Meteor entry & breakup based on evolution of NASA's entry capsule design tools

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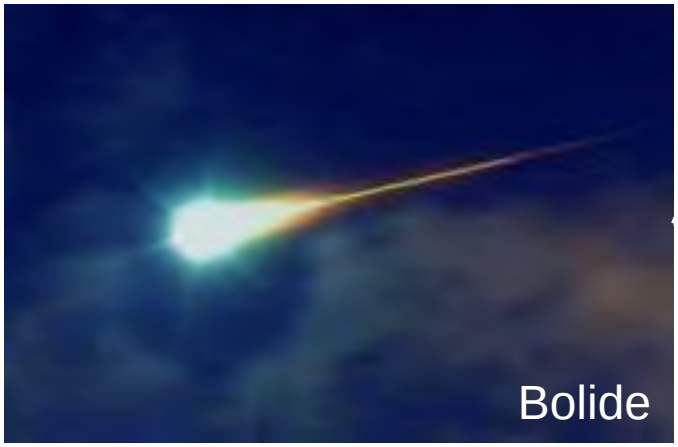
Motivation

Capsule Entry

(Figure from http://appel.nasa.gov/)

Meteoroid Entry



(Figure from http://en.wikipedia.org/wiki/Impact_event)

- Can some of the modern computational analysis tools used in design of heatshields of capsules be used (repurposed?) for simulation of meteoroid entries?
- Can we build or develop, across various classes of meteoroids, models for:
  - Material thermal response
  - Material structural response, including fragmentation
  - Energy deposition along meteor trajectory in the atmosphere, *i.e.*, light curves
- How much would the results of these models differ from, and improve upon, those obtained from the equations of meteor physics?

Entry Capsules *vs* Meteors

	Capsule (Earth entry)	Meteoroid (Asteroid)
Shape	Regular and smooth geometry	Irregular and rough geometry
Material	Manufactured ablative material	Depends on asteroid class (S, M, X)
Structure	Minimal voids and cracks; Known structural properties	Could have voids & could be fractured; Structural properties of meteorites
Shape Change	Negligible recession/mass loss	Recession dominated
Fragmentation	Not an option!	S-class most likely to fragment

Recovered Stardust Capsule

Recovered Chelyabinsk Meteorite
(http://www.nbcnews.com)

	Capsule (Earth entry)	Meteoroid (Asteroid)
Validation Data	Sensors, imaging, capsule recovery	Light curves, infrasound, falls
Ground Testing	Ballistic ranges, arc jets, wind tunnels, laser facilities	Probably same facilities as capsules, but with limitations

Although meteor physics has some things in common with capsule entry physics, the approaches to the problem are different – reconstruction *vs* prediction

Focus Areas of Modeling

- **Flight Mechanics**
  - Ballistic vs Lifting entries
  - 3DoF vs 6DoF
  - See poster by Allen in this workshop

- **Aero/Aerothermodynamics**
  - Turbulent convective heating
  - Thermal radiation heating
  - This presentation

- **Material Thermal Response**
  - Ablation & Recession
  - Melt *vs* Vaporization
  - See poster by Stern *et al*. in this workshop

- **Structural Response**
  - Pressure & shear loads
  - Dynamic loads
  - See poster by Agrawal *et al*. in this workshop

All four disciplines have to be coupled for the asteroid/meteoroid problem!

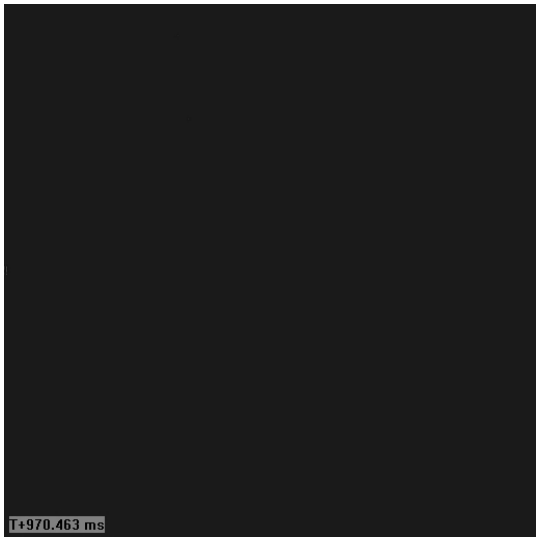
Mass Loss Model – Single Body

$$\frac{dm_m}{dt} = -\frac{1}{2}\rho_a u_m^3 \frac{C_H A_m}{Q}$$

ρ_a	Ambient density	Q	Heat of ablation
u_m	Meteor velocity	m_m	Meteor mass
C_H	Heat transfer efficiency	t	Time
A_m	Area (x-section or wetted?)		

- C_H is efficiency of conversion of freestream energy into heating of meteor surface
- Heat of ablation, Q, is a big source of uncertainty
  - Need to understand energetics of melt *vs* vaporization
- Exploratory test on meteoritic materials performed at LHMEL*
  - Surface irradiation with CO_2 laser

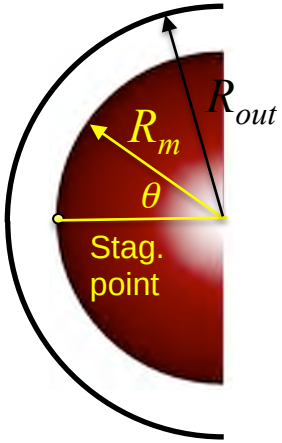
LHMEL Test of H chondrite (Tamdakht) @ 5 kW/cm^2



*Laser Hardened Materials Evaluation Laboratory
(see poster by Stern *et al*. for details about estimating Q)

What can flow computations provide?

- Flow computations for a (hemi)spherical geometry can provide C_H



$$C_H = \frac{\int_0^{\frac{\pi}{2}} 2\pi R_m^2 q(\theta) \sin\theta \, d\theta}{\frac{1}{2}\rho_a u_m^3 A_m}$$

Flow computation (*DPLR* code)

Radiation computation (*NEQAIR* code)

$$q(\theta) = q^{Convective}_{Turbulent}(\theta) + q^{Radiative}_{Nonadiabatic}(\theta)$$

$$q^{Radiative}_{Nonadiabatic}(\theta) = \frac{q^{Radiative}_{Adiabatic}}{(1+3.4\Gamma)}$$

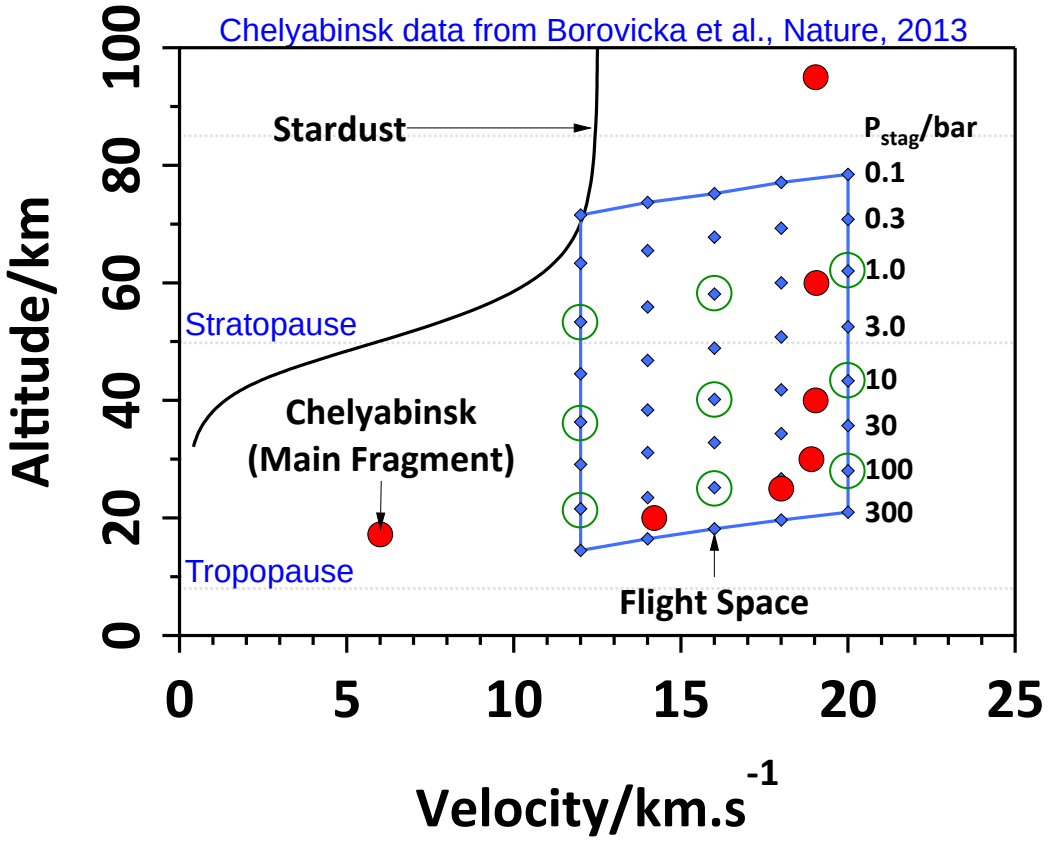
$$\Gamma = \frac{2q^{Radiative}_{Adiabatic}}{\frac{1}{2}\rho_a u_m^3}$$

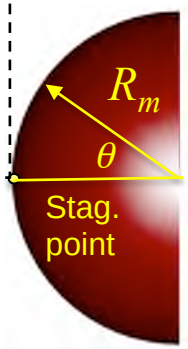
Tauber-Wakefield radiation cooling correlation

- Flow computations can also provide estimate of energy radiated in a specific wavelength interval, *e.g.* V-band, from the shock layer
  - Luminosity can be converted to a “magnitude”
  - Construct a synthetic light curve for direct comparison to observations

$$P^{out}_{\lambda_1,\lambda_2} = \int_0^{\frac{\pi}{2}} 2\pi R_{out}^2 \sin\theta \left(\int_{\lambda_1}^{\lambda_2} I^{out}_{\lambda_1,\lambda_2}(\lambda;\theta) d\lambda \right) d\theta$$

Flight Space Concept"
(Uses US 1976 Standard Atmosphere)





Scaling Laws

$$p_{stag} \propto \rho_a u_m^2$$

$$q_{stag}^{Conv} \propto \frac{1}{\sqrt{R_m}} \sqrt{\rho_a} u_m^3$$

$$q_{stag}^{Rad} \propto R_m \rho_a u_m^8$$

- Hemispheres of radii (R_m) – 1, 3, 10, 20, 30, & 100 m
- Spheres of radii – 1, 3, 10, 20, & 30 m

- Flight Space is a way to delink trajectory from environments; X-33, Orion, …
- Flight Space is specific to a given shape – (hemi)sphere for now
- Compute aerothermal environments at nodes
  - Heat transfer efficiency and energy deposition are functions of R_m, $\rho_a(Z)$, u_m

High-Fidelity Computations

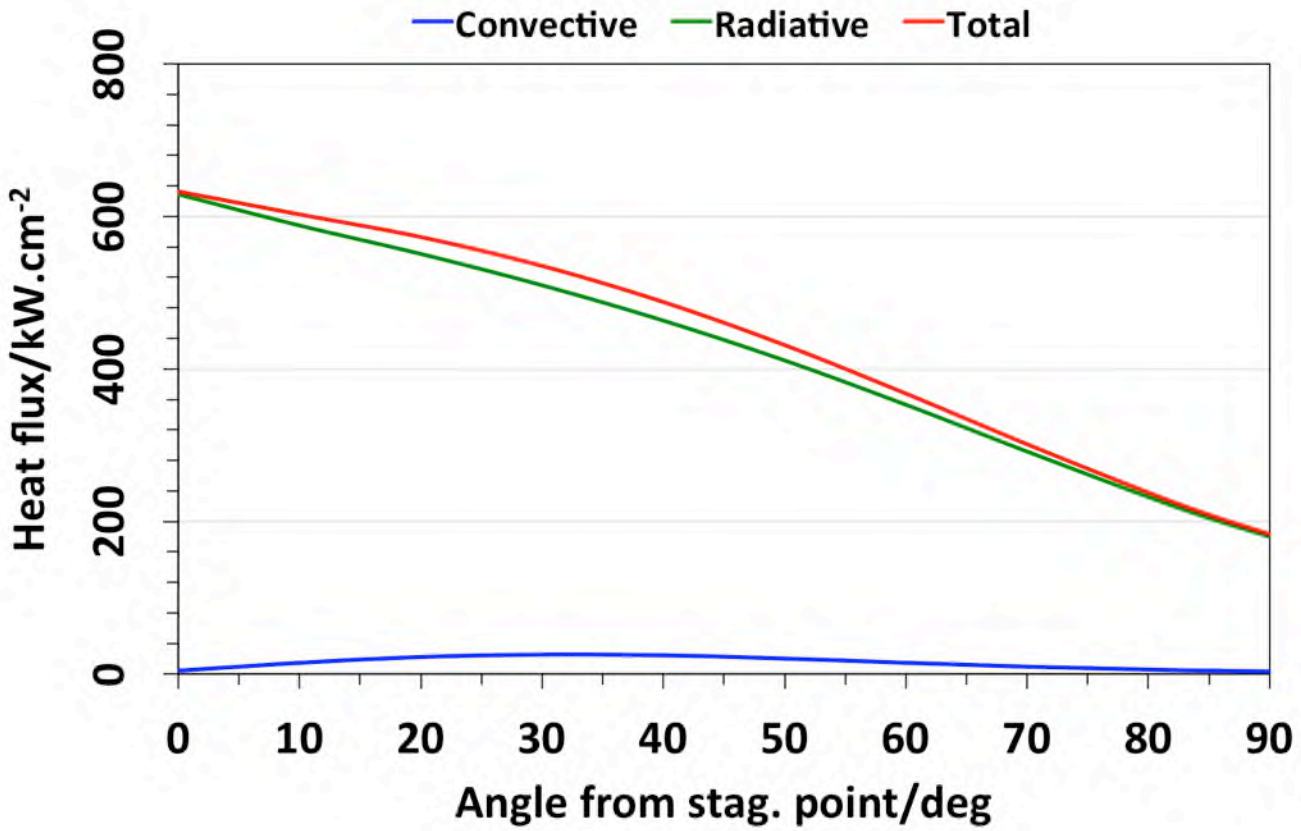
The meteor body *does not* ablate and *does not* cool by re-radiation (cold wall)

- Allows application of physically meaningful surface boundary conditions
- Provides the upper bound on heating (convective and radiative)
- No blockage by vapor phase of meteoritic material!!

- Flow computations:
  - Axisymmetric Navier-Stokes calculations for body in a fixed frame of reference
  - Turbulent flow of 11-species air (N_2, O_2, NO, N_2^+, O_2^+, NO^+, N, O, N^+, O^+, & e^-)
    - Does not account for any surface roughness
  - Gas phase rate chemistry, but thermal equilibrium
- Radiation computations:
  - Decoupled from flow computations (adiabatic inviscid shock layer assumption)
  - Line-by-line simulations with temperatures & number densities from flow solutions
    - Includes discrete transitions (atomic lines) and continua (bound-free & free-free)

Convection *vs* Radiation

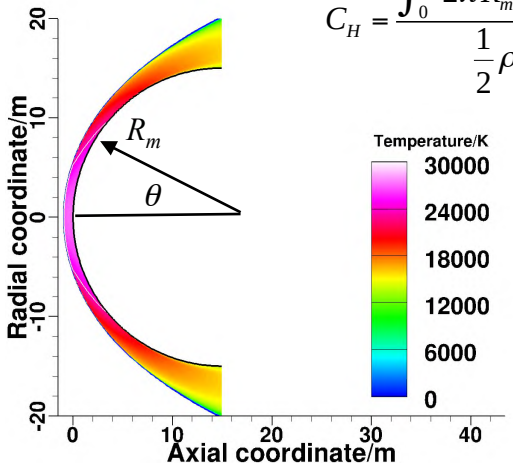
Sample surface heat flux distribution
(u_m = 20 km/s, p_{stag} = 30 bar, R_m = 15 m)



- Surface heating completely dominated by shock-layer radiation
  - True across all velocities and hemisphere diameters, except for small (1 m diameter) hemispheres at high altitudes when convection and radiation become comparable

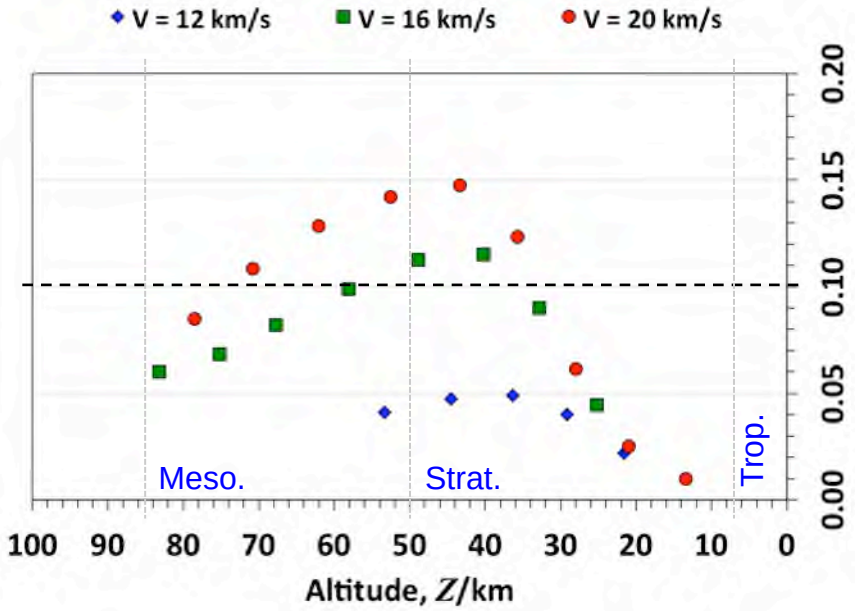
Heat Transfer Coefficient, C_H

$$C_H = \frac{\int_0^{\frac{\pi}{2}} 2\pi R_m^2 q(\theta) \sin\theta \, d\theta}{\frac{1}{2}\rho_a u_m^3 A_m}$$

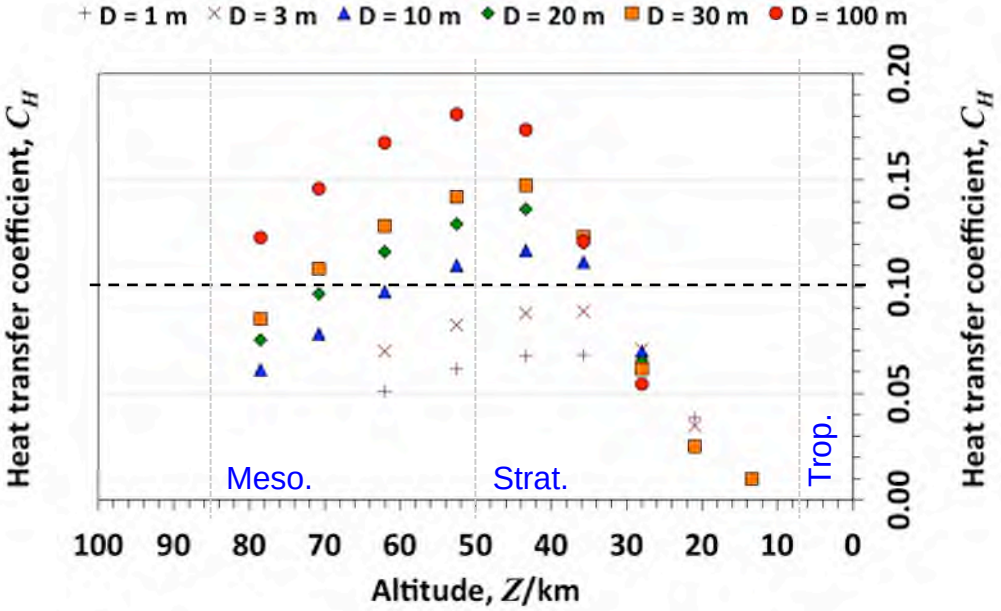


- C_H based on hemisphere computations
  - Will be slightly different from full sphere (wake)
  - Peaks at stratopause (roughly)
  - C_H decrease in stratosphere due to exponentially increasing atmospheric density
  - Discrete data curve fit in altitude (Z), velocity (u_m), and radius (R_m)

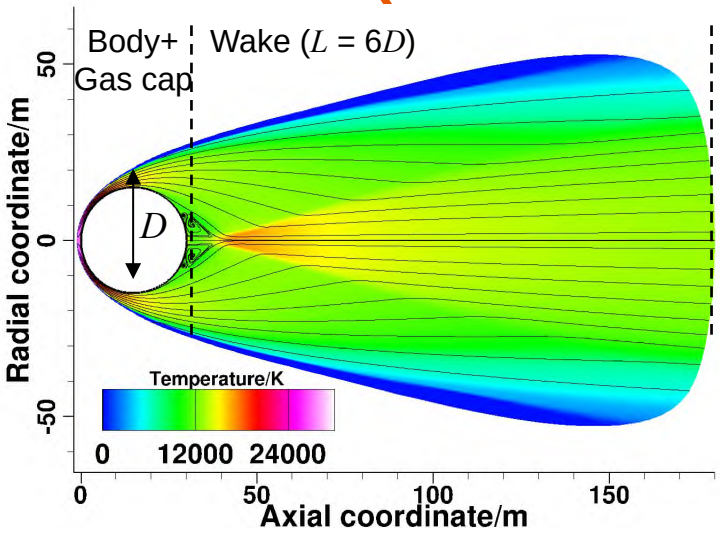
30 m diameter, Velocity variation



20 km/s Velocity, Diameter variation

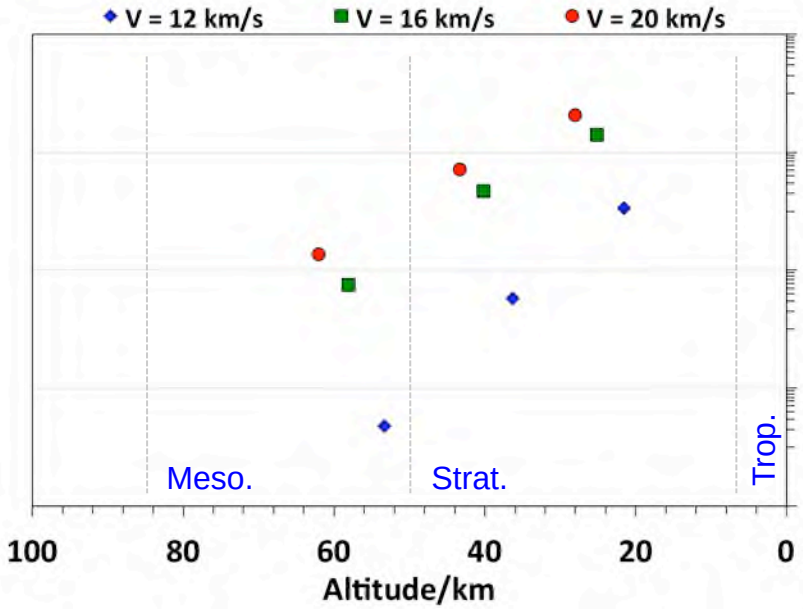


Luminosity"
(Methodology from Stardust Mission)

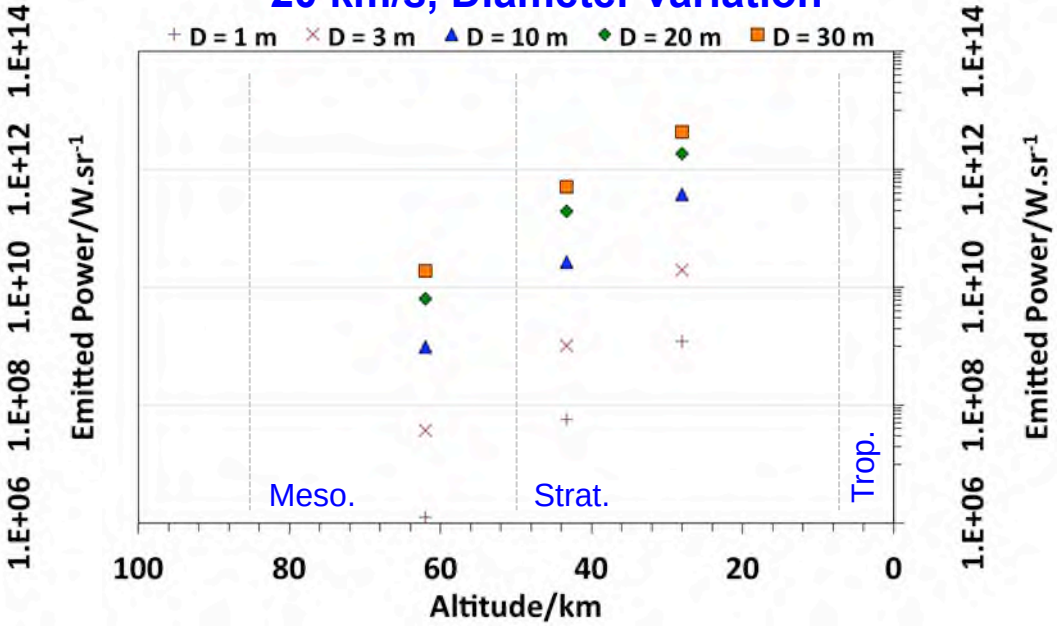


- Modest number of computations for sphere
  - Diameters: 1, 3, 10, 20, and 30 m
  - Velocities: 12, 16, and 20 km/s
  - Stagnation pressures: 1, 10, and 100 bar
- Lines of sight divided into 3 groups – nosecap, body, and wake
- Wavelength range: 85 nm to 4 μm
- Radiance integrated over *projected* area

30 m diameter, Velocity variation

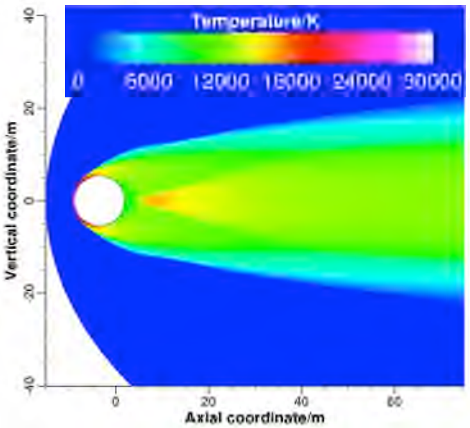


20 km/s, Diameter variation

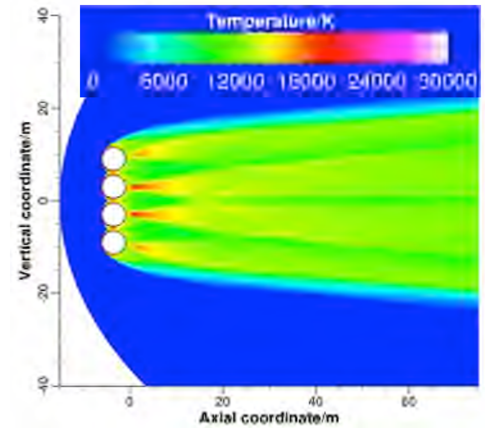


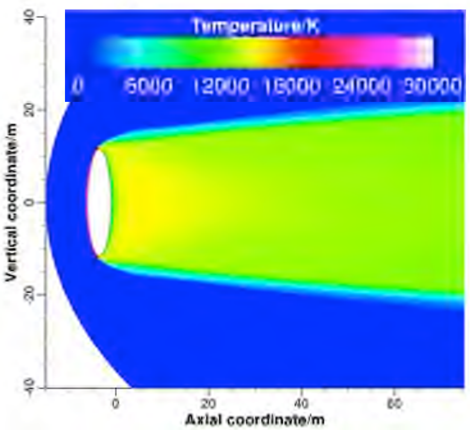
Multiple Bodies & Interactions

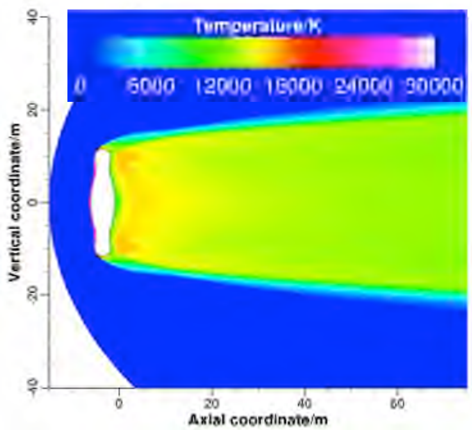
- Currently no model/mechanism for fragmentation – various hypotheses
- Supplement current knowledge with computations for idealized shapes

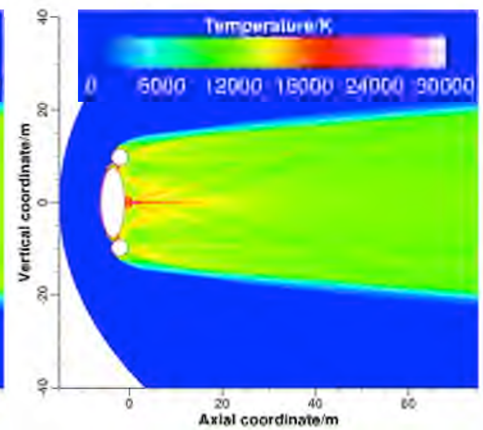


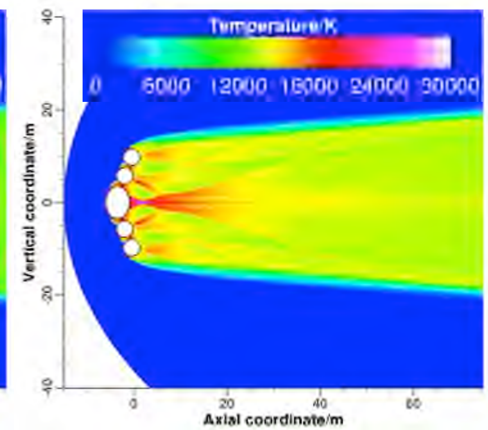
- 3D computations for various idealized shapes and arrangements
  - Extraction of wake luminous energy
  - Extraction of aerodynamic/ aerothermodynamic interaction forces/ energies from computations
- Significant resources required!!









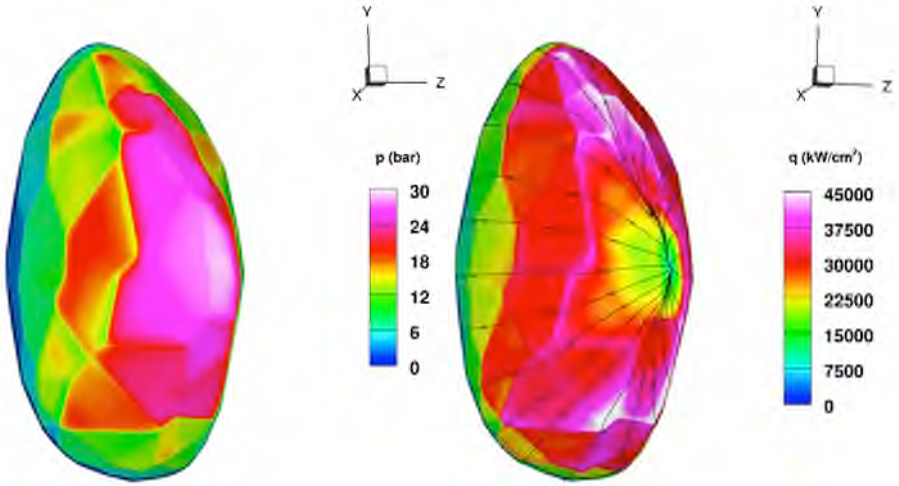


All results shown here are for a velocity of 20 km/s and 30 bar of stag. pressure

Irregular Shapes

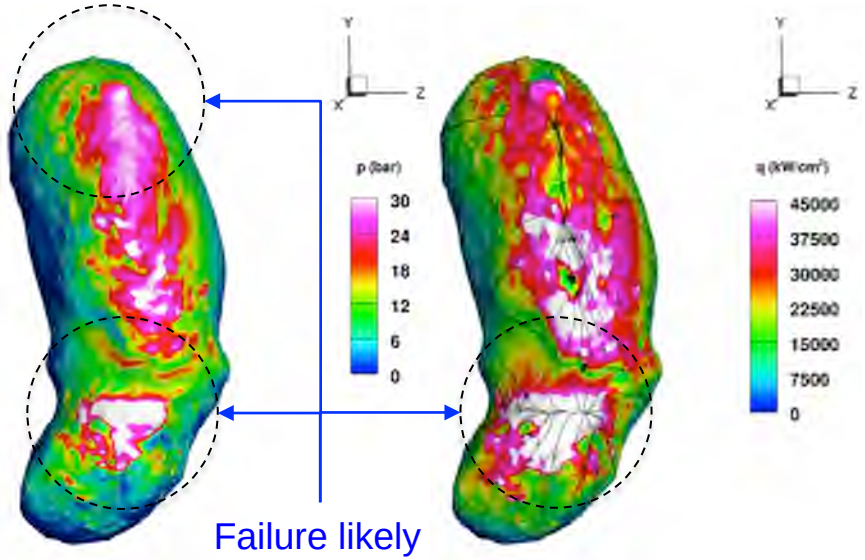
- Conventional meteor physics assumes a spherical shape at entry
- Computations on scaled versions of Asteroid Itokawa & NEO 2008 TC_3
  - Itokawa is a dumbbell shape with “weakness” at the neck
  - NEO 2008 TC_3 most likely oriented in flight
- Irregular shapes will require full 6DoF analysis
  - Will require mass moments of inertia of the object – difficult!

2x-scale NEO 2008 TC_3



2008 TC_3 geometry – Scheirich et al., *MAPS*, 2010

1/38-scale Itokawa



Failure likely

All results shown here are for a velocity of 20 km/s and 30 bar of stag. pressure
Peak radiative heating (not shown) for 1/38-scale Itokawa roughly 1.8 MW/cm^2!

Circling Back

- Can some of the modern computational analysis tools, used in design of heatshields of capsules, be used (repurposed?) for simulation of meteoroid entries?
  - Current limitation on entry velocity 20 km/s will be removed by improvement of thermodynamic and transport properties
    - Include doubly- and triply-ionized species (N^{2+}, O^{2+}, N^{3+}, and O^{3+}) up to 50,000 K
    - Paper by Jaffe *et al*. to be presented at AIAA SciTech 2016 in San Diego
  - Thermal response models (ablation/recession) being developed for silicates
    - Paper by Y-K Chen to be presented at AIAA SciTech 2016 in San Diego
  - Expansion of spectroscopic databases for silicates and metals under way
    - Effort led by C. Bauschlicher and A. Brandis
  - Radiative heating computations are not very efficient – need to replace process
    - Opacities for high-temperature air & stony meteoritic vapor
    - Account for radiation blockage by meteoritic vapor
  - Tighter coupling of analysis tools is required
    - Rapid recession is a hurdle, but not an insurmountable one

Supplemental Questions

- How could the simulation tools and processes be enhanced/improved?
  - Development of material thermal response models, including multiphase flow
  - Physics-based models of fracture based on observation of recovered meteorites, fracture mechanics tools
    - Guidance from Ames Chief Engineer
- How could these tools be verified/validated?
  - Simulation of well-known bolides (Chelyabinsk, 2008 TC_3, …)
    - Look to the meteor physics community to define test cases
  - Pathfinder experiments (see posters of Entry Technology Division)
    - ARC ballistic range or DLR wind tunnel for fragmentation
    - Arc jet for material response to convective heating and spectra of shock-heated air and ablation products from meteorites (or surrogates)
    - High pressure arc jet testing possible at AEDC
    - Shock tube for thermochemistry of shock-heated gases and “end wall” testing of meteorites for fragmentation
  - Airborne observation campaign(s) (see poster by Jay Grinstead)
    - To obtain flight data on fragmentation and bolide spectra

Final Thoughts/Opinions

Predicted outcomes & associated risks are only as good as the models used

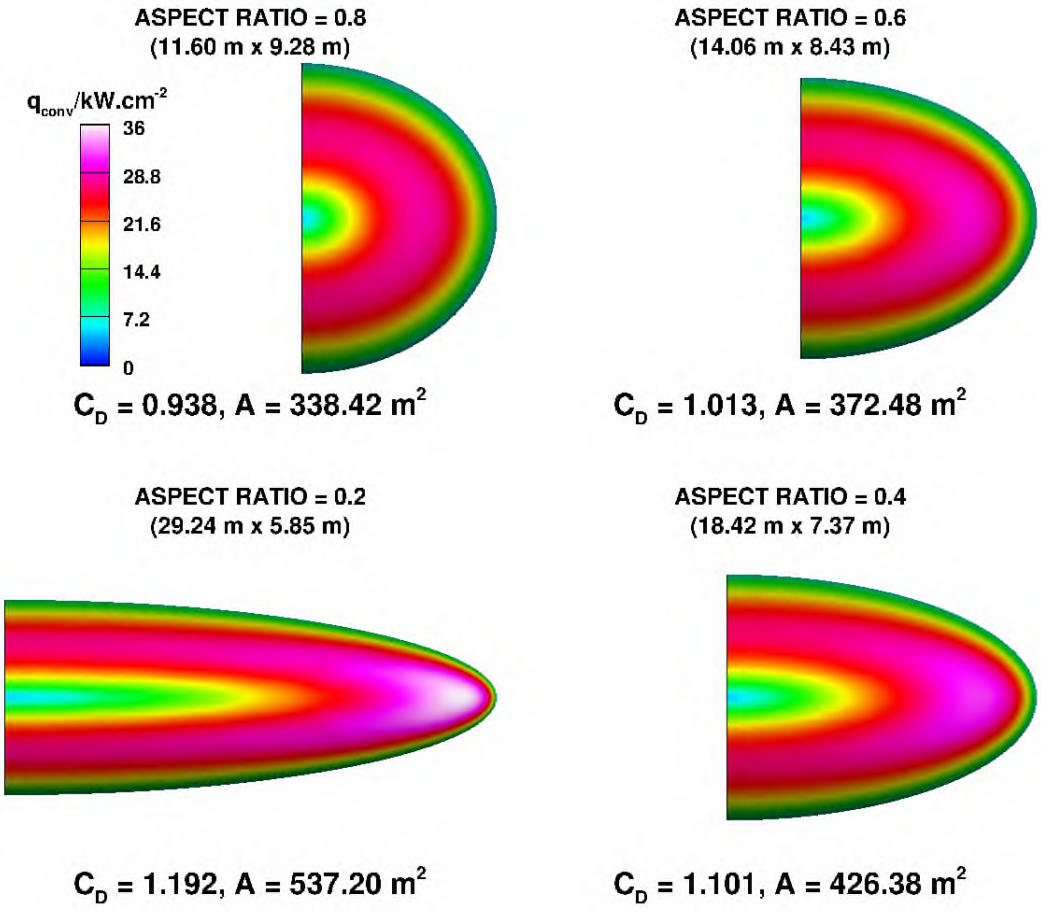
- How valid and useful is the assumption that a large asteroid is a sphere?
  - Entry vehicle heatshields are no longer designed by stagnation point environments alone – size *and* shape matter
- How valid and useful are the "textbook equations" of meteor physics?
  - Meaningful for a single body, but perhaps not for a collection of objects, especially if there are interactions and a large loss of mass during atmospheric flight
- How valid and meaningful is the mass loss equation of meteor physics?
  - A surface mass and energy balance seems to be the right way to go
  - Reformulation is necessary if multiple phases are involved
- How do material properties scale from the lab to an exo-atmospheric body?
  - How valid is the assumption of isotropy?
  - Will require a new approach to structural analysis of porous media with internal cracks

Backup

Importance of Shape

$$\beta_m = \frac{m_m}{C_{D_m} A_m}$$

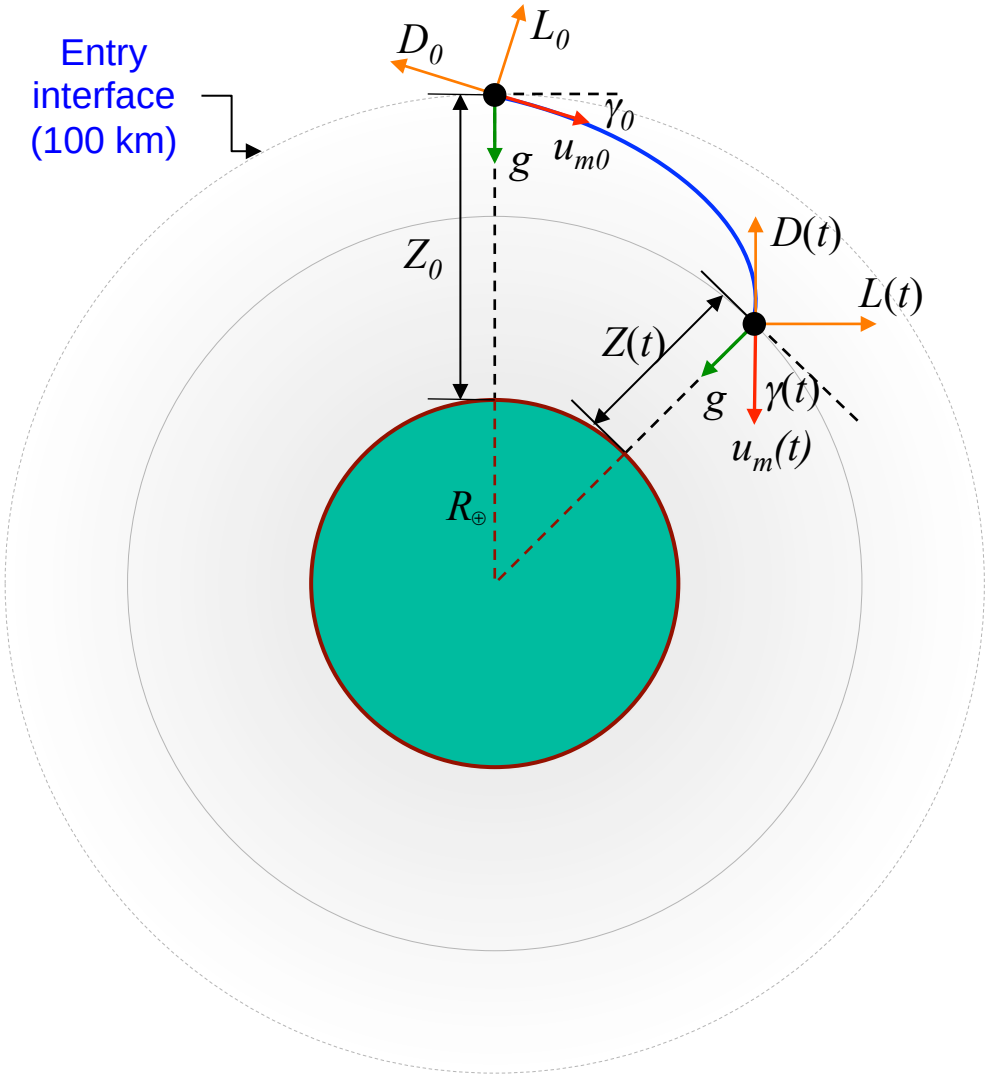
Ballistic coefficient



- For the same entry velocity and flight path angle, two bodies of different shapes and sizes, but identical ballistic coefficients, will fly the same trajectory
- Shape and size determine heating, and hence, mass loss
  - Insufficient to use albedo inferred dimension to estimate the mass for a spherical shape
- It is important to know both entry mass and cross sectional area
  - Drag coefficient can be estimated easily using simple Newtonian impact theory
- Videos of Chelyabinsk dust trail suggest a prolate ellipsoid shape

All shapes shown enclose the same volume as a 20 m diameter hemisphere

Equations of Meteor Physics



$$\beta_m = \frac{m_m}{C_{D_m} A_m}$$

Ballistic coefficient

$$\frac{dZ}{dt} = -u_m \sin\gamma$$

$$\frac{d\gamma}{dt} = \frac{g}{u_m}\cos\gamma - \frac{u_m}{R_\oplus + Z}\cos\gamma - \frac{1}{2}\frac{\rho_a u_m}{\beta_m}\left(\frac{C_{L_m}}{C_{D_m}}\right)$$

$$\frac{du_m}{dt} = -\frac{1}{2}\frac{\rho_a u_m^2}{\beta_m} + g\sin\gamma$$

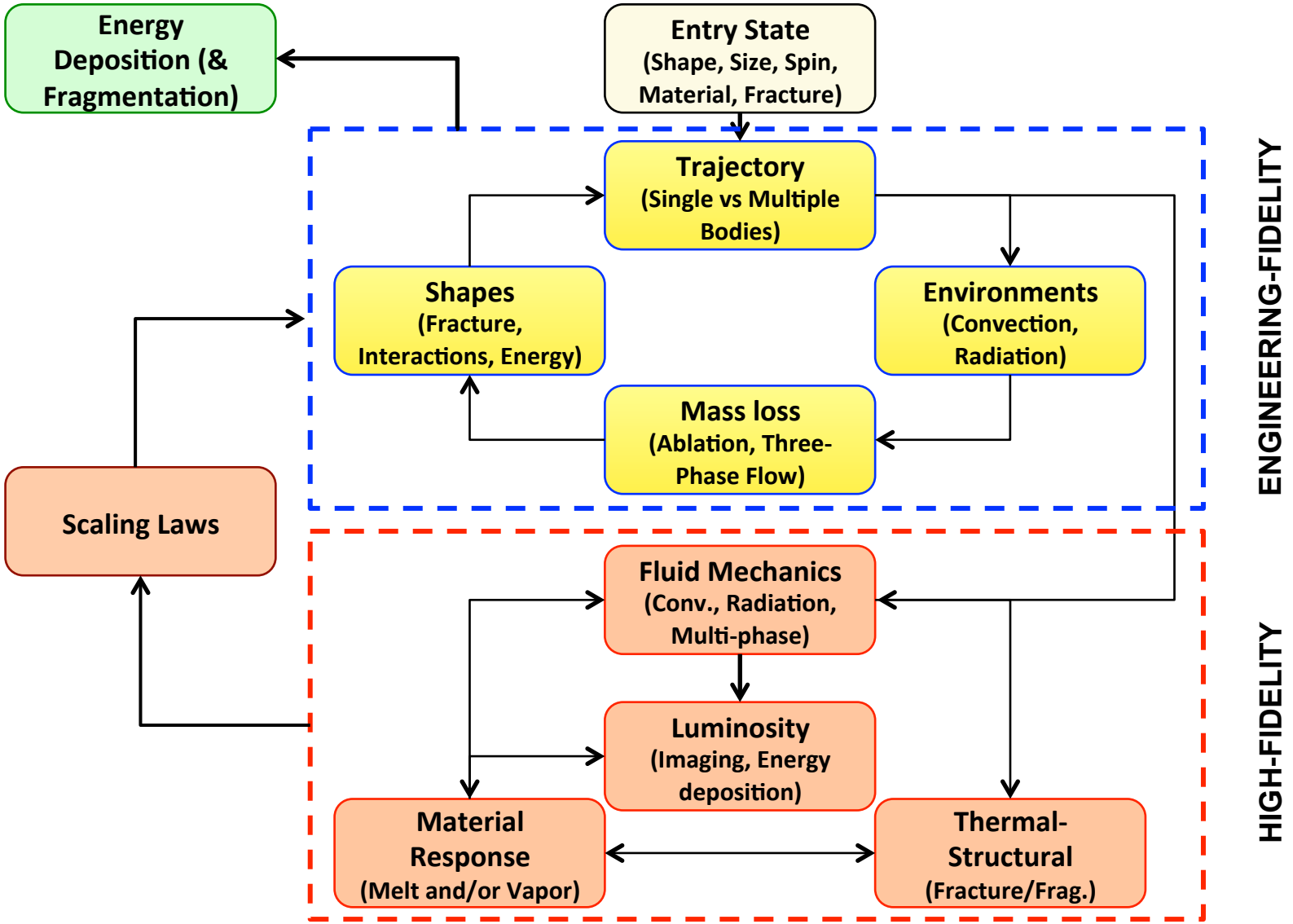
$$\frac{dm_m}{dt} = -\frac{1}{2}\rho_a u_m^3 \frac{C_H A_m}{Q}$$

$$\frac{A_m}{A_{m,0}} = \left(\frac{m_m}{m_{m,0}}\right)^{\mu}$$

μ=2/3: spherical shape

Mass loss equation is new – Galileo (to Jupiter) is the closest relevant NASA mission

Simulation Process



Analysis Tools, I:"
Flight Mechanics

- Single body; point mass (3DoF)
- Runge-Kutta time-integration of equations of motion
- Requires:
  - Shape and dimensions of entry object
  - Entry mass
  - Entry velocity (inertial)
  - Entry flight path angle (inertial)
  - Lat./Long. at atm. pierce point
- Modification to include mass loss
  - Time-varying heat transfer coefficient based on flow computations for spheres
- **Open Issues**
  - Multiple bodies (due to fragmentation) and their interactions
  - Irregular geometries/shapes

Analysis Tools, II:"
Aero/Aerothermodynamics

- **Flow (11-species – N_2,O_2,NO,NO^+,N_2^+,O_2^+,N,O,N^+,O^+,e^- – air model)**
  - Eulerian frame of reference – flow past a fixed body (shape, size, orientation)
  - 3D Navier-Stokes equations
    - Turbulent flows use simple eddy viscosity model
    - Thermal and chemical non-equilibrium (rate processes)
    - Bow shock captured as part of solution and grid tailored to bow shock
    - Variety of surface BCs – radiative eq., recombination rate chemistry, …
- **Radiation**
  - Line-by-line spectral simulation; continuum included
    - Atomic line and diatomic spectral databases
  - Tangent slab model for radiation transport
- **Open issues**
  - Multi-stage ionization required for velocity > 20 km/s
  - Coupling between material response and flow/thermal radiation fields
    - Solution turnaround time and computer resource requirements
  - Tangent slab transport model is somewhat restrictive

Analysis Tools, III:"
Material Thermal Response

- Multi-dimensional analysis of ablation
  - Detailed surface energy and mass balance
    - Ability to handle ablation of silica-based or pyrolysis of organic (phenolic) materials
  - Mass transfer handled through non-dimensional parameter called B-prime
    - B-prime tables (equilibrium) computed over a range of pressures and temperatures
    - Provide blowing rate (& composition) of pyrolysis products
  - Ability to handle recession of wetted surface
- Requires (especially at temperatures above 298 K):

Mass density (and porosity)	Elemental composition of material
Heats of formation of constituent species	Specific heats of constituent species
Thermal conductivity	Coefficient of thermal expansion

- **Open issues**
  - Compositions of meteoritic materials vary
  - Complexity of thermochemistry of ablation products and shock-heated gas
  - Tight coupling between flow/radiation and thermal response is a challenge
    - This is required to assess radiation blockage by meteoritic vapor

Analysis Tools, IV:"
Material Structural Response

- 3D finite-element approach to static and dynamic loading; nonlinear analysis
  - Variety of elements; 6-noded hexahedral elements preferred
    - Easier data transfer between flow and structural meshes
  - Structural, thermal, and thermal-structural analysis
  - Anisotropy in material properties
  - Crack and crack propagation; strain energy release
- Requires (particularly at temperatures above 298 K):

Material density	Poisson's ratio
Material moduli	Shear moduli
Yield strengths (compression, tension)	Porosity

- **Open issues**
  - Relating meteorite internal structure (incl. cracks & voids) to actual object
  - Can codes based on the continuum hypothesis be applied to objects with large numbers of cracks and pores (micro-scale)?

Entry Capsules *vs* Meteors, I:"
Easily the Hard Part

	Capsule (Earth entry)	Meteoroid (Asteroid)
Size	Less than 6 m diameter	Varies from microns to (kilo)meters
Entry Mass	Usually small for robotic missions	Varies from few grams to millions of kg
Entry Type	Controlled; Ballistic or Lifting	Uncontrolled; Ballistic assumed
Entry Velocity	Between 7.5 and 13 km/s	Hyperbolic (11–30 km/s)
Entry Angle	No steeper than -13°	Varies between -90° and 0° (skip out)
Flight Dynamics	3DoF or 6DoF	3DoF (6DoF?)
Aerothermal	Dominated by convective heating	Dominated by radiative heating

The lower limit on size is dictated by airburst/terrestrial impact risk

The upper limit on size is dictated by computing resources & solution turnaround

The upper limit on entry velocity is dictated by gas-phase thermochemistry

Entry Vehicle Design Overview

Phenomena

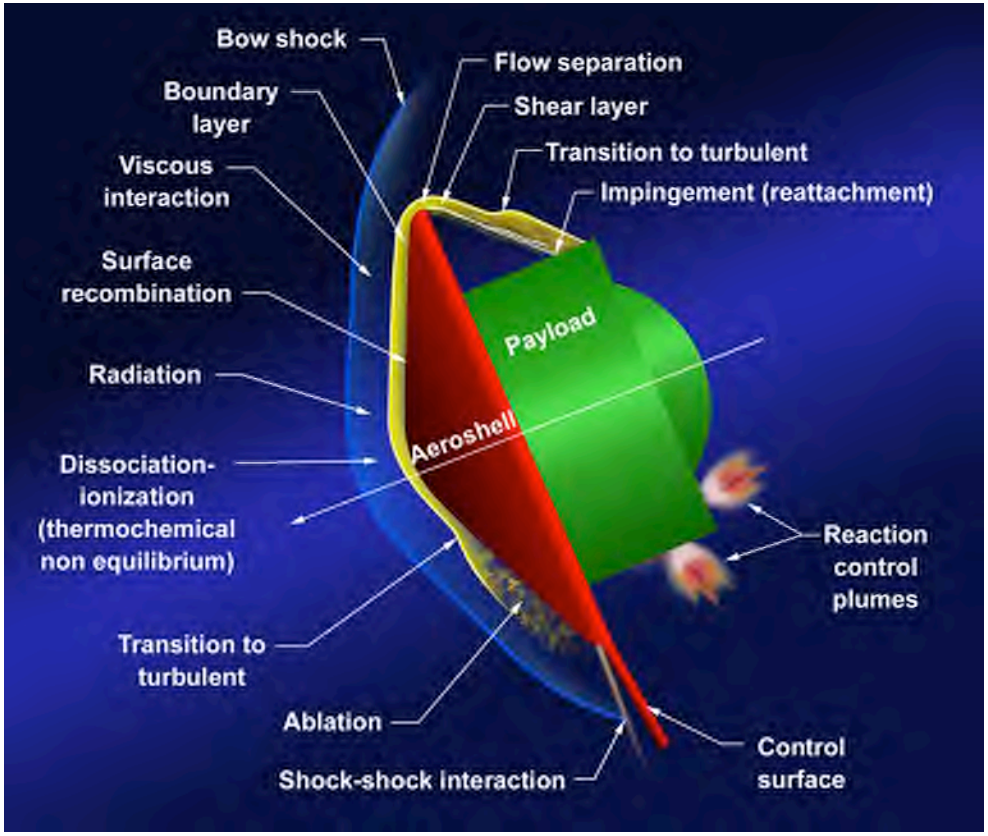


Figure courtesy R. Wheless & T. Horvath, NASA Langley Research Center

Modeling

- **Flight Mechanics**
  - Ballistic vs Lifting entries
  - 3DoF vs 6DoF
- **Aero/Aerothermodynamics**
  - Turbulent convective heating
  - Thermal radiative heating
- **Material Thermal Response**
  - Ablation & Recession
  - Melt *vs* Vaporization
- **Structural Response**
  - Pressure & shear loads
  - Dynamic loads

High-fidelity tools are used to anchor faster engineering-fidelity tools via scaling laws

All four models are strongly coupled for the asteroid/meteoroid problem!

Energy Deposition – Single Body

Ablation coefficient

$$I_m = \tau\left[\frac{1}{2}\sigma u_m^2 + 1\right]\frac{1}{2}\rho_a u_m^3 C_{D_m} A_m$$

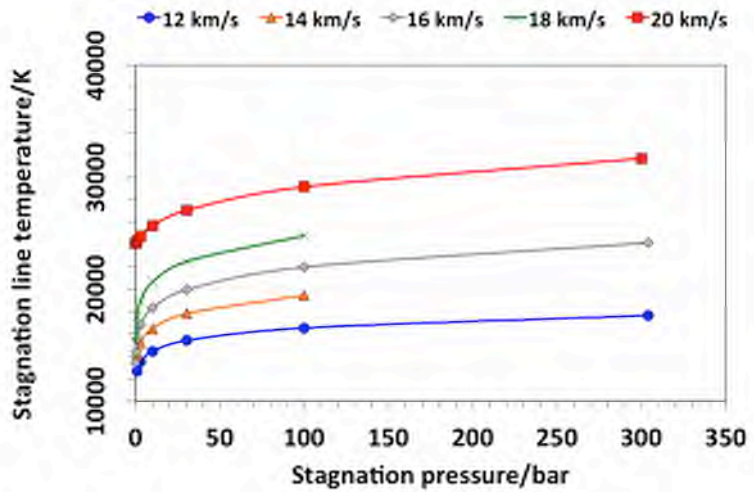
$$\sigma = \frac{C_H}{C_{D_m} Q}$$

- τ is the efficiency of converting kinetic energy ($m_m u_m{}^2/2$) into luminosity
  - Should A_m be the wetted area instead of X-sectional area?
- Luminous efficiency is either specified or varied to match observed data
- The heat of ablation, Q, a big source of uncertainty, shows up here too
  - Q is assumed same (8.08 MJ/kg) for stony and iron meteors, and everything in between
- If C_H and I_m can be computed for a range of R_m (hence A_m), ρ_a (from p_{stag}), and u_m of sphere, τ can be estimated

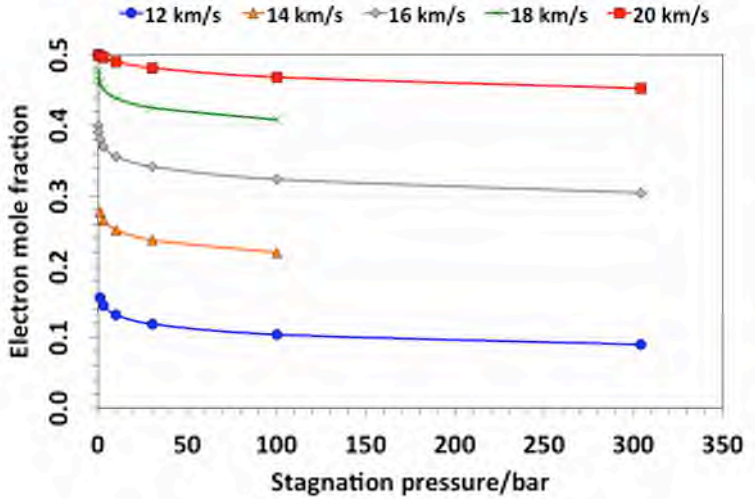
$$\tau = \frac{I_m}{\left[\frac{1}{2}\frac{C_H}{C_{D_m} Q}u_m^2 + 1\right]\frac{1}{2}\rho_a u_m^3 C_{D_m} A_m}$$

Flow Characteristics

Shock-layer temperature

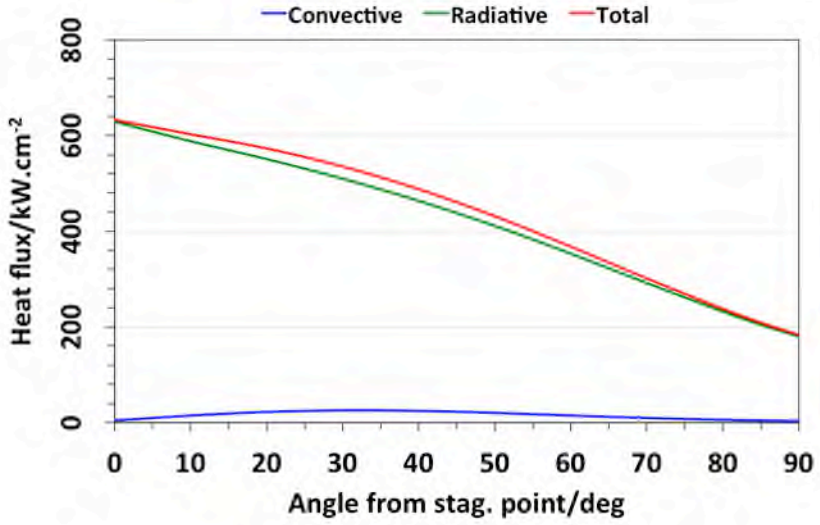


Free electron mole fraction



Surface heat flux distribution

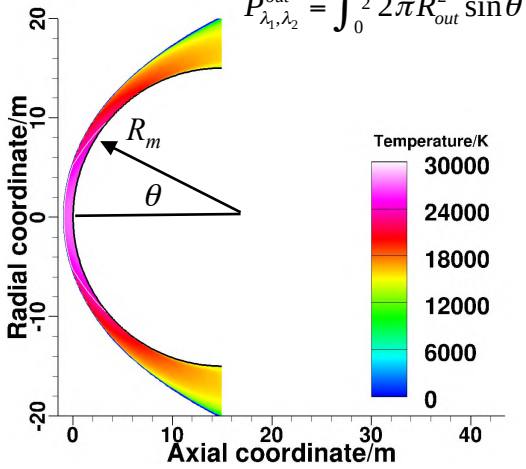
(u_m = 20 km/s, p_{stag} = 30 bar, R_m = 15 m)



- High stag. pressure => low altitude
- At 20 km/s nearly fully ionized flow
- Boundary-layer is fully turbulent
  - Surface imperfections may enhance convective heating locally
- Surface heating completely dominated by shock-layer radiation, especially at large length scales

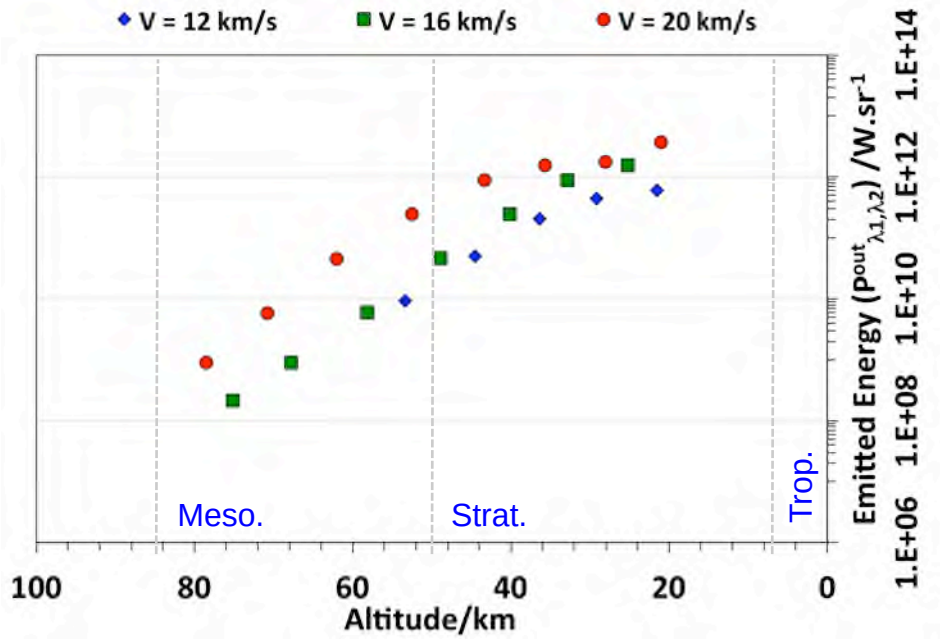
Luminosity: Gas Cap

$$P^{out}_{\lambda_1,\lambda_2} = \int_0^{\frac{\pi}{2}} 2\pi R^2_{out} \sin\theta \left(\int_{\lambda_1}^{\lambda_2} I^{out}_{\lambda_1,\lambda_2}(\lambda;\theta) d\lambda \right) d\theta$$

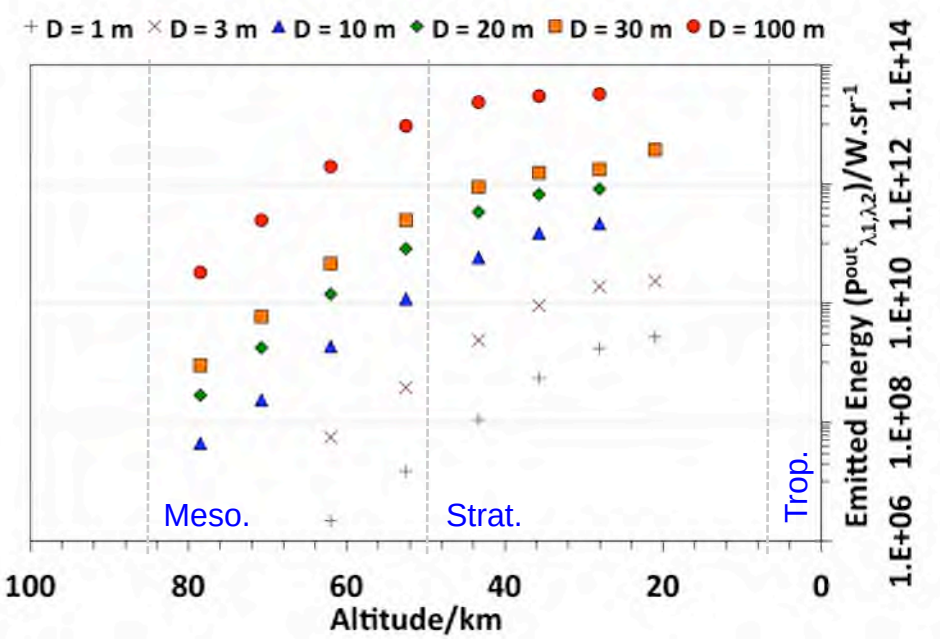


- Gas cap luminosity is simply total energy radiated into a hemisphere enclosing the bow shock
  - Wavelength range: 85 nm to 4 μm
    - Can be tailored for any passband filter
  - Conversion of energy to magnitude over a flight trajectory provides a synthetic light curve

30 m diameter, Velocity variation



20 km/s, Diameter variation



Circling Back, II

- Can we build or develop, across various classes of meteoroids, models for:
  - Material thermal response – ablation (vaporization *vs* melting)
    - Attempt at estimating enthalpy of ablation
    - Intense CO_2 laser heating (5 – 20 kW/cm^2) of meteoritic materials (Tamdakht, …)
    - See poster by Stern *et al*. in this workshop
  - Material structural response – fragmentation (internal structure)
    - Conversion of cracks/fractures in meteorites (falls) to unit problems for structural analysis
    - Design of Experiments approach to “unit problem” of matrix+inclusions
    - Influence of structural properties, including material anisotropy, of meteoritic material
    - See poster by Agrawal *et al*. in this workshop
  - Energy deposition along the meteor trajectory in the atmosphere – light curves
    - Attempt to reconstruct Chelyabinsk trajectory using constant C_H and time-varying C_H derived from flow and radiation computations
    - Fragmentation (Borovicka *et al*., *Nature*, 2010) imposed at 40 and 30 km altitude
    - See poster by Allen *et al*. in this workshop