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Physics-Based Modeling of Meteor Entry and Breakup

Dinesh K. Prabhu,** Parul Agrawal,** Gary A. Allen, Jr.,** Charles W. Bauschlicher, Jr.,*
Aaron M. Brandis,** Yih-Kanq Chen,* Richard L. Jaffe,* Grant E. Palmer,**
David A. Saunders,** Eric C. Stern,** Michael E. Tauber,** and Ethiraj Venkatapathy*
Entry Systems and Technology Division
*NASA Ames Research Center, Moffett Field, CA 94035, USA
**ERC, Incorporated at NASA Ames Research Center, Moffett Field, CA 94035, USA

OBJECTIVES

NEAR TERM: To apply state-of-the-art entry physics simulation tools (developed for entry capsules) to atmospheric flight of potentially hazardous asteroids (PHAs)

LONG TERM: To develop models/mechanisms for energy deposition into the atmosphere and fragmentation/airbursts of PHAs of various sizes and spectral classes

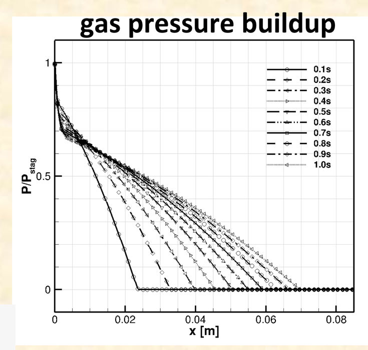
SINGLE BODY ANALYSIS – (HEMI)SPHERICAL SHAPE

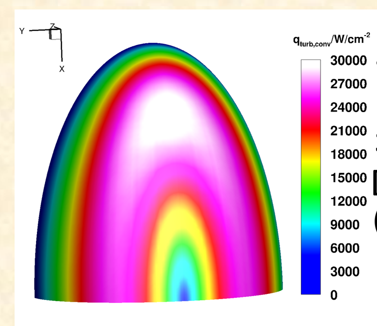
ANALYSIS TOOLS

- ***Traj***: In-house 3DoF trajectory simulation code; include mass loss equation
- ***Dplr***: In-house 2D/3D flow simulation code; thermochemical nonequilibrium & variety of surface boundary conditions
- ***Neqair***: In-house line-by-line spectral code; tangent slab approximation for radiation transport
- ***Fiat & Titan***: In-house material thermal response codes (1D and 2D)
- ***Marc***: Commercial finite-element analysis code (for structural and thermal-structural analysis)
- ***Other***: Numerous small software utilities developed in support of several NASA flight programs

ANALYSIS COMPLEXITY

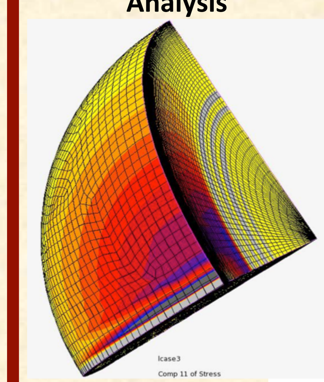
Influence of internal gas pressure buildup



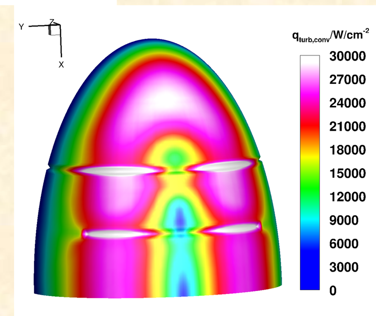


Turbulent convective heat flux contours 32x16x16 m spheroid [smooth & "fissured"] (20 km/s, 30 bar stag. pressure)

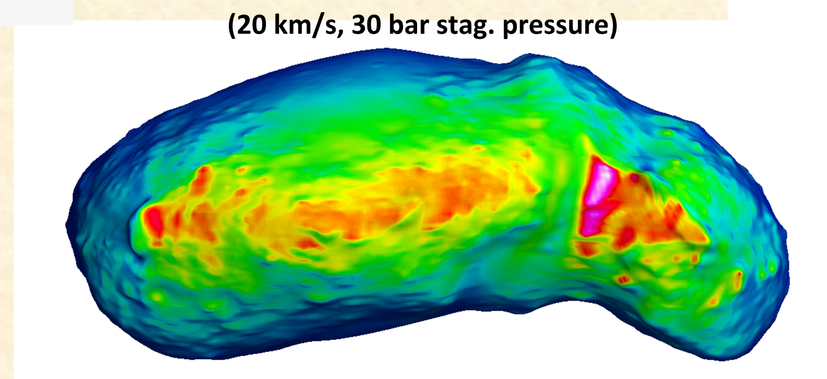
Structural and Thermal-structural Analysis



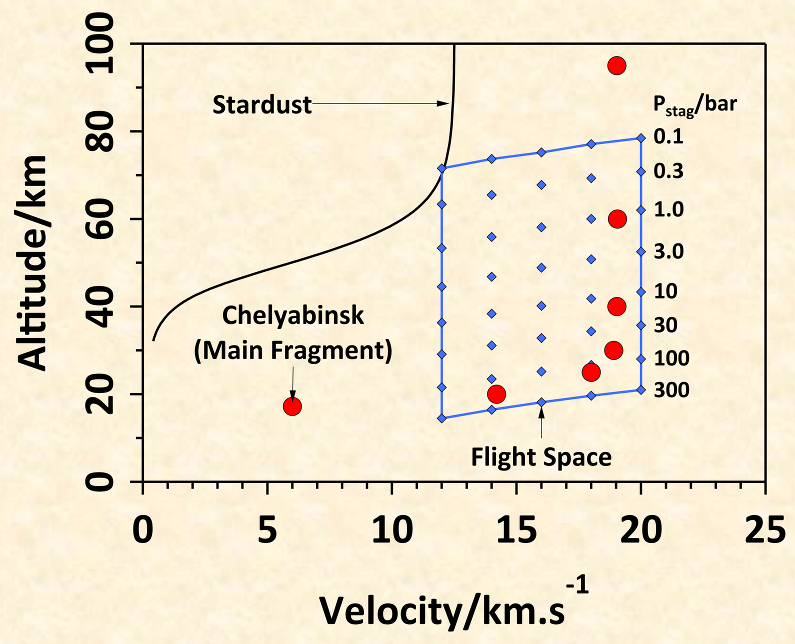
Results of high-fidelity flow computations serve as boundary conditions to materials and structural/thermal-structural simulations

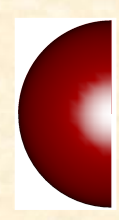


Pressure contours 1/38-scale Itokawa (20 km/s, 30 bar stag. pressure)



FLIGHT SPACE





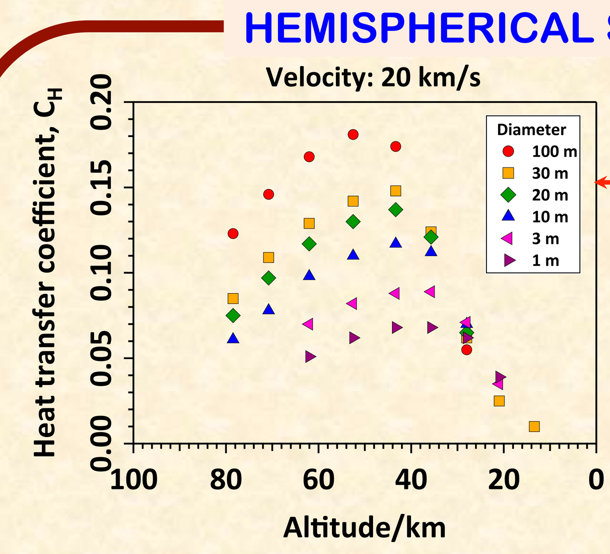
Hemisphere of radius R

Stardust,* at ≈13 km/s entry velocity, is the "calibration" point for the analysis tools listed. All velocities greater than 12–13 km/s, especially Chelyabinsk at ≈19 km/s, are new challenges for high-fidelity entry physics simulations.

*See the special issue of *Journal of Spacecraft and Rockets*, 47(6), 2010.

- Flight space parameterized by flight velocity, freestream density, and object size
- Trajectory delinked from high-fidelity analysis; predicted heat transfer and brightness to be included in trajectory code via scaling laws
- Current flight space covers: (1) velocity ranging from 12 to 20 km/s, stagnation pressure (eq. density) of 0.1 to 300 bar, and hemisphere diameters from 1 to 100 m
- Can replace hemisphere with another shape, and can include the wake for estimates of energy deposition

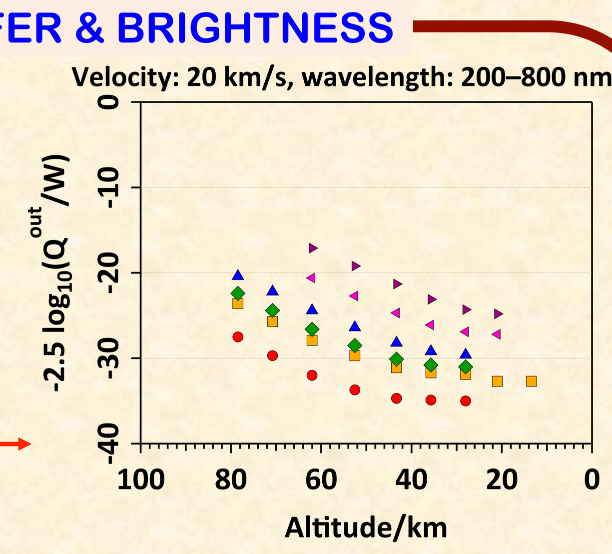
HEMISPHERICAL SHAPE: HEAT TRANSFER & BRIGHTNESS



$$C_H = \frac{\int q(x,y)\,dA}{\frac{1}{2}\rho_\infty u_\infty^3 A_{wet}}$$

$$q(x,y) = q_{conv}(x,y) + q_{rad}^{in}(x,y)$$

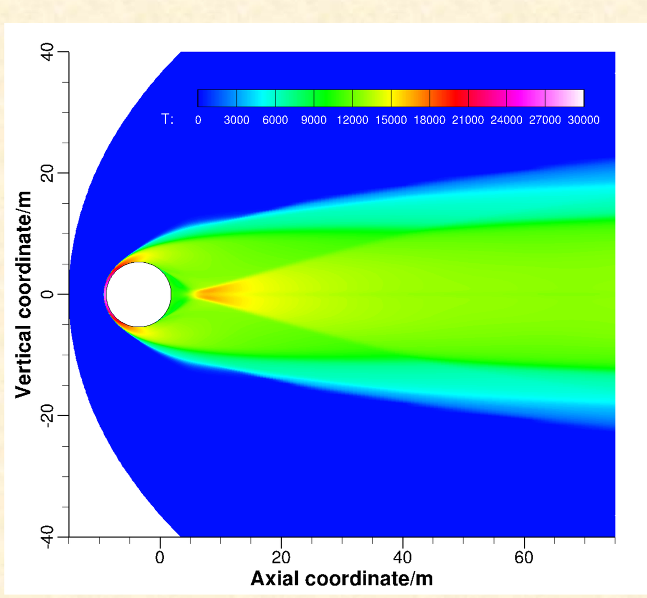
$$Q = \int q_{rad}^{out}(x,y)\,dA$$



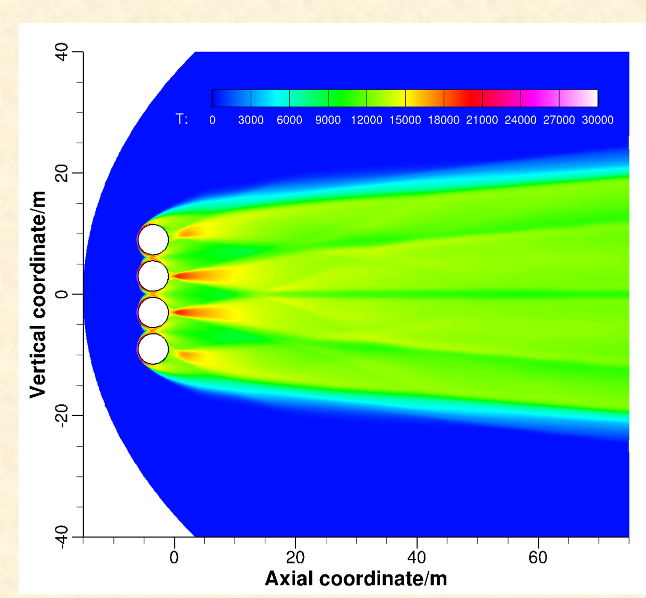
- The heat transfer coefficient reaches a maximum between 35 and 55 km depending on size
- The energy output in 200-800 nm range appears to reach an asymptotic value
- Time-varying heat transfer coefficient is incorporated in the trajectory simulation tool - ***Traj***

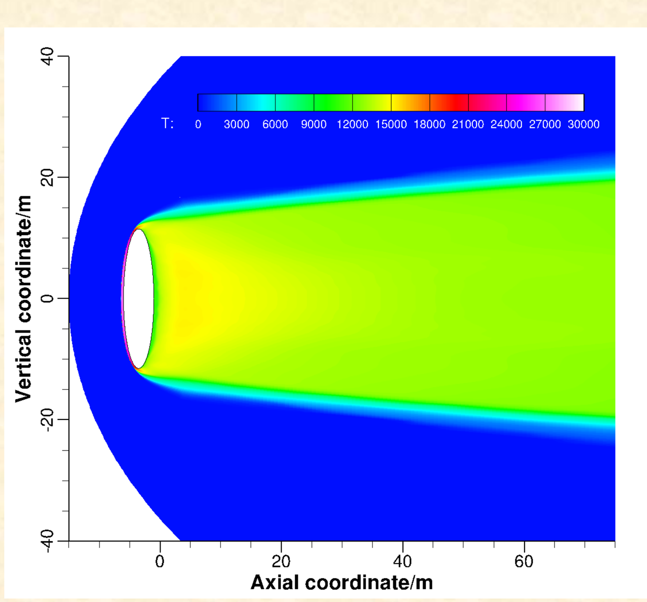
ALTERNATE SHAPES AND MULTIPLE BODY ANALYSIS

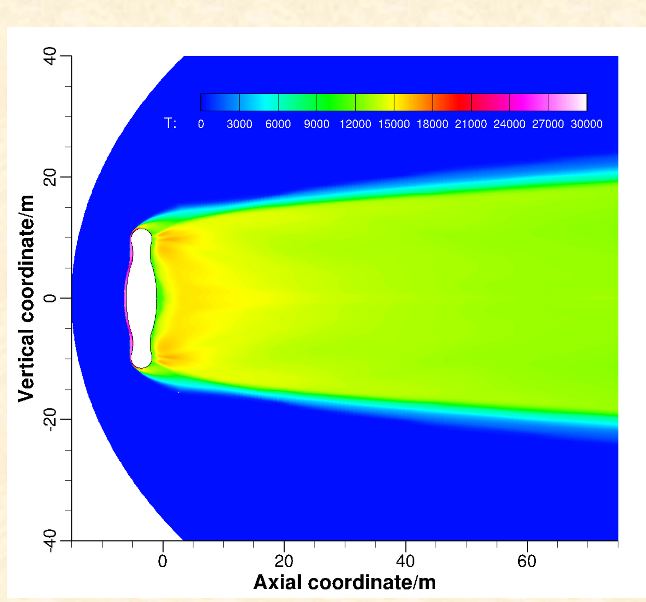
SHAPES AND FRAGMENTATION

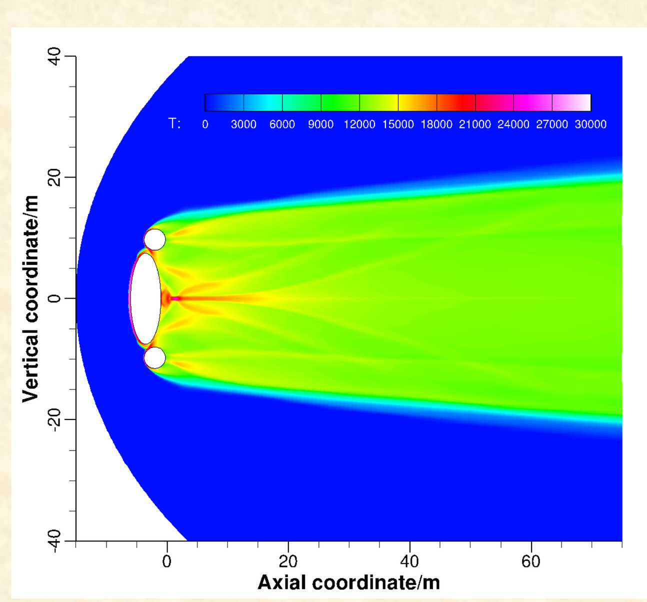


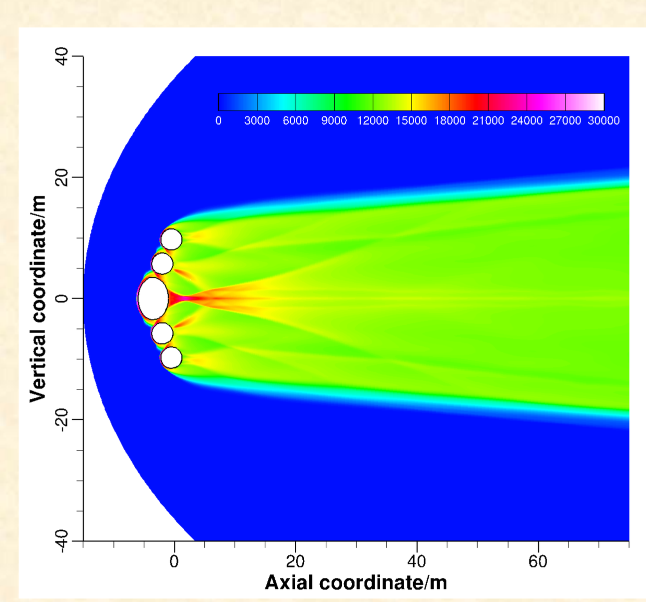
- Traditional analyses in meteor physics rely on spherical shape that "pancakes" for increased drag area (equivalent to reduction in ballistic coefficient)
- Does the shape of the object matter? What is the influence of the shape on the light curve?
- Is the light curve affected by the number of fragments and/or their arrangement relative to each other?
- Three-dimensional computations performed for spheres, prolate spheroids, and lobed geometries – all single body with one axis of symmetry (rotational)
- Static analyses, i.e., bodies are in fixed locations relative to each other, with the intent of determining the influence of shock-shock interactions on aerodynamics (drag and side forces) and wake structures
- *Preliminary* results shown here are for a velocity of 20 km/s and a stagnation pressure of 30 bar











OUTLOOK

- Enhancements to thermodynamic and transport properties to include multiply-ionized species – N^{2+}, N^{3+}, O^{2+}, O^{3+} – to open up velocity space (V > 20 km/s)
- Improvements to radiation energy transport through the use of Rosseland mean opacity
- Development of process to construct synthetic light curves from high-fidelity solutions; will be tested against light curves for well known bolides
- Material thermal response (ablation and recession) and its coupling to flow solver
- Structural response for flight loads *and* inclusion of voids and cracks in the structure; brittle fracture perspective
- Several lines of inquiry to test fragmentation hypotheses: (a) mechanical, (b) thermo-mechanical, and (c) thermo-chemical

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