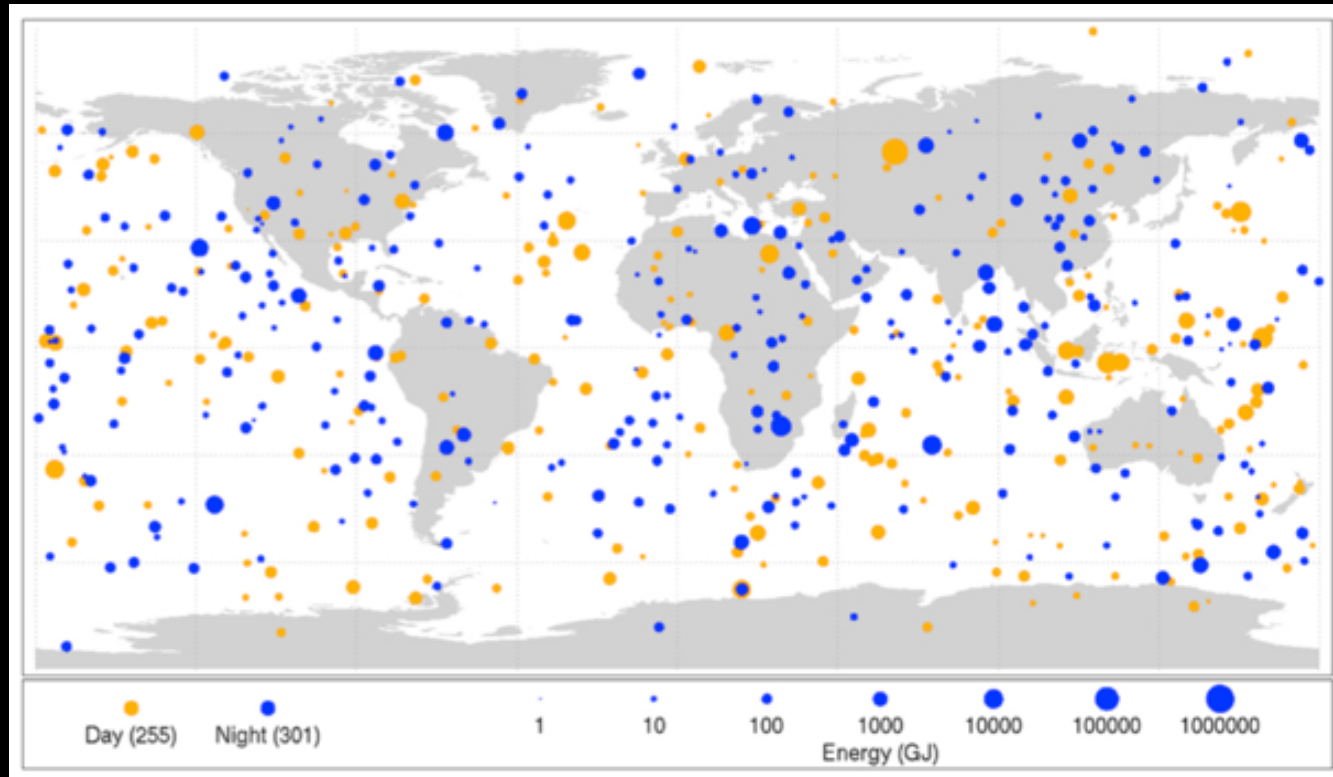
Threat from Small Asteroids



*JPL NEO Program

Detected Bolide Events from 1994 - 2014

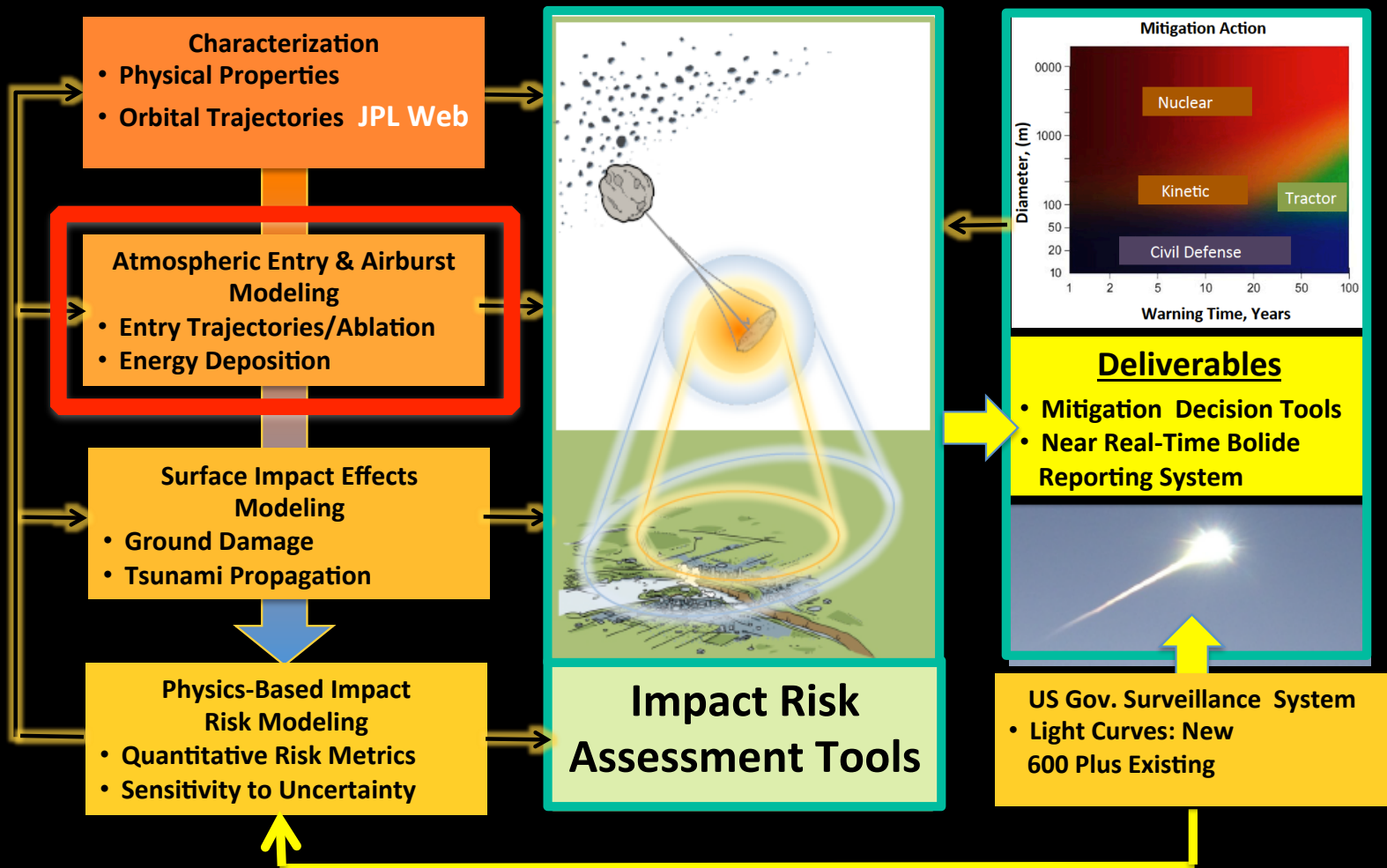
Threat from Small Asteroids



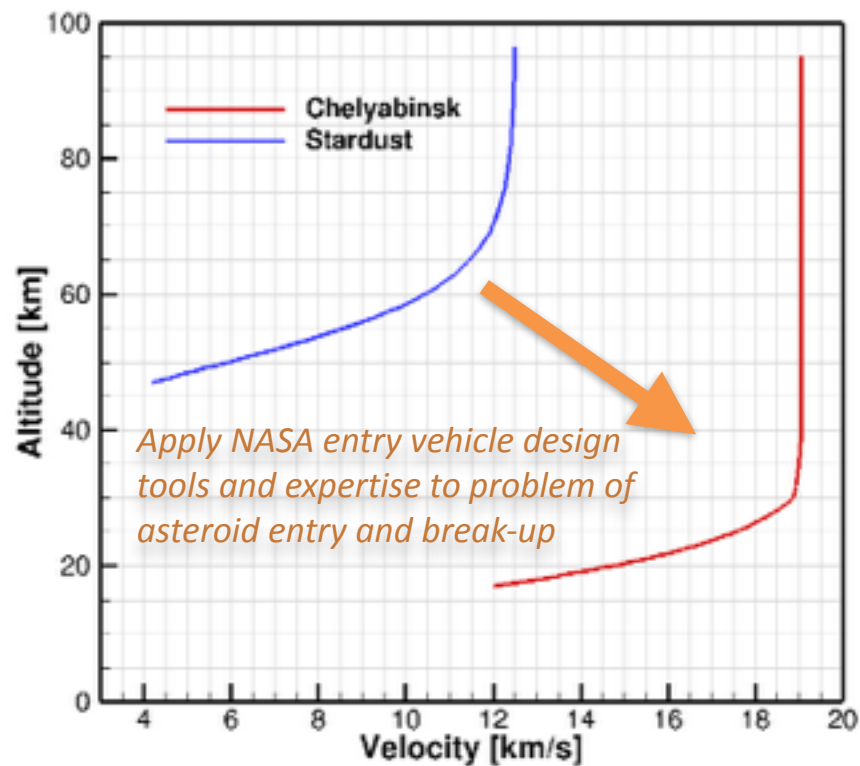
**JPL NEO Program*

- Majority of NEO's $>1\text{km}$ have been observed
- Estimated $<1\%$ of NEO's $<100\text{m}$ have been observed

Asteroid Threat Assessment Project (ATAP)

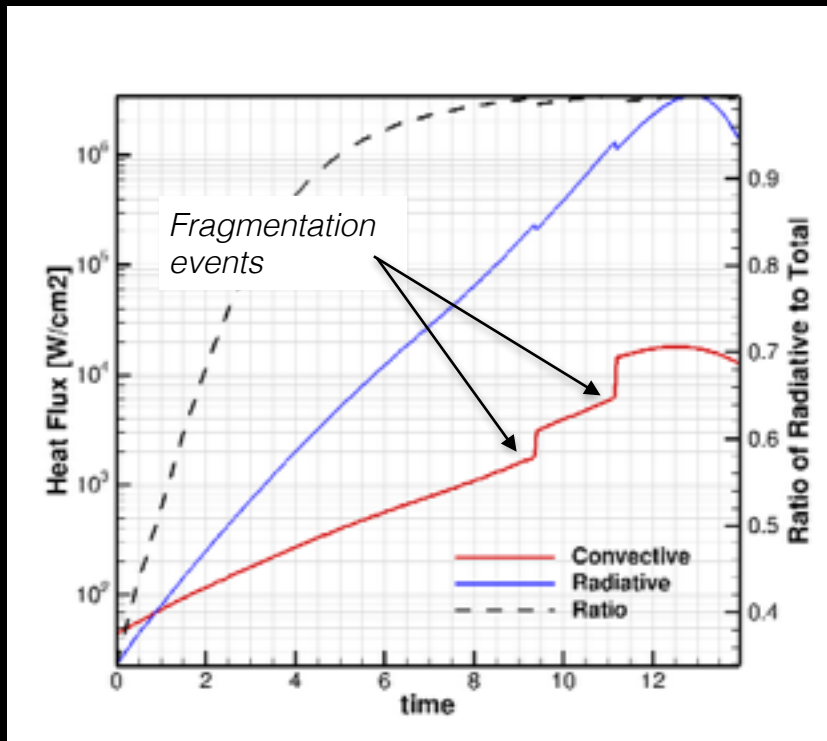


Meteor Entry Environment



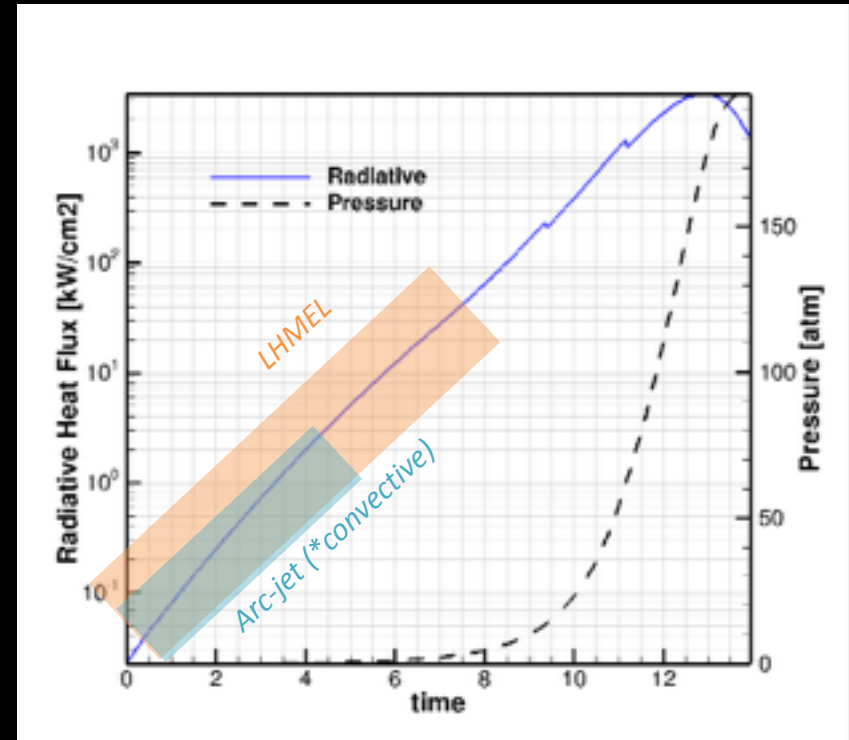
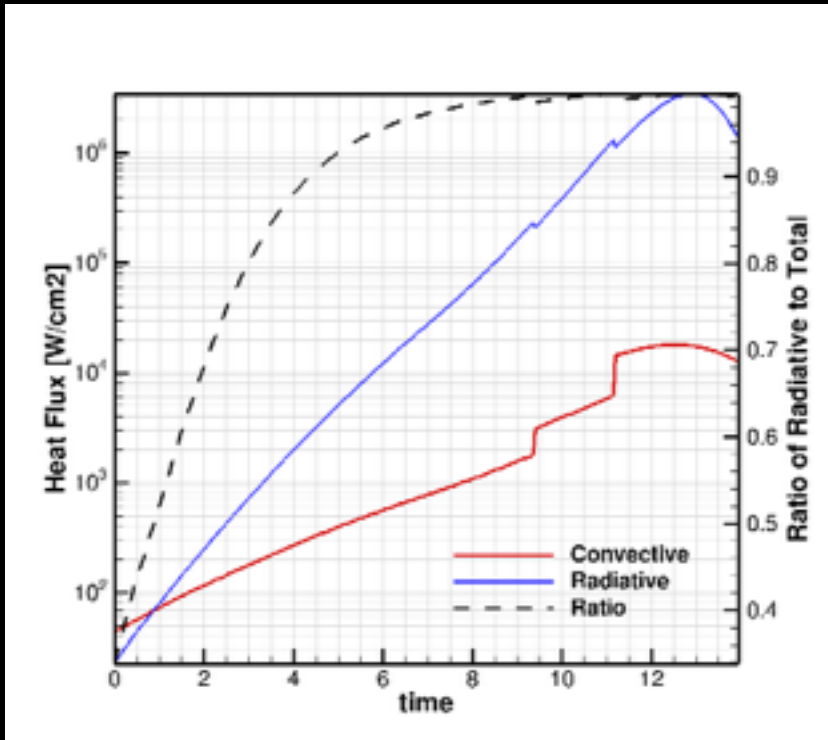
**cite*

Meteor Entry Environment



- Meteor entry environment different in many ways than that of typical spacecraft entry
 - ▶ Heating is *dominated* by radiation
 - ▶ Massive ablation
 - Chelyabinsk class asteroid may lose ~90% of mass during atmospheric passage

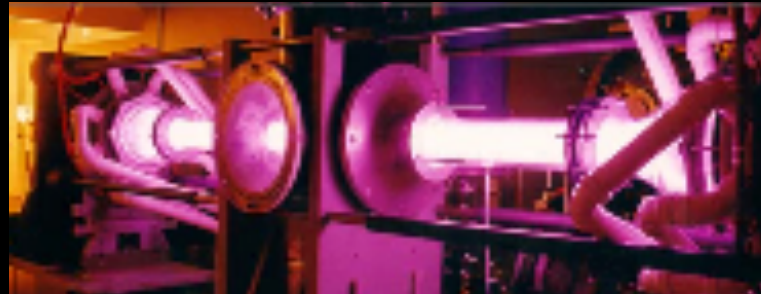
Meteor Entry Environment



- Arc-jet most often used to approximate entry environment for spacecraft
 - Convective heating rates up to $\sim 2 \text{ kW/cm}^2$ not representative of meteor flight
- Laser testing provides radiant heating rates representative of much of trajectory

LHMEL

- Laser Hardened Materials Evaluation Laboratory

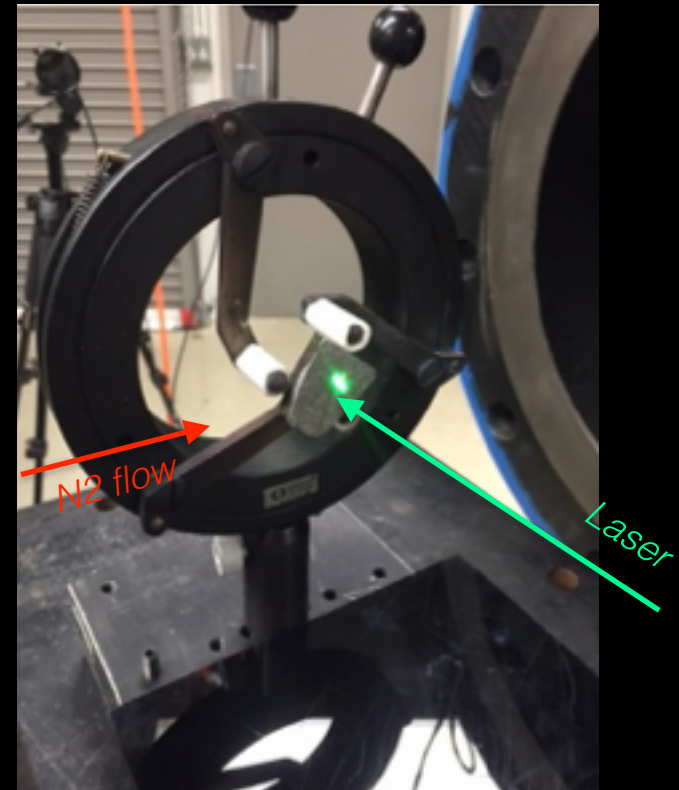
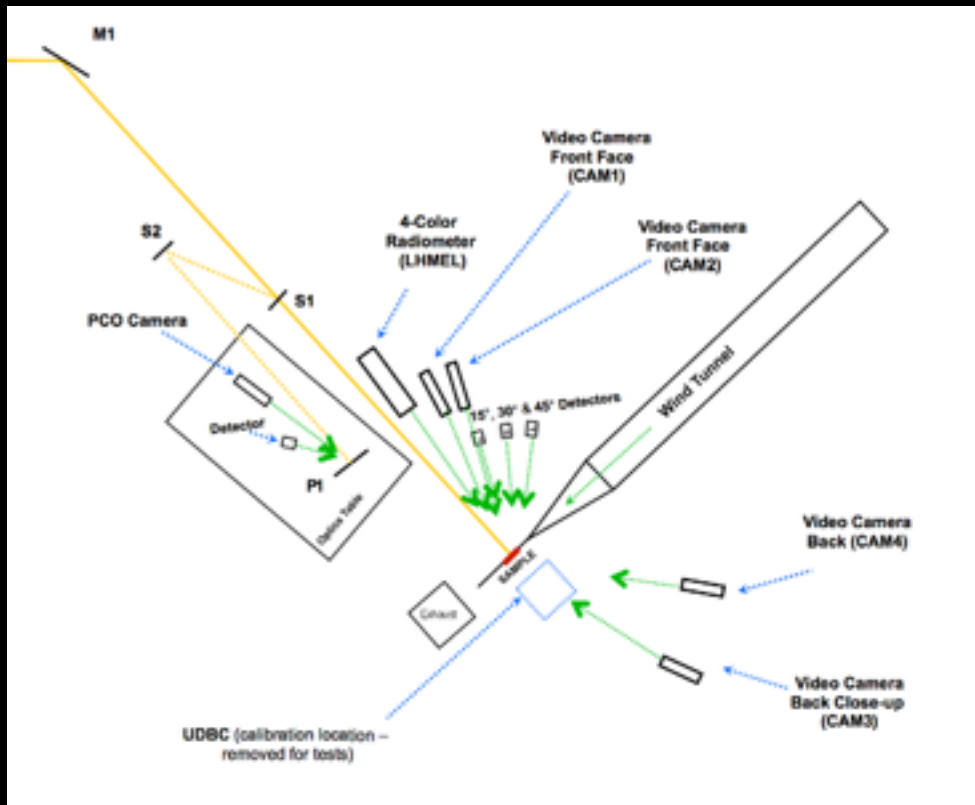


- Located at Wright-Patterson AFB in Dayton, Ohio
- Three facilities in one
 - ▶ LHMEL I: 10kW CO₂ laser (10.6 micron)
 - ▶ LHMEL II: 100kW CO₂ laser (10.6 micron)
 - ▶ Fiber Laser: 10 & 20kW (1.07 micron)

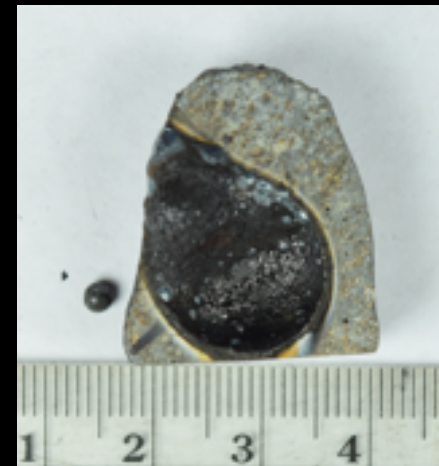
Pathfinder Experiment Objectives

- Gain a better understanding of the phenomenology of the ablation process for actual meteoritic material in a flight relevant heating environment
- Measure the effective heat of ablation for the experiment and compare to Classical Meteor Physics value, as well as model predictions
- Compare experimentally derived fusion crusts to those from flight

Test Set-up



Test Execution



Data

Classical Meteor Physics

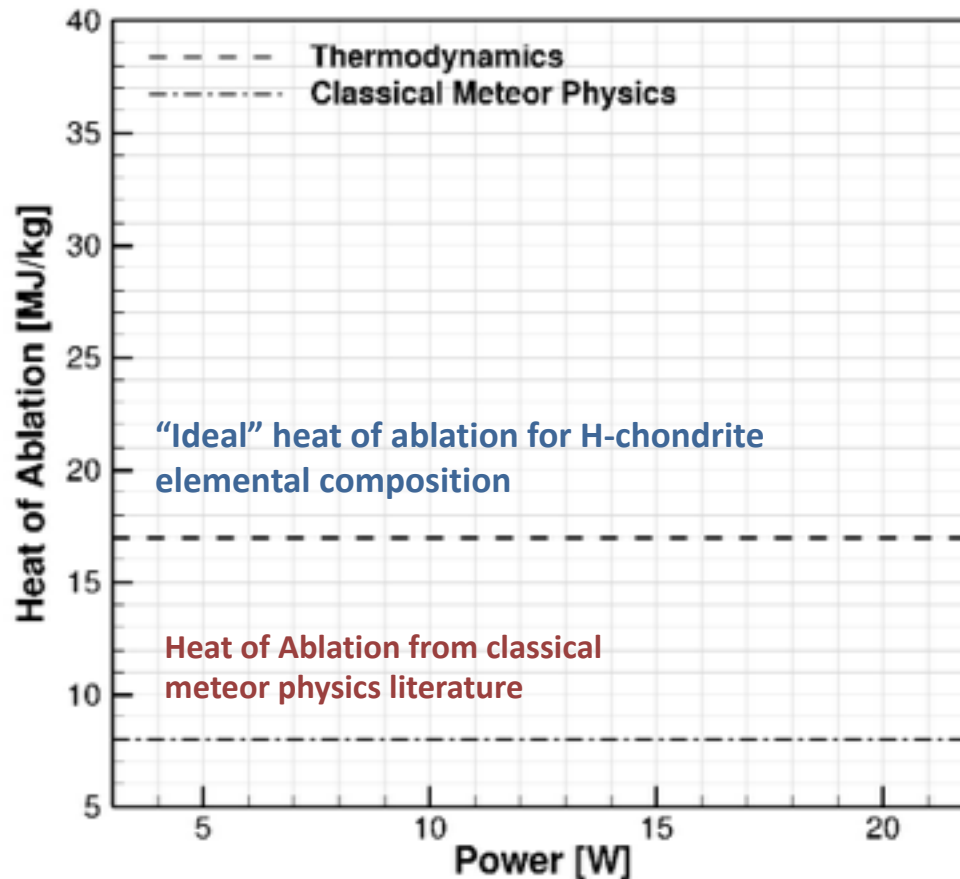
- Classical meteor physics equations originate in the 1950's (*often attributed to Öpik*) **cite*
- There have been many upgrades to this model since, mostly focus on fragmentation
- Ablation still typically modeled using “heat of ablation” model

$$\frac{dM}{dt} = - \Lambda \frac{S \rho v^3}{2Q}.$$

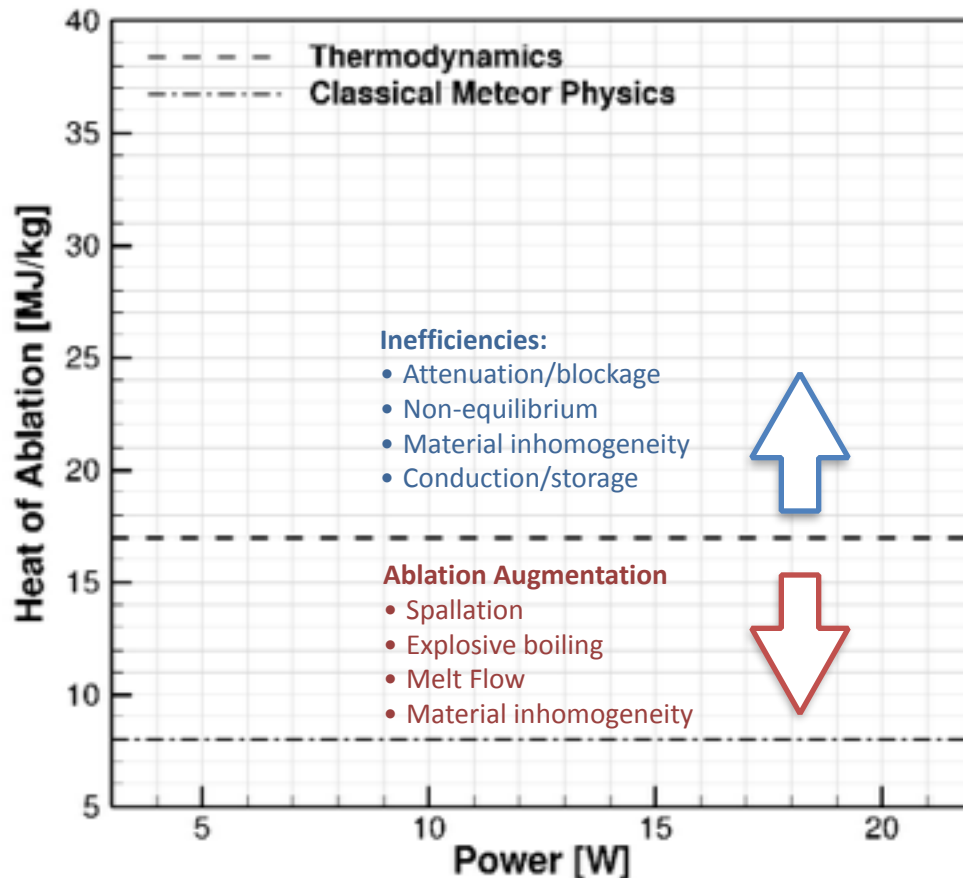
M = mass
 Λ = heat transfer coefficient
 S = wetted area
 ρ = gas density
 v = velocity
 Q = heat of ablation

- All the physics of ablation is included in the term Q , which is generally taken to be ~ 8 MJ/kg for stony meteoroids (chondrites)

Heat of Ablation

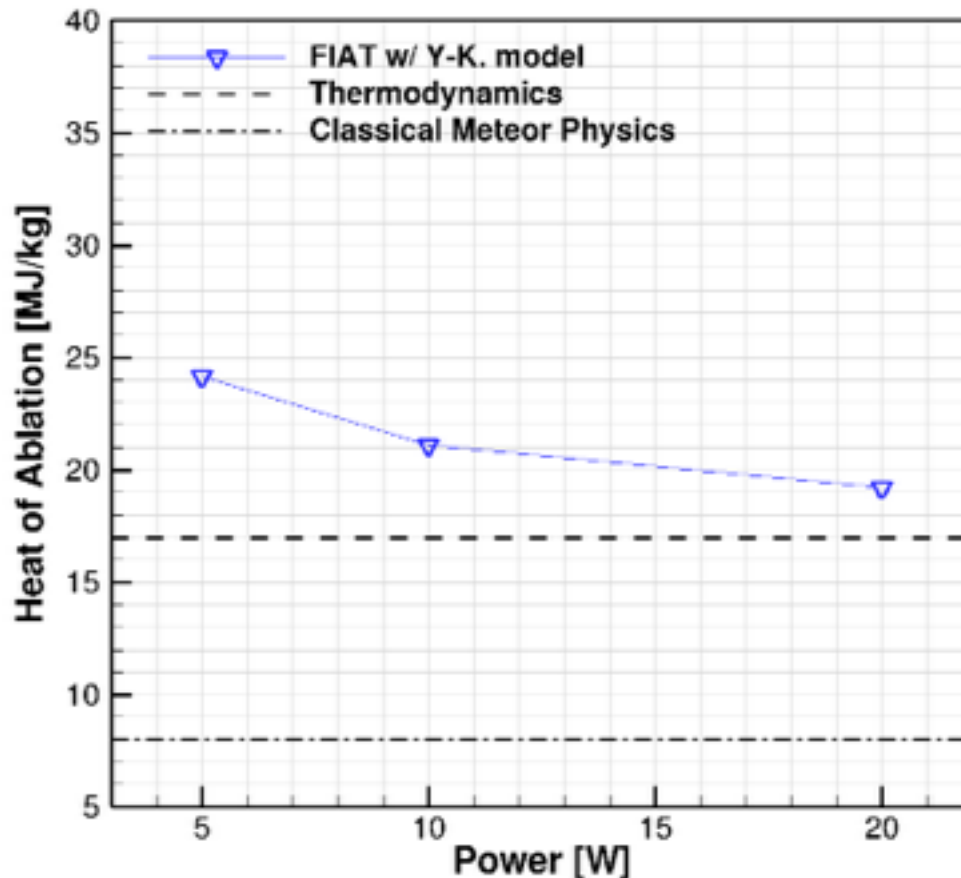


Heat of Ablation



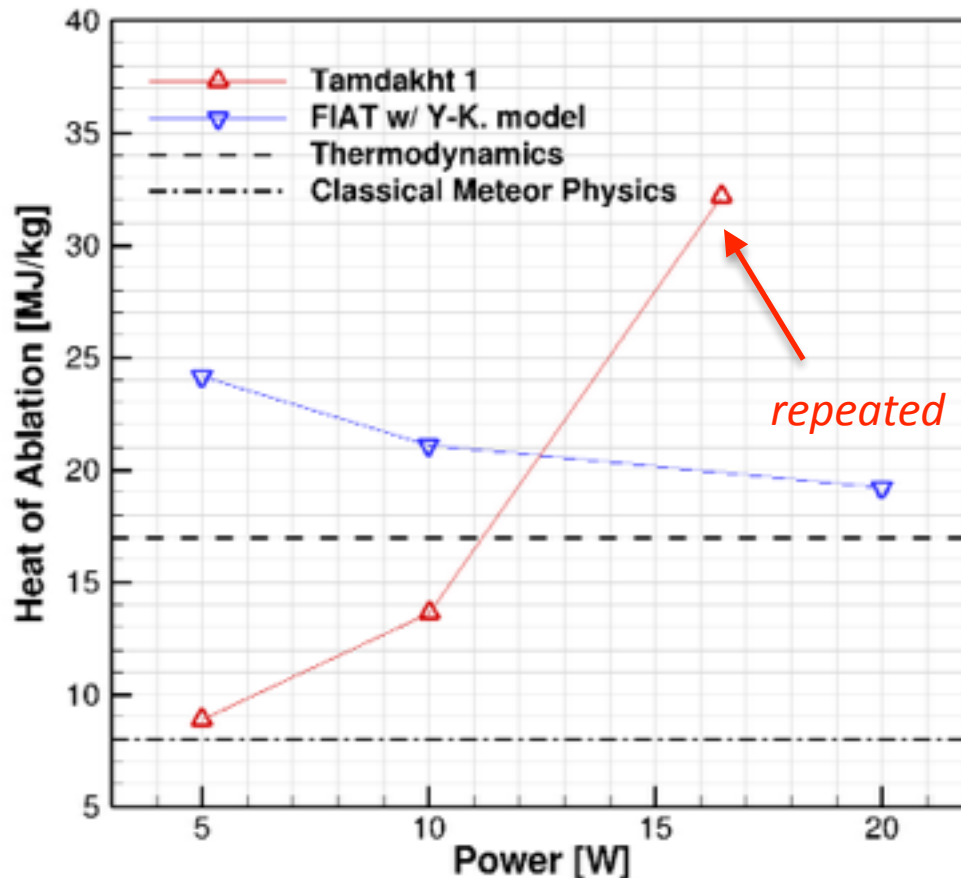
- Values above “ideal” imply energy being consumed through other means
- Below “ideal” implies additional ablation mechanisms beside vaporization

Heat of Ablation



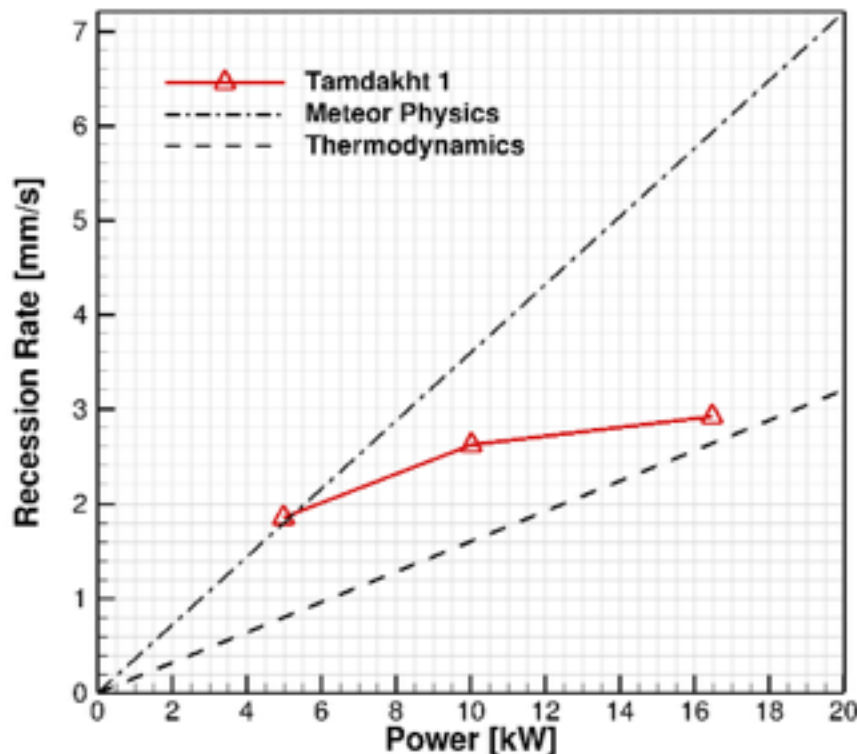
- Pre-test predictions (Y-K.) give higher values of Q^* , but seem to be asymptot'ing to ideal value
- “Inefficiency” due to conduction and storage of energy in bulk

Heat of Ablation



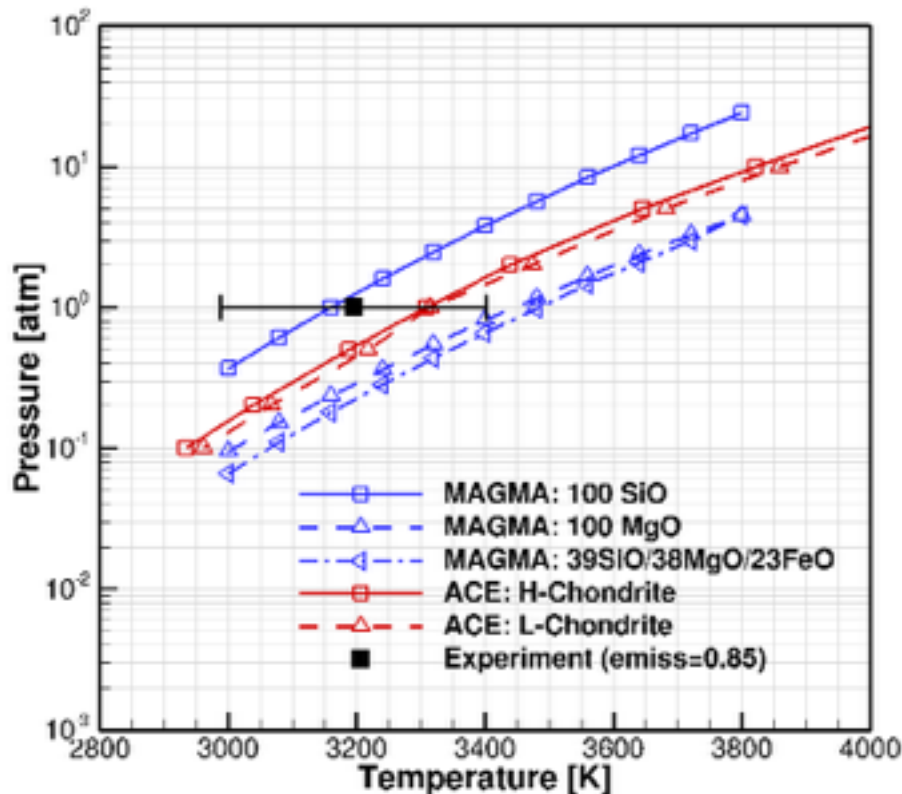
- Experimentally derived value has opposite trend
- Melt and spallation not included in prediction
- Value at facility max was *repeatable**

Recession Rate



- Due to the potentially confounding presence of the melt run-off, recession rate provides independent assessment of effective heat of ablation
- Still observe some reduced efficiency at higher flux, though not as pronounced
- Note that recession measured at deepest point

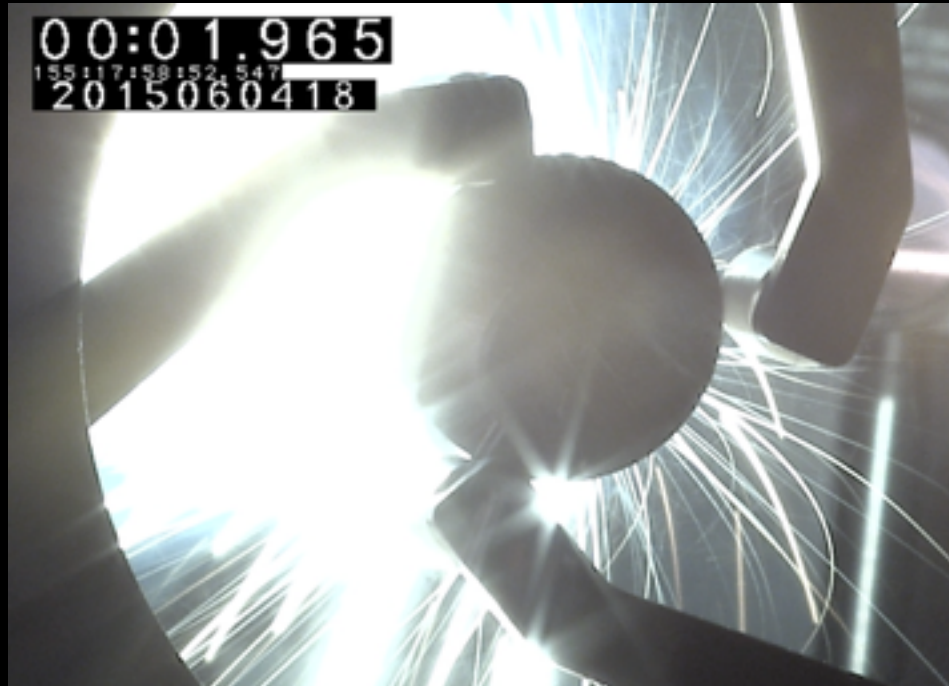
Surface Temperature



- Surface Temperature from pyrometers in-family with predictions from thermodynamics
- Had to use assumed emissivity for the surface

Observations

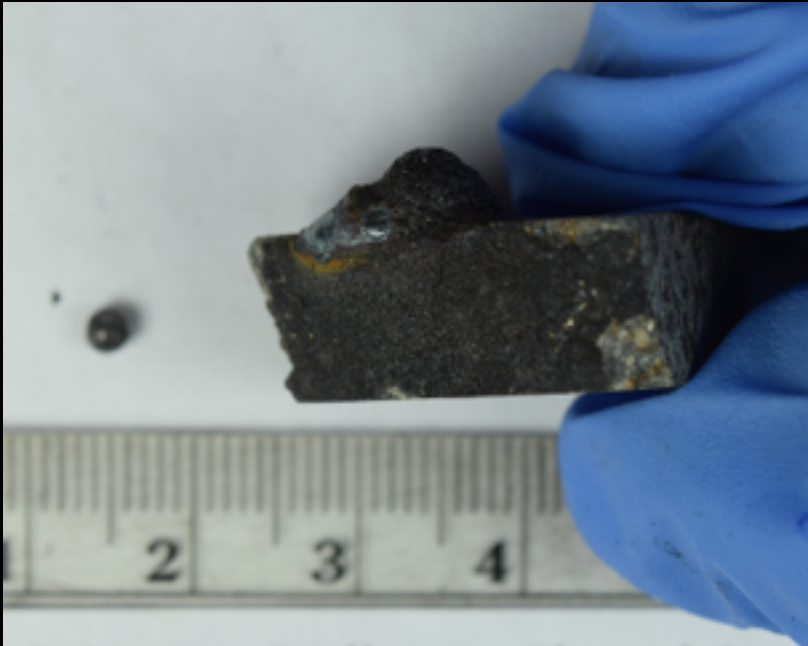
Spallation



Low Density Basalt @ 10kW

- Significant amount of spallation observed
 - ▶ This seems to include both solid material and molten droplets

Melt



- Two competing effects observed:
 - ▶ Most samples had large “glob” of residual melt
 - ▶ Gravity driven melt flow result in augmented ablation

Opacity of the “Vapor”



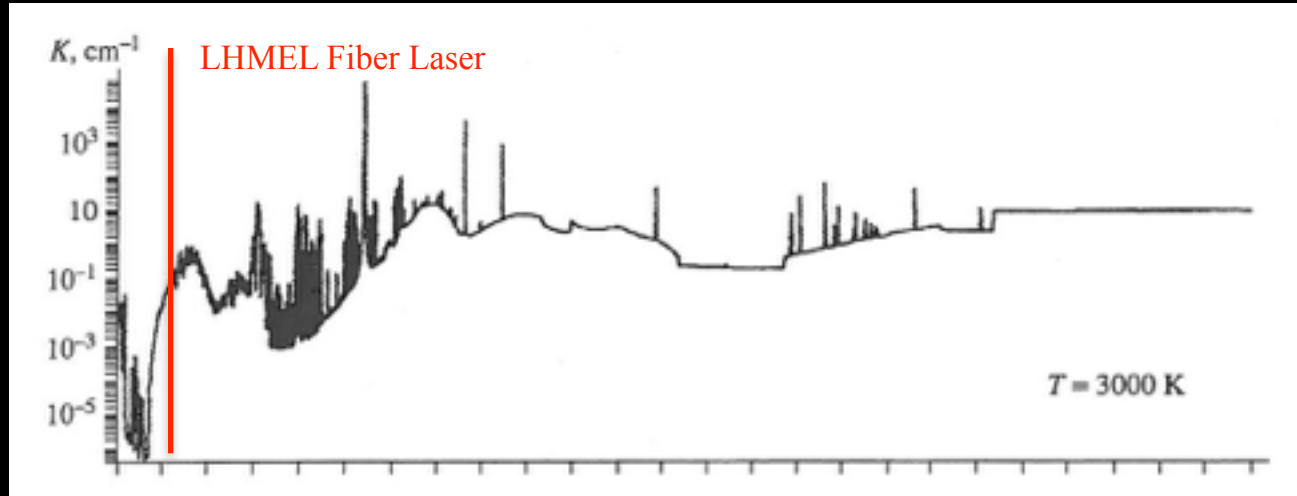
Chondrite 5kW



Chondrite 20kW

Opacity of the “Vapor”

Kosarev, et al. 1996



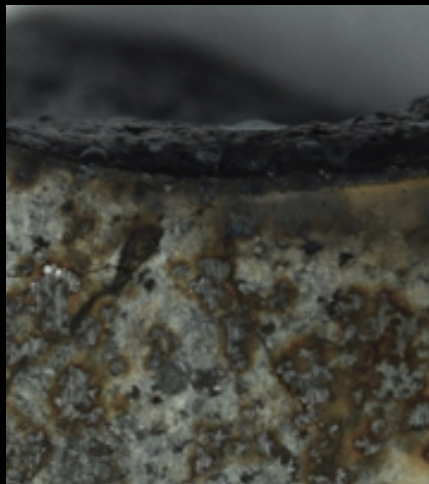
- Literature suggests fairly low absorption at this wavelength
 - ▶ However, it appears that the vapor thickness could be quite large
- “Soot” or small particulates in the vapor could result in significant blockage

Conclusions

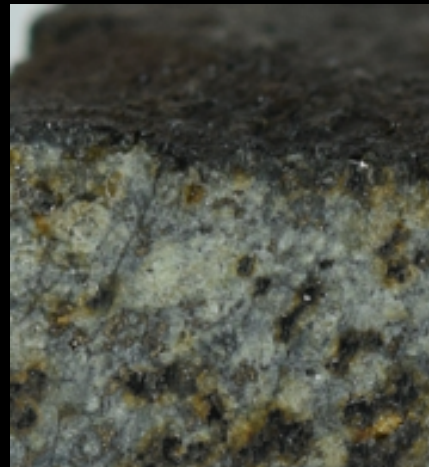
- Phenomenology of Meteoroid Ablation
 - ▶ Significant “auxiliary” ablation mechanisms observed
 - Melt flow
 - Spallation
 - “Explosive boiling”
 - ▶ Highly energetic ablation plume
 - ▶ Likely “soot” or small particles in plume particularly at high temperatures
- Effective Heat of Ablation
 - ▶ *All* measured values above meteor physics value
 - ▶ Trend of increase in Q^* with increase in irradiance
 - ▶ Significant reduction in efficiency at maximum power

Conclusions

- Fusion Crust Characteristics
 - ▶ Preliminary examination shows similar fusion crust morphology



Experiment



Flight

- ▶ More rigorous analysis on-going in collaboration with characterization task

Future Testing

- Different pressures: Vacuum and 20atm
- High shear flow
 - ▶ More realistic mass loss due to melt flow
- Absorption Spectroscopy
- Bigger Samples
 - ▶ Negate cavity effect
- Higher Power
- Demonstrate Repeatability
- Manufactured meteorite analogs

Acknowledgements

<https://planetary-defense.arc.nasa.gov/workshop2015/>

- **TSM**

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