Ablation and Heating During Atmospheric Entry and Its Effect on Airburst Risk

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Heating and Ablation in Threat Assessment

Asteroid Entry Equation of Motion *

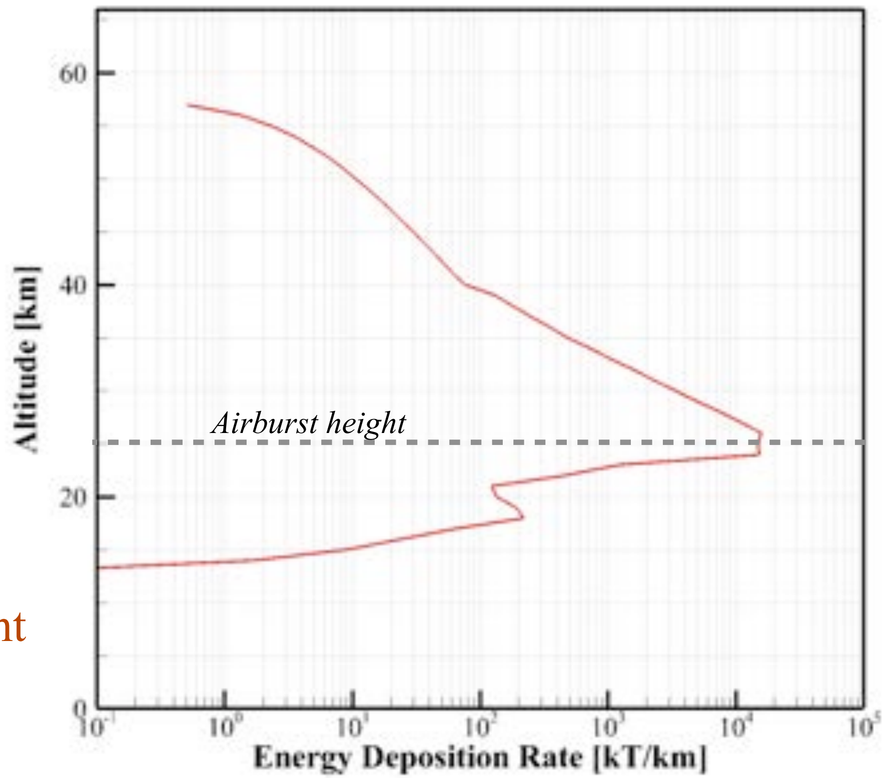
$$dv = \left(-\frac{1}{2}C_d\rho_A v^2 A/m + g\sin\theta\right)dt$$

$$d\theta = \left(\frac{v}{R_E + h} + \frac{g}{v}\right)\cos\theta \ dt$$

$$dm = -\frac{1}{2}\rho_A v^3 A\sigma_{ab}dt$$

$$\sigma_{ab} = \frac{C_H}{Q^*}$$

Heat Transfer Coefficient / Heat of Ablation



* *Wheeler et al., 2017*

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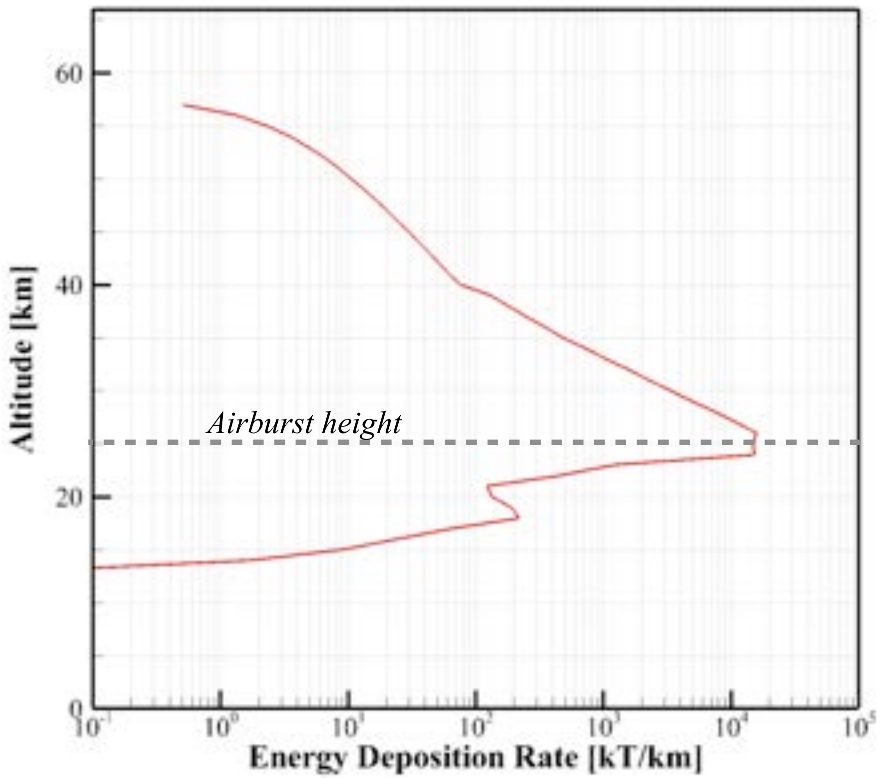
$$\sigma_{ab} = \frac{C_H}{Q^*} \quad \frac{= 0.1}{= 8 \text{ MJ/kg}}$$

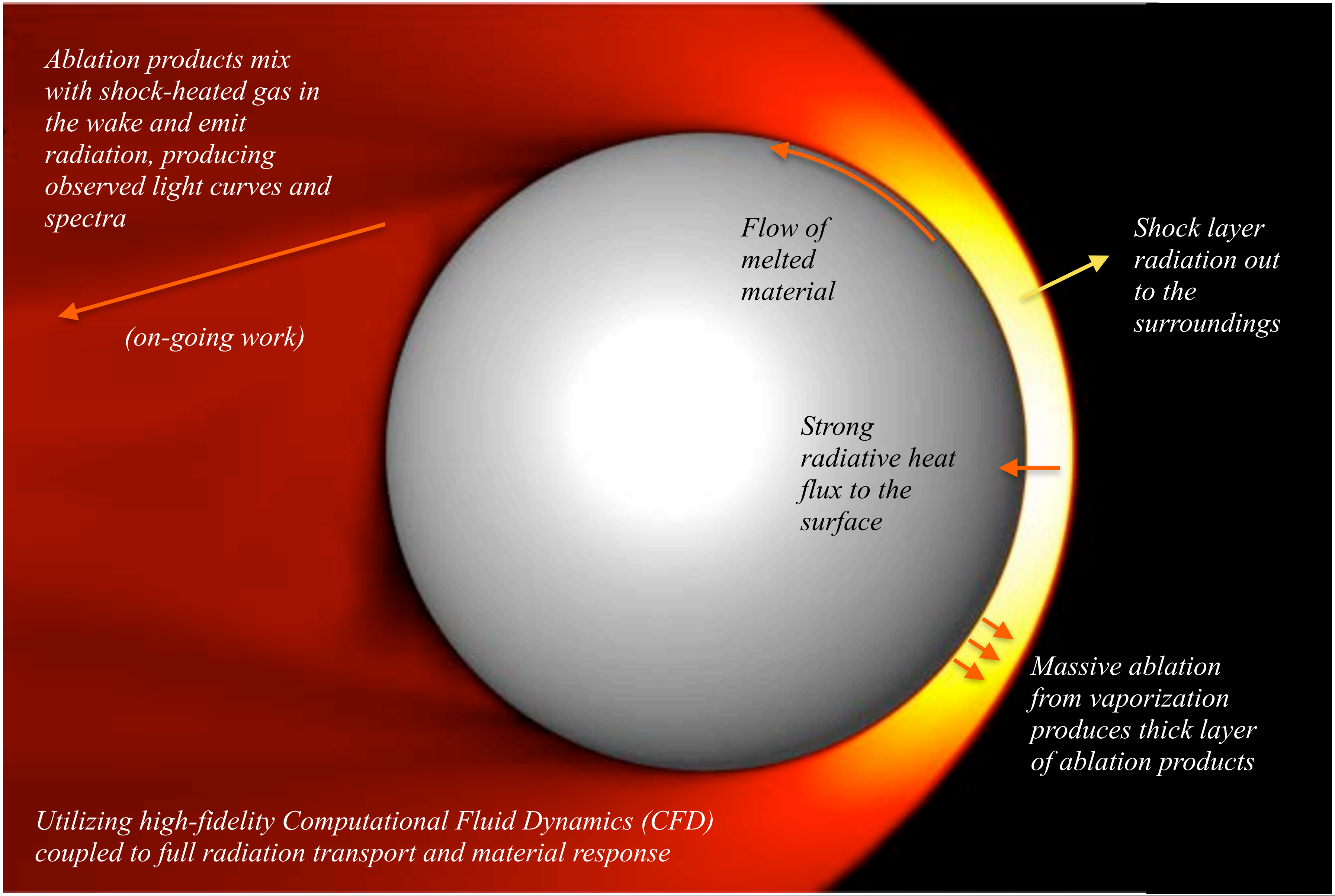
Nominal Values



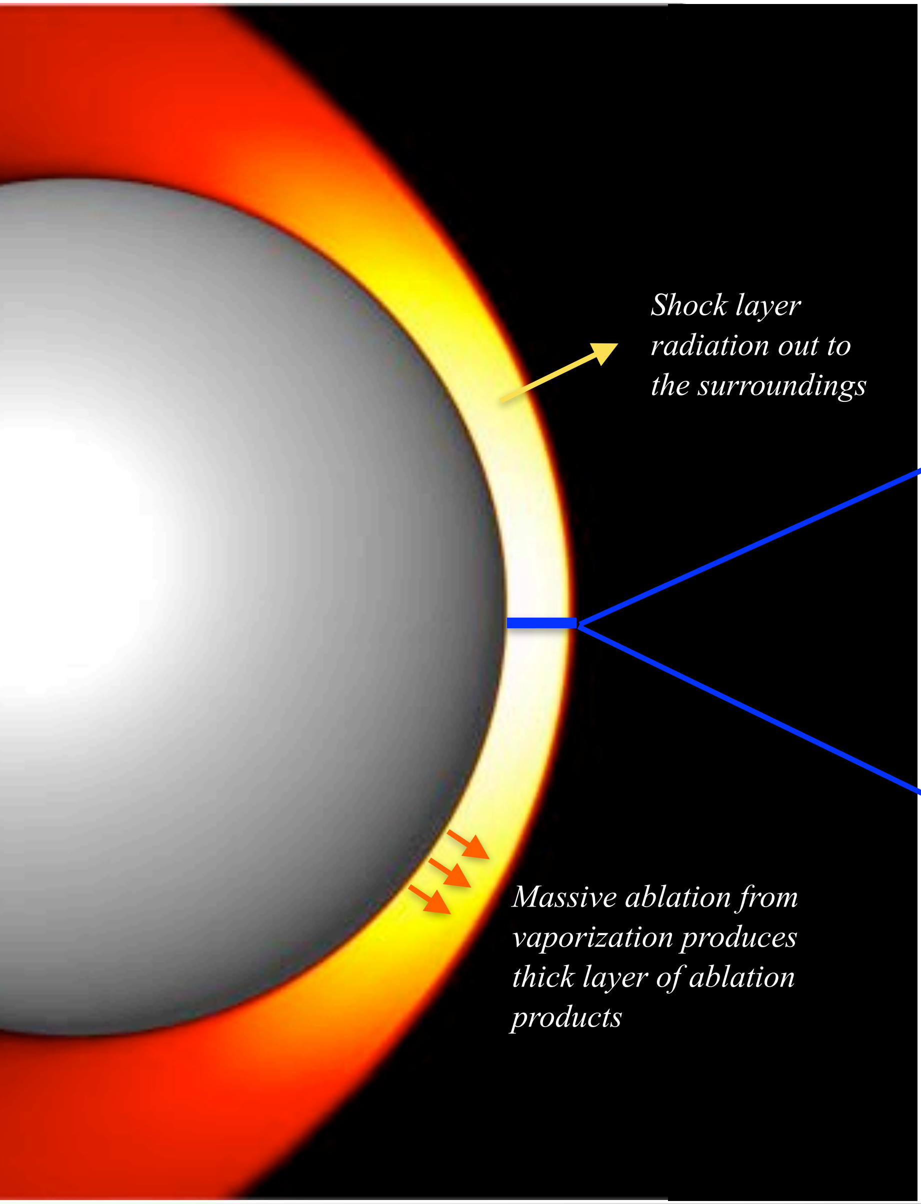
NASA Asteroid Threat Assessment Project working to improve models for these phenomena

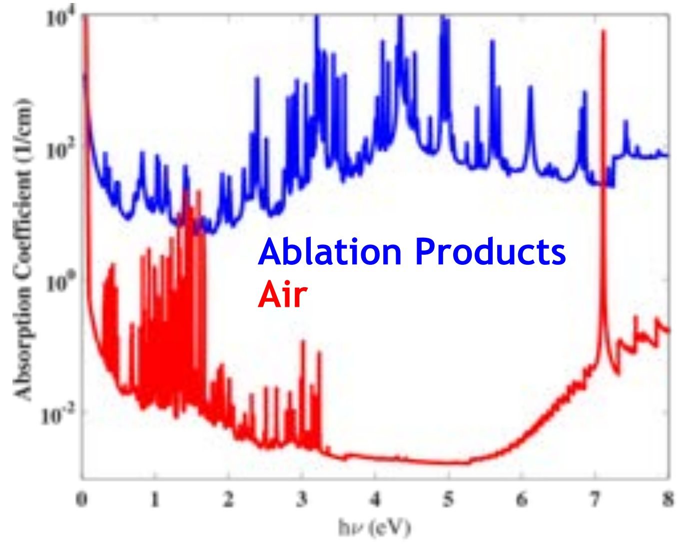
* *Wheeler et al., 2017*

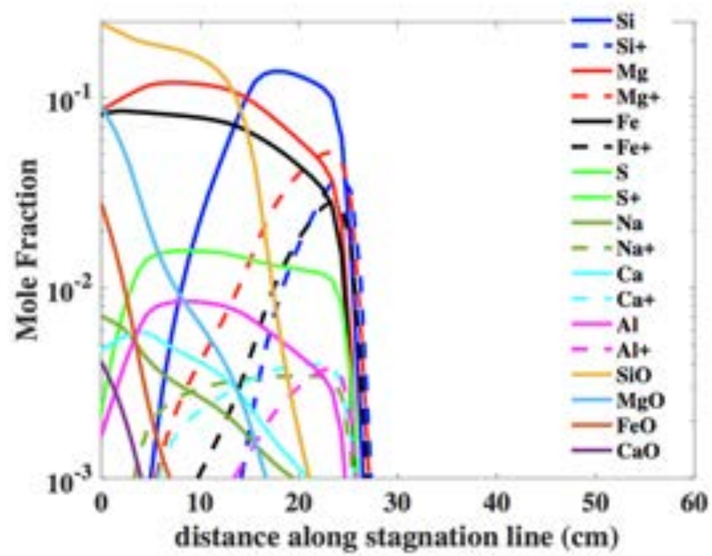
Asteroid Entry Environment



Coupled Ablation and Radiation Modeling

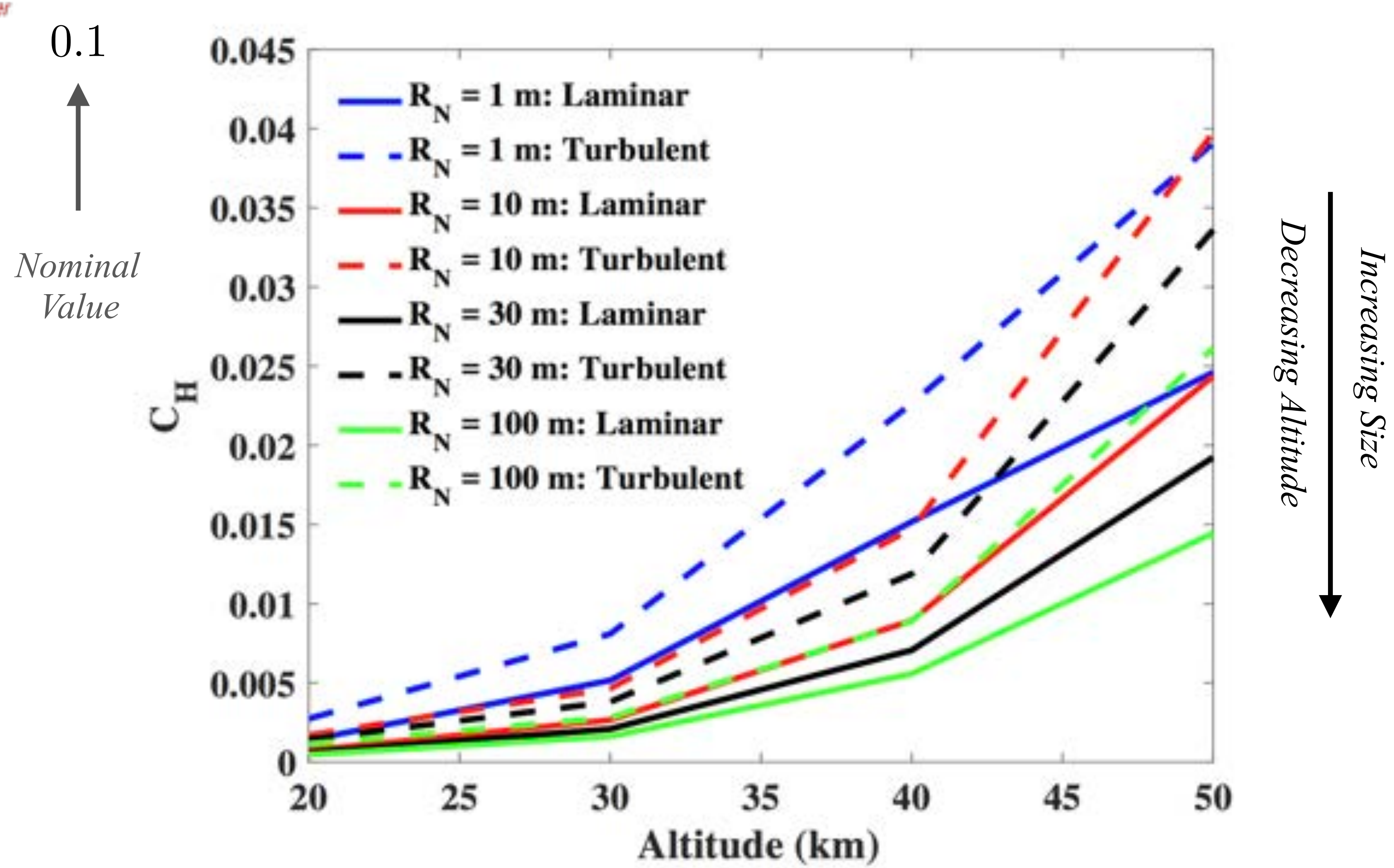






* Johnston and Stern., 2017

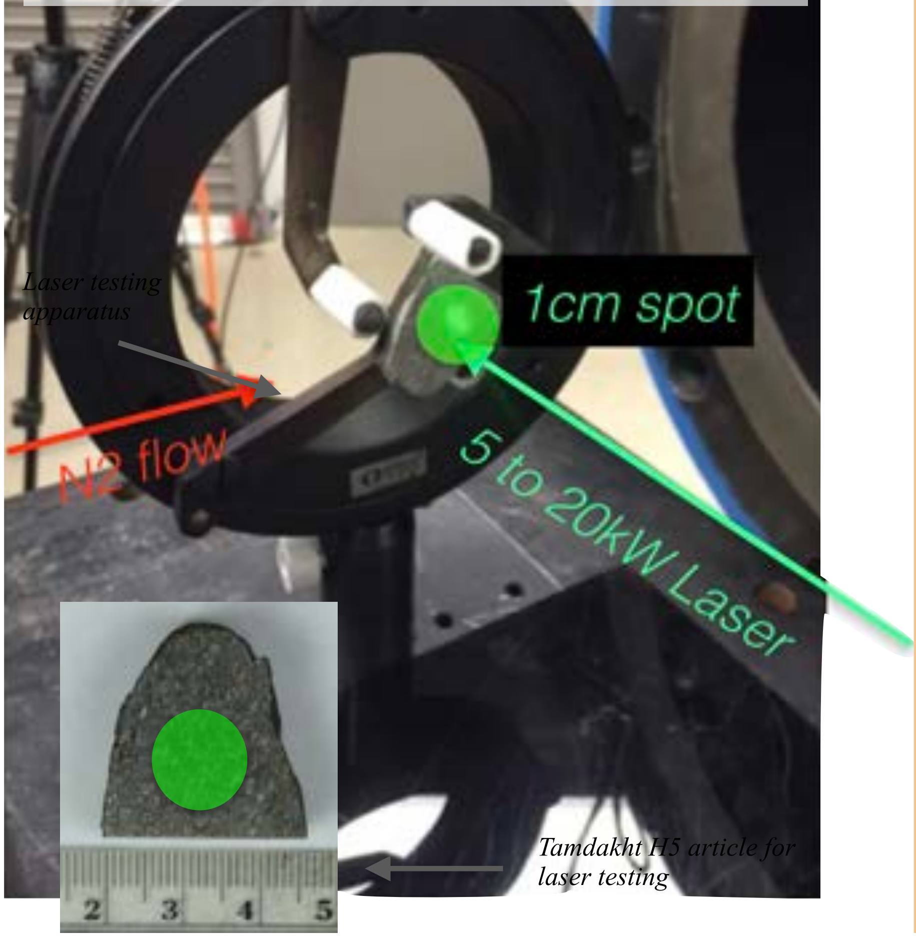
Coupled Ablation and Heat Transfer Modeling



- Fully coupled radiation and ablation results reduces the heat transfer coefficient by nearly ***two*** orders of magnitude in some cases
- C. Johnston, E. C. Stern, L. F. Wheeler, "Radiative Heating of Large Meteoroids During Atmospheric Entry," *Icarus*, Vol. 31, p. 25-44, doi:10.1016/j.icarus.2018.02.026

Meteoroid Ablation Experiments

- Continuous Wave Laser Experiment
  - Tamdakht H5 Chondrite samples tested at heating rates from 5 to 16 kW/cm^2

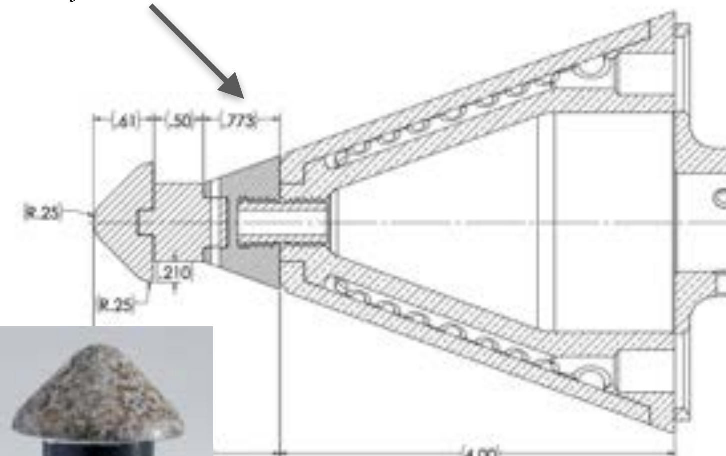


Laser testing apparatus

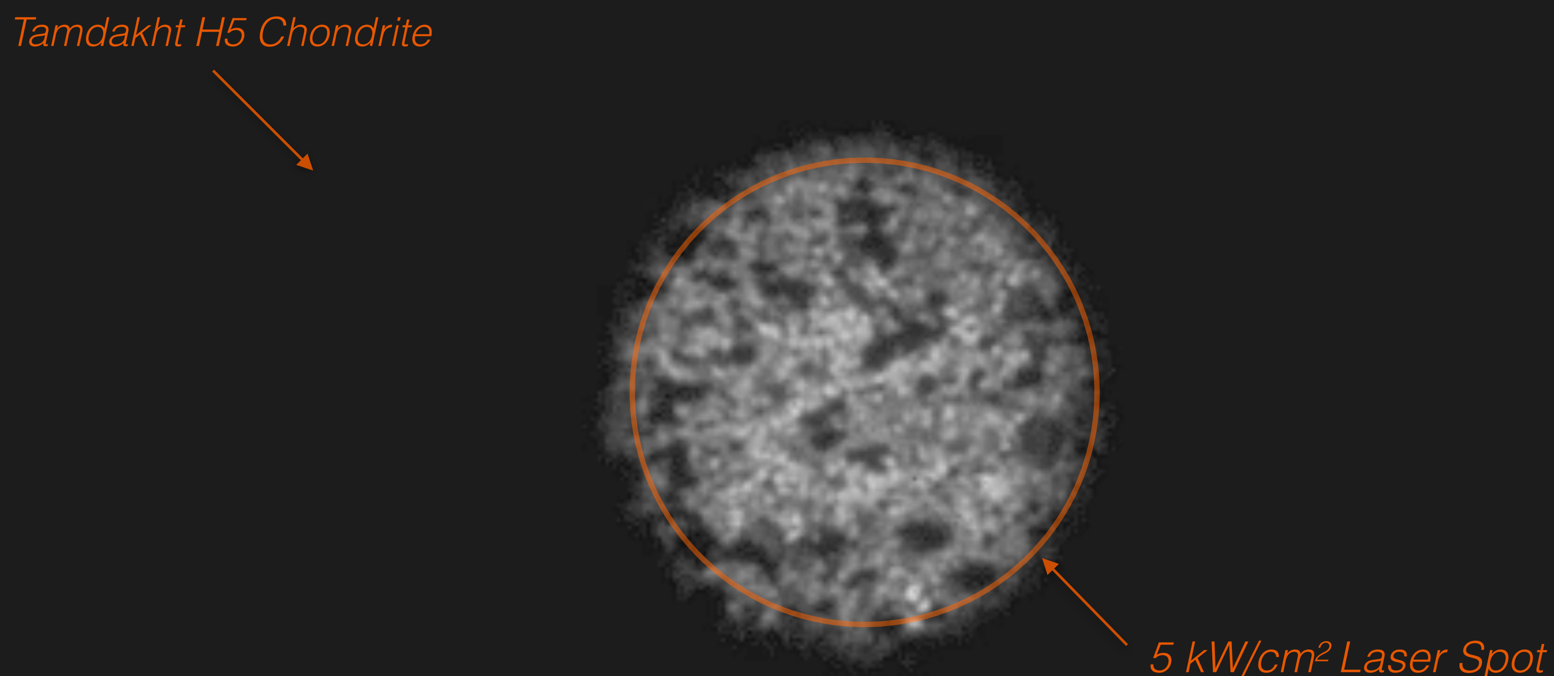
Tamdakht H5 article for laser testing

- Arc Jet Experiment
  - Heating rates (~4 kW/cm^2) produced in the experiment comparable to 30m asteroid at 20 km/s at 65km altitude
  - Machined sphere-cone model allows for high-fidelity simulation of the test environment and material response

Schematic arc jet test article

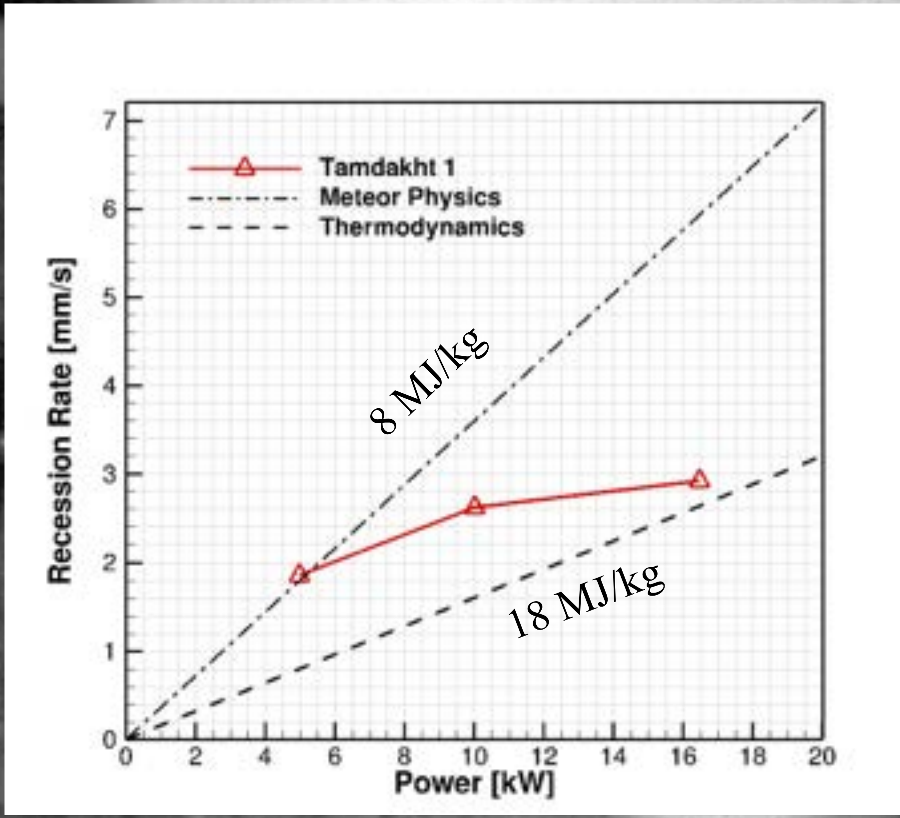


Tamdakht H5 model for arc jet testing



High-speed video showing boiling meteorite surface

Laser Experiment Findings

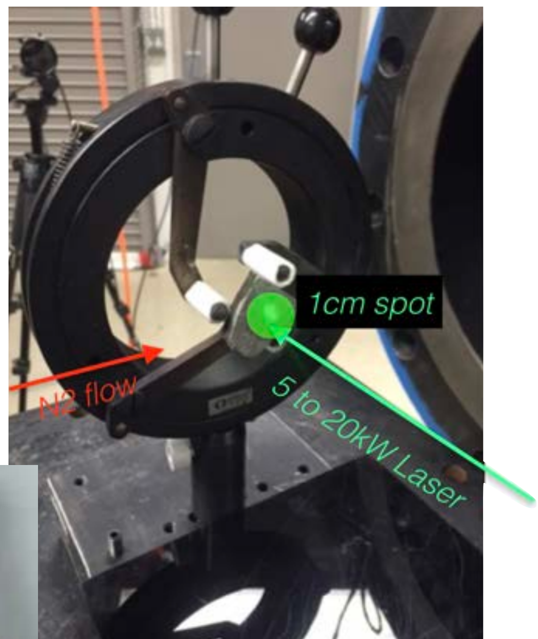


- At low heat flux, effective heat of ablation value close to canonical value of 8 MJ./kg
- Reduction in ablative efficiency at high heat fluxes attributed primarily to radiation blockage from ablation products

Meteoroid Ablation Experiments

- Continuous Wave Laser Experiment
  - Source of heating is radiation, which is the dominant source of heating for large meteoroids
  - Tamdakht H5 Chondrite samples tested at heating rates from 5 to 16 kW/cm^2

Laser testing apparatus



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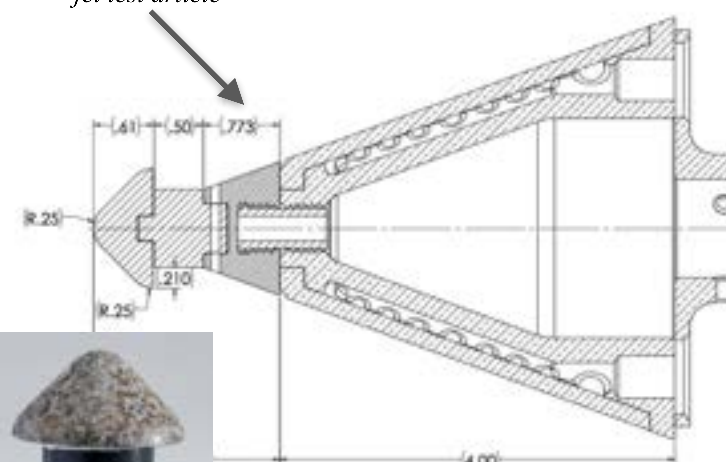
Schematic arc jet test article

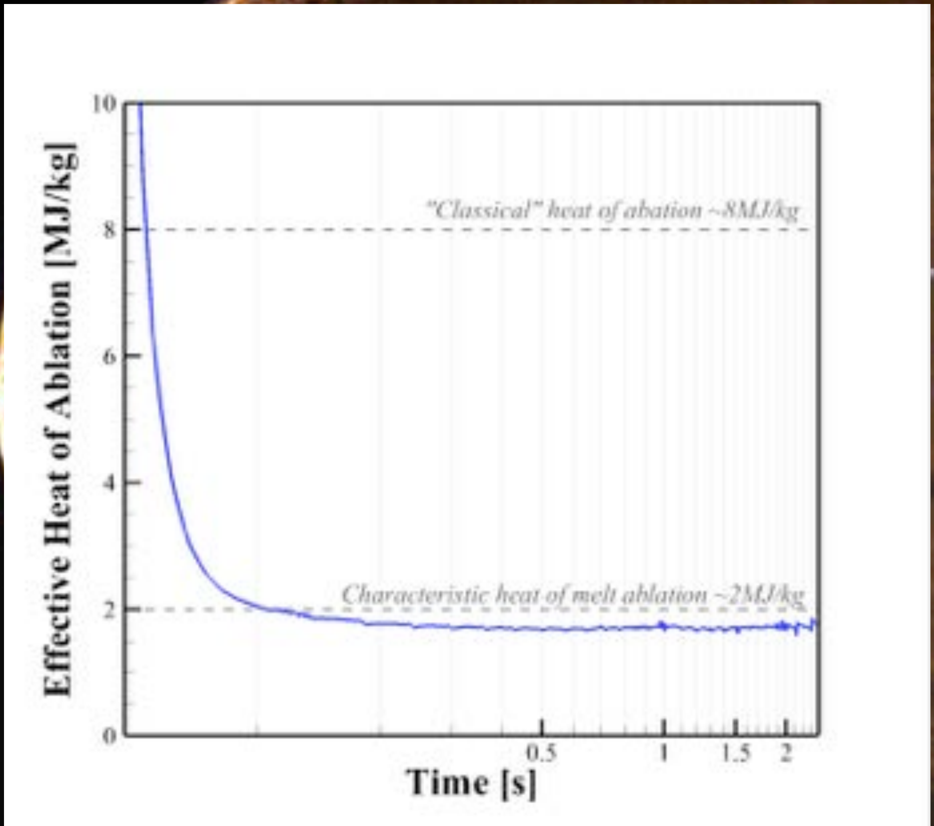


Tamdakht H5 model for arc jet testing

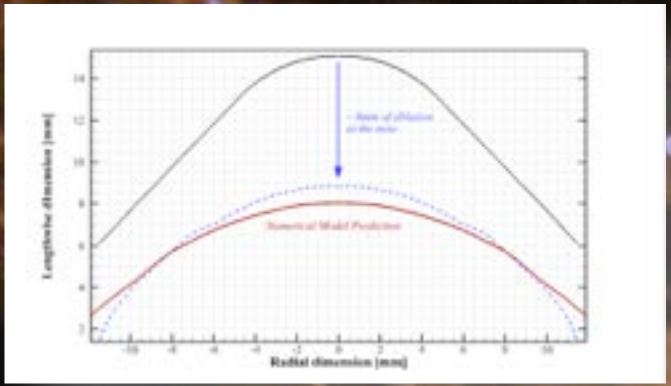
High-speed video from arc jet experiment showing widespread melt flow

Arc Jet Experiment

Findings



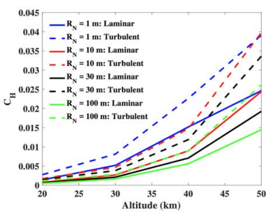
- Effective heat of ablation (*Q**) from the experiment ~ 2 MJ/kg
- Heat is well below the canonical value of 8 MJ/kg for chondrite vaporization
    - Indicates we are in a *melt* dominated regime

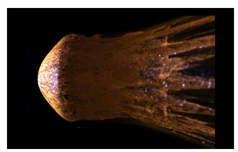


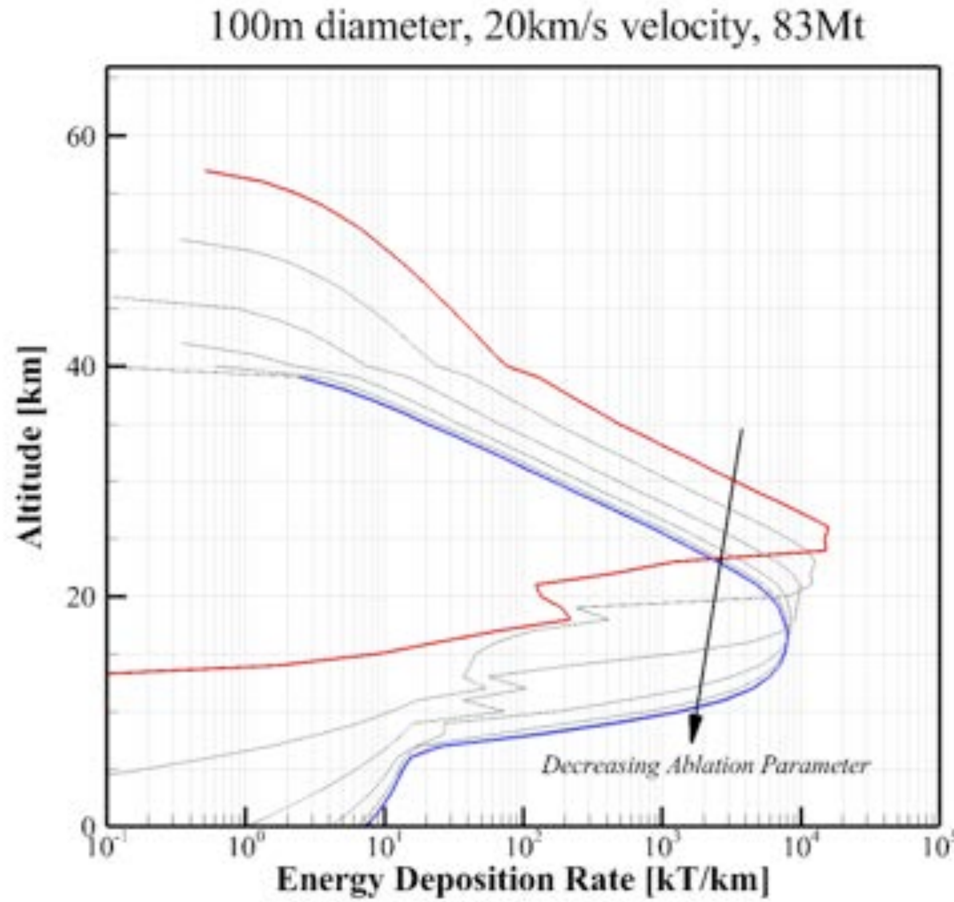
P. Agrawal, E. C. Stern, J. O. Arnold, Y-K. Chen, P. Jenniskens, "Arcjet Ablation of Stony and Iron Meteorites," AIAA Paper, Atlanta, Georgia, June 2018

Effect of Ablation Parameter on Energy Deposition

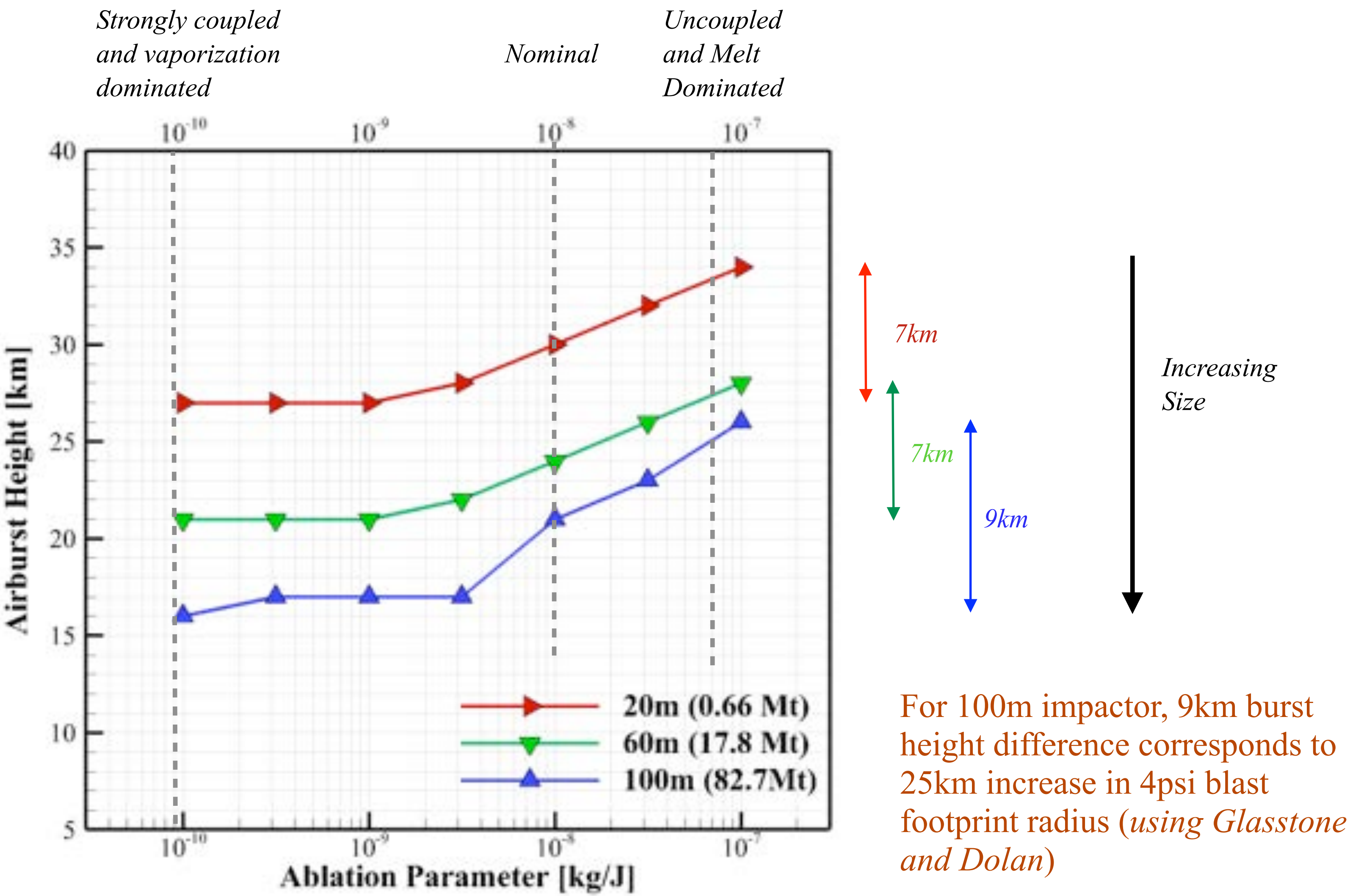
	Nominal Value	Range based on preceding analysis
C_H	0.1	0.001 0.04
Q^*	8.0	1.8 8.0
$\sigma_{ab} = \frac{C_H}{Q^*}$		1.25×10^{-10} 2.20×10^{-8}







Effect of Ablation Parameter on Energy Deposition



For 100m impactor, 9km burst height difference corresponds to 25km increase in 4psi blast footprint radius (*using Glasstone and Dolan*)

Conclusions

- Coupled Fluid Dynamics-Ablation-Radiation calculations show significant reduction in heating over canonical value, particularly at larger sizes relevant to planetary defense
- Ground test experiments yielding insight into ablation phenomena, and being used to develop and validate numerical models
- Bias in ablation parameter toward the low-end results in lower altitude airburst, and therefore larger ground damage footprints

Acknowledgments

- Work was performed under the Asteroid Threat Assessment Project, administered by the NASA Planetary Defense Coordination Officer, Lindley Johnson
- The NASA Interaction Heating Facility (IHF) Team is gratefully acknowledged for supporting the arc jet test
- The Air Force Research Laboratory Laser Hardened Material Evaluation Laboratory is gratefully acknowledged for supporting the laser testing
- Thanks to Greg Gonzalez and Val Kasvin for machining the models for the experiments