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

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Motivation

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

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

### Validation Data
- Capsule (Earth entry): Sensors, imaging, capsule recovery
- Meteoroid (Asteroid): Light curves, infrasound, falls

### Ground Testing
- Capsule (Earth entry): Ballistic ranges, arc jets, wind tunnels, laser facilities
- Meteoroid (Asteroid): Probably same facilities as capsules, but with limitations

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

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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

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

- \( C_H \) 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

\*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 $C_H$

\[ C_H = \frac{\int_0^{\pi/2} 2\pi R^2 q(\theta) \sin \theta d\theta}{\frac{1}{2} \rho_a u_m^3 A_m} \]

\[ q(\theta) = q_{\text{Turbulent}}(\theta) + q_{\text{Radiative}}(\theta) \]

\[ \Gamma = \frac{2q_{\text{Radiative}}}{\frac{1}{2} \rho_a u_m^3} \]

- 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

\[ P_{\lambda_1,\lambda_2}^{\text{out}} = \int_0^{\pi/2} 2\pi R_{\text{out}}^2 \sin \theta \left( \int_{\lambda_1}^{\lambda_2} I_{\lambda_1,\lambda_2}^{\text{out}}(\lambda; \theta) d\lambda \right) d\theta \]
Flight Space Concept"
(Uses US 1976 Standard Atmosphere)

- 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 aero thermal environments at nodes
  - Heat transfer efficiency and energy deposition are functions of $R_m$, $\rho_a(Z)$, $u_m$

Scaling Laws

\[
\begin{align*}
  p_{stag} &\propto \rho_a u_m^2 \\
  q_{stag}^{\text{Conv}} &\propto \frac{1}{\sqrt{R_m}} \sqrt{\rho_a u_m^3} \\
  q_{stag}^{\text{Rad}} &\propto R_m \rho_a u_m^8
\end{align*}
\]

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

Chelyabinsk data from Borovicka et al., Nature, 2013
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)
• 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, $C_H$

- $C_H$ 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 ($R_m$)

$$C_H = \frac{\int_0^{\pi/2} 2\pi R_m^2 q(\theta) \sin \theta d\theta}{\frac{1}{2} \rho a u_m^3 A_m}$$
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
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 TC₃
  - Itokawa is a dumbbell shape with “weakness” at the neck
  - NEO 2008 TC₃ most likely oriented in flight
- Irregular shapes will require full 6DoF analysis
  - Will require mass moments of inertia of the object – difficult!

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/cm²!
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

\[ \frac{dZ}{dt} = -u_m \sin \gamma \]

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

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

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

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

\[ \mu = 2/3: \text{spherical shape} \]

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

- **Entry State** (Shape, Size, Spin, Material, Fracture)
- **Shapes** (Fracture, Interactions, Energy)
- **Environments** (Convection, Radiation)
- **Mass loss** (Ablation, Three-Phase Flow)
- **Trajectory** (Single vs Multiple Bodies)
- **Fluid Mechanics** (Conv., Radiation, Multi-phase)
- **Luminosity** (Imaging, Energy deposition)
- **Material Response** (Melt and/or Vapor)
- **Thermal-Structural** (Fracture/Frag.)
- **Scaling Laws**
- **Energy Deposition ( & Fragmentation)**

**HIGH-FIDELITY**

**ENGINEERING-FIDELITY**
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 (\textit{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)
  - Heats of formation of constituent species
  - Thermal conductivity
  - Elemental composition of material
  - Specific heats of constituent species
  - 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

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

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

- 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

Modeling

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

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

\[ \sigma = \frac{C_H}{C_{D_m} Q} \]

- \( \tau \) 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 \( A_m \)), \( \rho_a \) (from \( p_{stag} \)), and \( u_m \) of sphere, \( \tau \) can be estimated

\[ \tau = \frac{I_m}{\frac{1}{2} \frac{C_H}{C_{D_m} Q} u_m^2 + 1} \frac{1}{2} \frac{1}{2} \rho a u_m^3 C_{D_m} A_m \]
Flow Characteristics

Shock-layer temperature

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

- 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

- 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

\[
P_{\lambda_1,\lambda_2}^{\text{out}} = \int_0^{\frac{\pi}{2}} 2\pi R_m^2 \sin \theta \left( \int_{\lambda_1}^{\lambda_2} I_{\lambda_1,\lambda_2}^\text{out} (\lambda; \theta) \, d\lambda \right) \, d\theta
\]
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