Thermophysics issues relevant to high-speed Earth entry of large asteroids

Asteroid Threat Assessment Project

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AIAA SciTech 2016
Special Session: Aerothermodynamics of Meteor Entries

January 4 – 8, 2016, San Diego, California

Ames Research Center

Acknowledgments

- Jim Arnold, Craig Burkhard, Ethiraj Venkatapathy, Derek Sears, Donovan Mathias, Jessie Dotson, David Morrison, Peter Jenniskens, Michael Aftosmis, Katie Bryson, and Marian Nemec are thanked for helpful discussions

- V&V computations of Chris Johnston (NASA LaRC) are gratefully acknowledged

- NASA Ames Research Center contracts NNA15BB15C (to AMA, Inc.), and NNA10DE12C (to ERC, Inc.) funded the present work

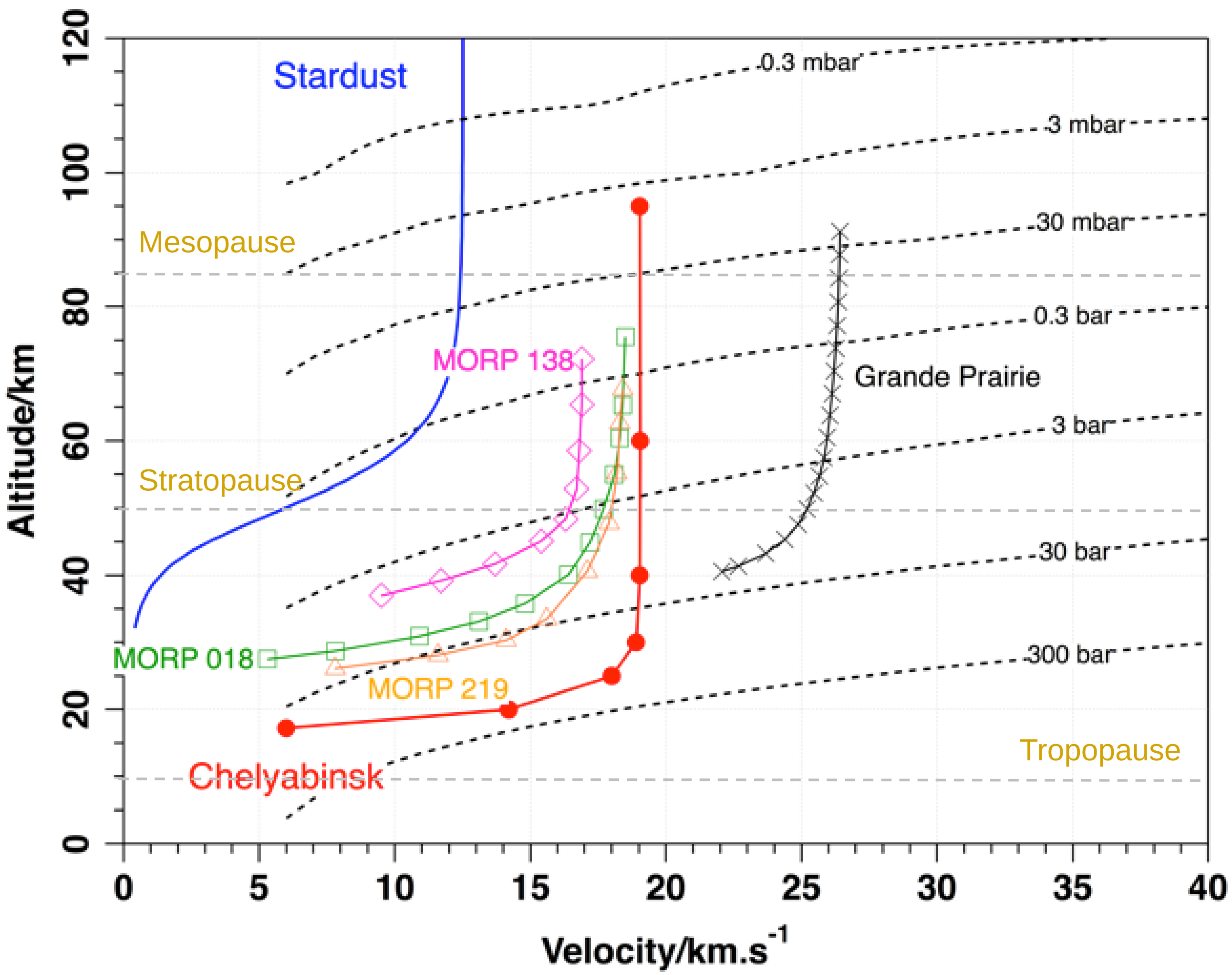
The Big Picture

- What size asteroid?
  - Shape and size
- (of) What spectral type?
  - Stony (S)
  - Stony-iron (X)
  - Iron (M)
- (at) What entry conditions?
  - Entry velocity (u_0)
  - Entry flight path angle (γ_0)
- (causes) What kind of damage on the planet via …
  - Airburst, or Cratering, or Tsunami?

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

Bringing *reliable predictive* capabilities to bear on meteoroid entries is the focus of efforts

Entry Capsules *vs.* Meteors



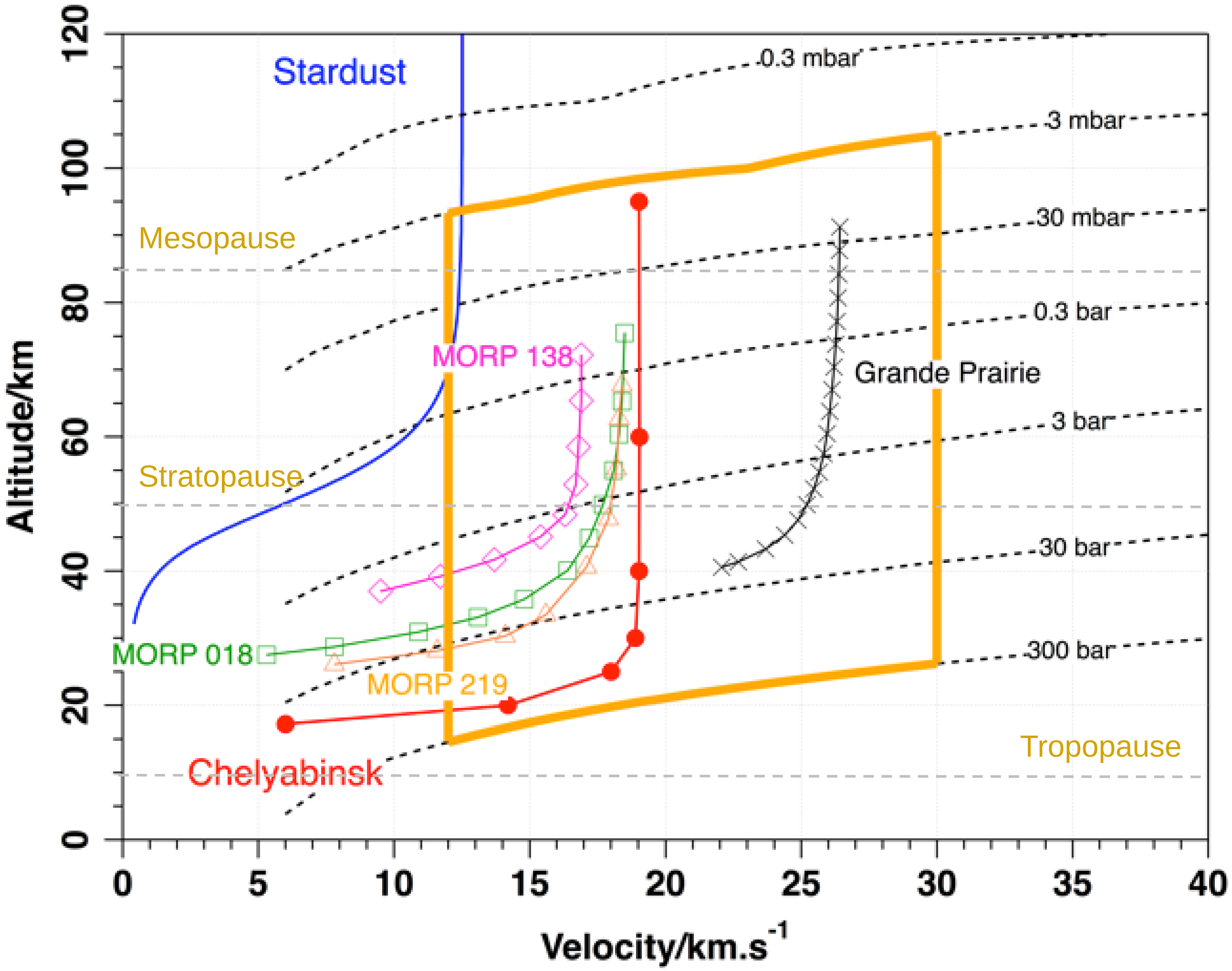
- Stardust [1]
  - Size was 0.8 m (dia)
  - Velocity < 13 km/s
  - Low ballistic coefficient
- Meteoroids/Asteroids [2]
  - Sizes >> 1 m (dia)
  - Velocities > 12 km/s
  - High ballistic coefficients
  - High stag. pressures
  - High Reynolds numbers

MORP = Meteorite Observation & Recovery Project [3,4]

References:

1. **Desai, P., Qualls, G., & Levit, C.,** "Stardust Entry Reconstruction," AIAA Paper 2008-1198, Jan. 2008.
2. **Borovicka, J. *et al.*,** "The trajectory, structure, and origin of the Chelyabinsk asteroidal impactor," *Nature*, **503**, 2013, pp. 235-237.
3. **Gritsevich, M., & Koschny, D.,** "Constraining the luminous efficiency of meteors," *Icarus*, **212**, 2011, pp. 877-884.
4. **Halliday, I.**, "The Grande Prairie Fireball of 1984 February 2," *J. Roy. Soc. Astro. Canada*, **79**(5), 1985, pp. 197-214.

Flight Space



- Assume entry interface (EI) at 100 km
  - If Kn ≤ 0.005 is a criterion for using a continuum CFD approach, then min. diameter of a sphere is 28.4 m
- Computations performed for various size (hemi)spheres at conditions within the FLIGHT SPACE shown

References:

1. **Desai, P., Qualls, G., & Levit, C.,** "Stardust Entry Reconstruction," AIAA Paper 2008-1198, Jan. 2008.
2. **Borovicka, J. *et al.*,** "The trajectory, structure, and origin of the Chelyabinsk asteroidal impactor," *Nature*, **503**, 2013, pp. 235-237.
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Motivation

- Can some of the modern computational analysis tools used in heatshield design be used (repurposed?) for simulation of asteroid entries?
- For various classes of asteroidal materials, can we build/develop models for:
  - Aero/aerothermodynamics
  - Material thermal response?
  - Material structural response, including fragmentation?
  - Energy deposition along meteor trajectory in the atmosphere?
- How much would the results of these models differ from, and improve upon, those obtained from the equations of meteor physics?

Mass Loss – Single Body

Mass loss

$$\frac{dm}{dt} = -\frac{\sigma}{2}\rho_a u^3 C_D A$$

$$\sigma = \frac{C_H}{C_D Q}$$

Luminosity

$$I = \tau \frac{dE}{dt} = -\tau \left[\left(\frac{\sigma}{2} u^2 + 1 \right) \left(\frac{1}{2} \rho_a u^3 C_D A \right) \right]$$

ρ_a	Ambient density	Q	Heat of ablation
u	Meteor velocity	m	Meteor mass
C_H	Heat transfer efficiency	t	Time
A_m	Cross sectional area	σ	Ablation coefficient
C_D	Drag coefficient	τ	Luminous efficiency

- C_H is efficiency of conversion of freestream energy into heating of surface
- Q, heat of ablation, is a big source of uncertainty
  - Need to understand energetics of melt *vs.* vaporization
  - Exploratory test on meteoritic materials performed at LHMEL [1]
    - Surface irradiation with 1.07 µm fiber laser
    - 2^{nd} round of testing of H chondrites scheduled for 2016
- τ is fraction of deposited energy captured as visible light on a detector

Reference:

1. **Stern, E. C. *et al.*,** "Numerical and Experimental Investigation of Meteoroid Ablation," poster presented at *First International Workshop on Potentially Hazardous Asteroids Characterization, Atmospheric Entry & Risk Assessment*, July 7-9, 2015, NASA Ames Research Center, Moffett Field, CA 94035

Objectives

- **To estimate** heat transfer efficiency, C_H
  - (Hemi)spherical shape is the focus – diameters ranging from 1 m to 300 m
  - Entry velocities ranging from 12 km/s to 30 km/s
  - Stagnation pressures ranging from 0.3 bar to 300 bar
- **To estimate** energy radiated (to ambient air)
  - Energy deposition (partly)
- **To explore** influence of surface blowing on flow characteristics
  - Equivalence to surface recession?
- **To explore** general flow characteristics of multiple bodies in proximity
  - Shock-shock interactions and their aero/aerothermal effects
  - How fragments interact with each other

Modeling Tools

- Flow computations (***DPLR***) [1]:
  - Navier-Stokes (axisym or 3D) 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^-)
    - Include N^{2+}, O^{2+}, N^{3+}, and O^{3+} for freestream velocities > 20 km/s
  - Gas phase rate chemistry
- Radiation computations (***NEQAIR***) [2]:
  - Line-by-line simulations with temperatures & number densities from flow solutions
    - Includes discrete transitions (atomic lines – nosecap, and molecular band systems - wake) and continua (bound-free & free-free)
  - Decoupled from flow computations (adiabatic inviscid shock layer assumption)
- Flow & radiation fields are tightly coupled with material thermal response
  - *DPLR-NEQAIR* coupling methodology currently under development
  - Material response code, *ICARUS*, is also under development

References:

1. **Wright, M. W., White, T., & Mangini, N.,**"Data Parallel Line Relaxation (DPLR) Code User Manual Acadia – Version 4.01.1," NASA/TM-2009-215388, 2009.
2. **Cruden, B. A., & Brandis, A. M.,** "Updates to the NEQAIR Radiation Solver," *Radiation in High Temperature Gases Workshop*, St. Andrews, UK, Nov.2014.

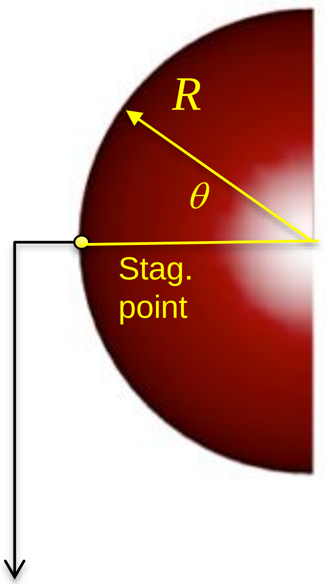
Modeling Assumptions

- Assumption #1: The meteor body *does not* ablate
  - No shape change
- Assumption #2: The meteor body *does not* cool by re-radiation (cold wall)
  - Allows application of physically meaningful surface boundary conditions, i.e., catalytic recombination of species (atoms and their ions)
- Assumption #3: No blockage by vapor phase of meteoritic material
  - Need material thermal response model
  - Need gas phase thermodynamic and transport properties of blown species

Assumptions provide upper bound on heating (convective and radiative)

Quantification will require coupled computations!

Computational Process



$$C_H = \frac{\int_0^{\pi/2} 2\pi R^2 q(\theta)\sin\theta \, d\theta}{\frac{1}{2}\rho_a u^3 A}$$

Flow computation
DPLR code

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

Tauber-Wakefield radiation cooling correlation [1]

$$q_{Nonadiabatic}^{Radiative}(\theta) = \frac{q_{Adiabatic}^{Radiative}}{\left(1+\kappa\Gamma^{\beta}\right)}$$

$$\Gamma = \frac{2q_{Adiabatic}^{Radiative}}{\frac{1}{2}\rho_a u^3}$$

Radiation computation
NEQAIR code

$$\kappa = 3.4, \quad \beta = 1$$

Scaling Laws

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

$$q_{stag}^{Conv} \propto \frac{1}{\sqrt{R}}\sqrt{\rho_a} u^3$$

$$q_{stag}^{Rad} \propto R \rho_a u^8$$

References:

1. **Tauber, M. E., & Wakefield, R. M.,** "Heating Environment and Protection During Jupiter Entry," *J. Spacecraft and Rockets*, **8**(6), 1971, pp. 630–636.

Gas Phase Properties

- Thermodynamics
  - Require $C_{p,s}$ (s = species) for air and surface species
    - Must be valid up to 50,000 K (for air) and 6,000 K (for blown species)
    - Must include atoms and their ions (including multiple stages)
    - Must factor in lowering of ionization potential for partition function cut off – $C_{p,s}(p, T)$!
  - H_s and S_s (needed for equilibrium constant) computed from $C_{p,s}$ as

$$\tilde{H}_s(T) = \frac{1}{T}\int_{T_{ref}}^{T} \tilde{C}_{p,s}(\zeta)\,d\zeta \qquad \tilde{S}_s(T) = \int_{T_{ref}}^{T} \frac{1}{\zeta}\tilde{C}_{p,s}(\zeta)\,d\zeta \qquad \tilde{C}_{p,s} = \frac{C_{p,s}}{R},\ \tilde{H}_s = \frac{H_s}{RT},\ \tilde{S}_s = \frac{S_s}{R}$$

- Transport
  - Require $\Omega_{i,j}^{(1,1)}$ *and* $\Omega_{i,j}^{(2,2)}$ (i,j = interacting pairs) up to 50,000 K
- Kinetics
  - Rates for second- and third-stage ionization reactions
    - Charge exchange or electron impact?

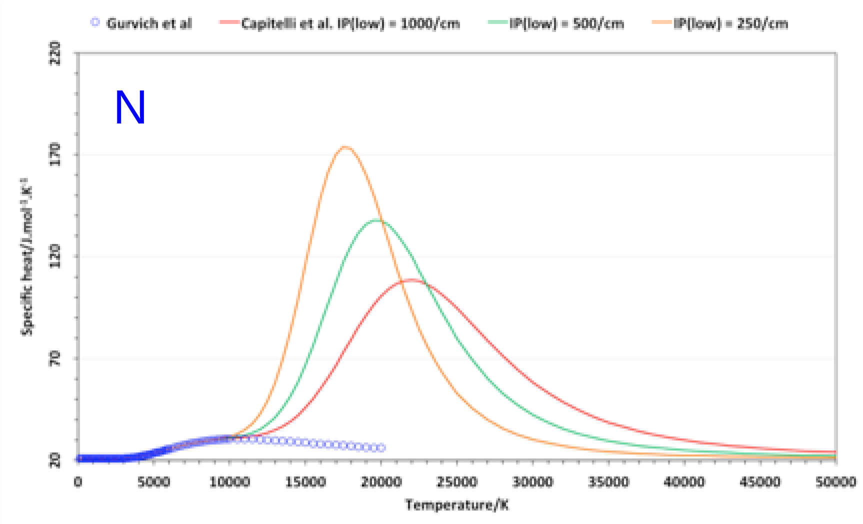
Thermodynamic Properties (1/2)

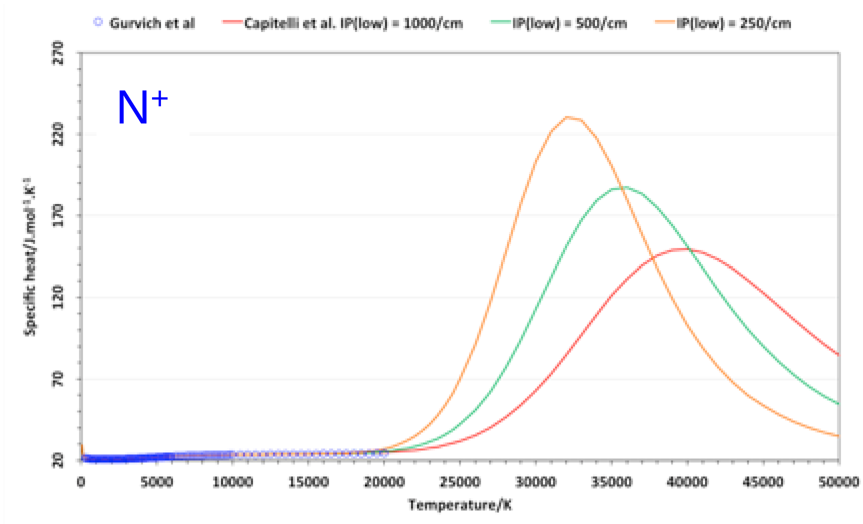
- Three possible approaches for thermodynamic properties
  - Approach #1: Use LeRC properties
    - Linear extrapolation of enthalpy for T > 20,000 K => constant specific heat
    - No data for higher stages of ionization
  - Approach #2: Use Capitelli *et al.* properties [1] --- included in v4.03 of *DPLR*
    - Claimed validity up to 50,000 K
    - Include higher stages of ionization *and* consider ionization potential (IP) lowering
    - Include autoionizing states in energy levels
  - Approach #3: Compute properties using NIST energy levels
    - Recent work of Johnston et al. [2] has thermo properties
      - Includes second stage ionization of N and O, but no partition function cut off
      - IP lowering (dependent on electron number density) included in enthalpy
    - Work of Jaffe [3] in this conference
      - Includes second and third stage of ionization of N and O *and* IP lowering
      - Does not include autoionizing states

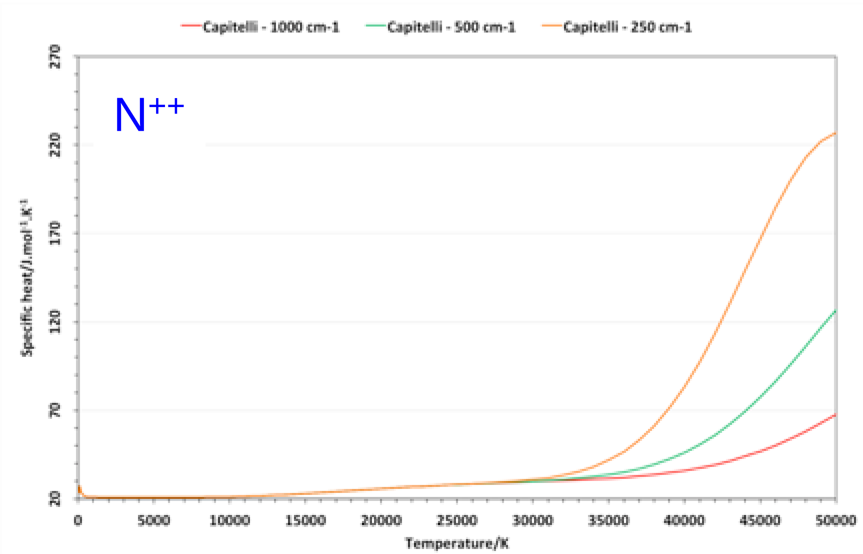
References:

1. **Capitelli, M. *et al*.**, "Tables of Internal Partition Functions and Thermodynamic Properties of High-Temperature Mars-Atmosphere Species from 50K to 50000K," ESA STR-246, October 2005.
2. **Johnston, C. O. *et al*.**, "Aerothermodynamic Characteristics of 16-22 km/s Earth Entry," AIAA Paper 2015-3110, June 2015.
3. **Jaffe, R. L.**, "Thermochemistry of strong air plasmas for hypervelocity Earth entry of asteroids," AIAA Paper 2015-xxxx, January 2016.

Thermodynamic Properties (2/2)

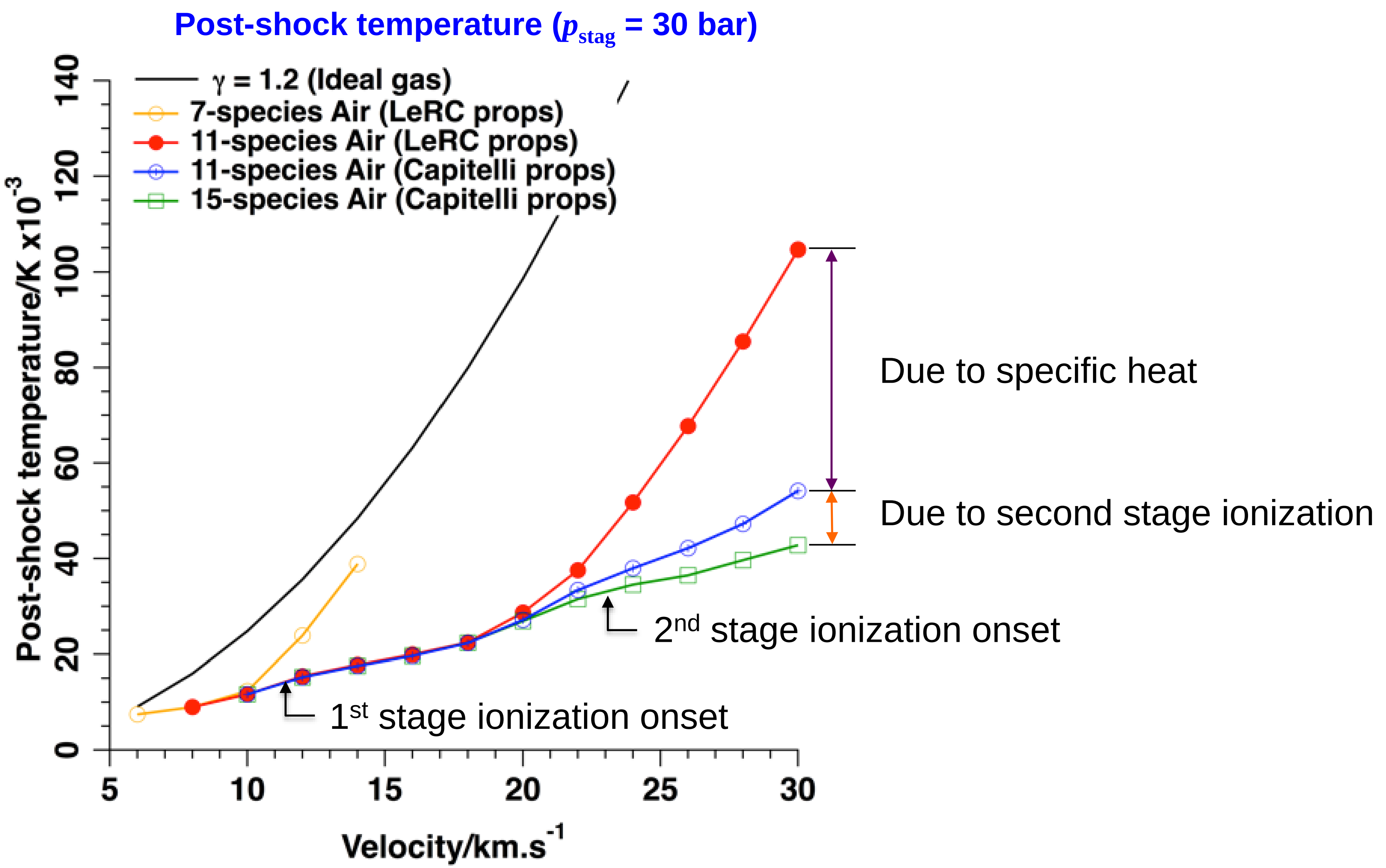






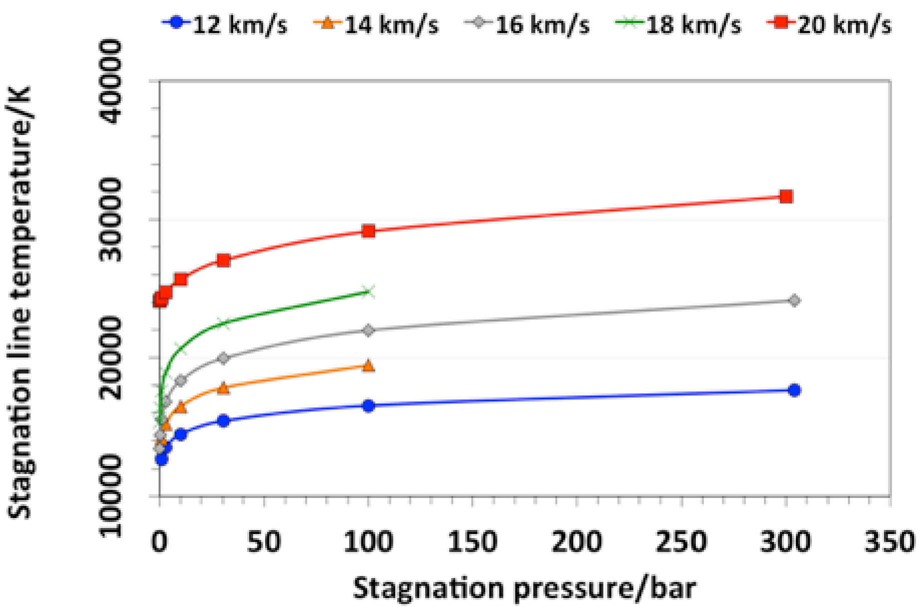
- IP lowering reduces number of electronic states included in partition function
- IP lowering of 1000 cm^{-1} selected for implementation in *DPLR*
  - Assumed adequate for high-pressure cases (> 1 bar)
- Should pressure dependence be included in math/CFD model?

Flow Characteristics (1/3)

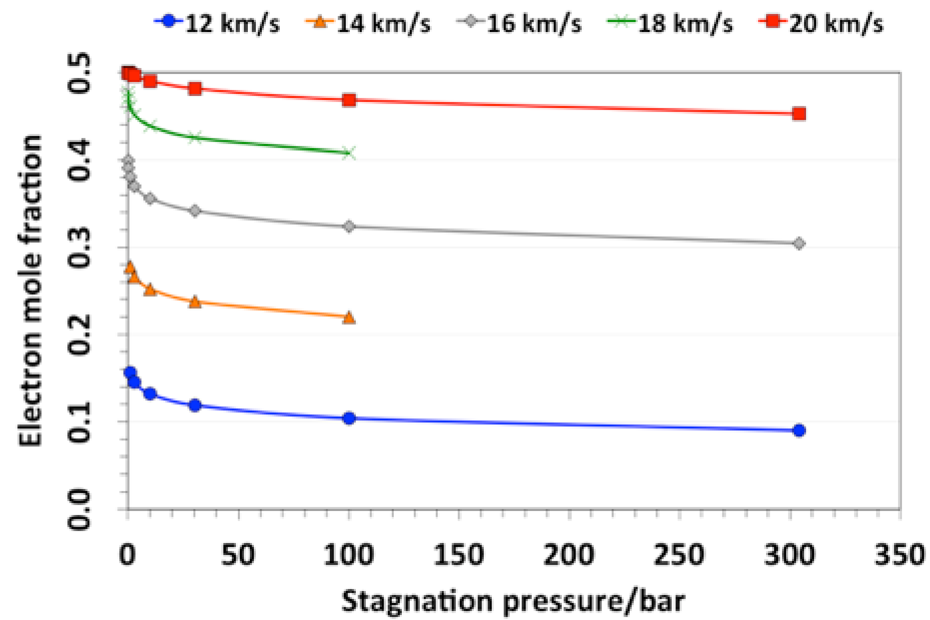


Flow Characteristics (2/3)

Shock-layer temperature



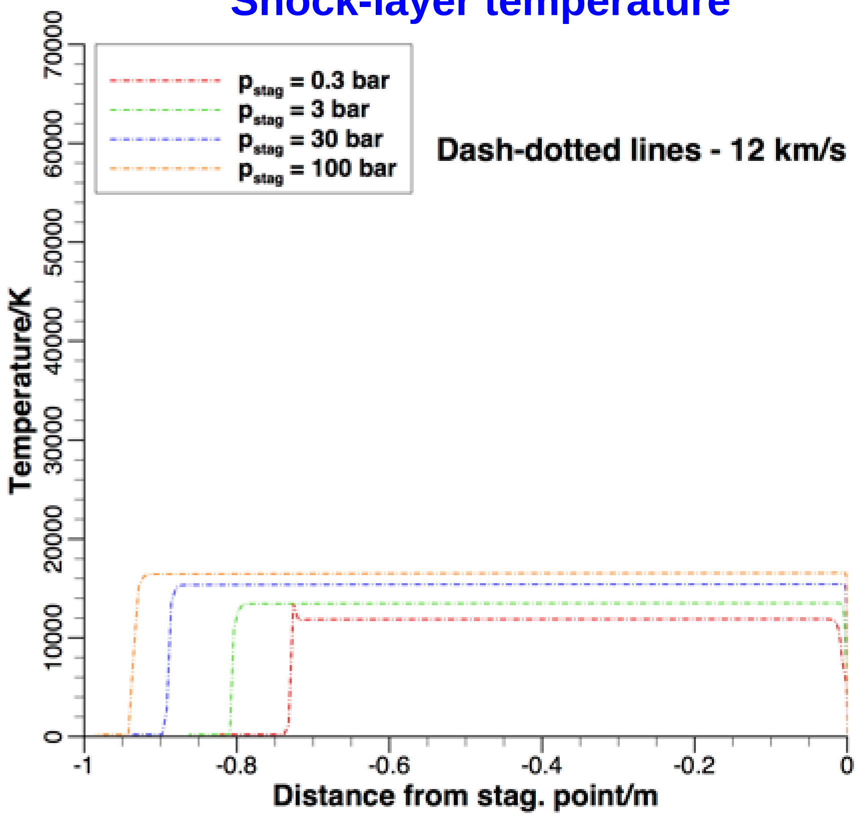
Free electron mole fraction



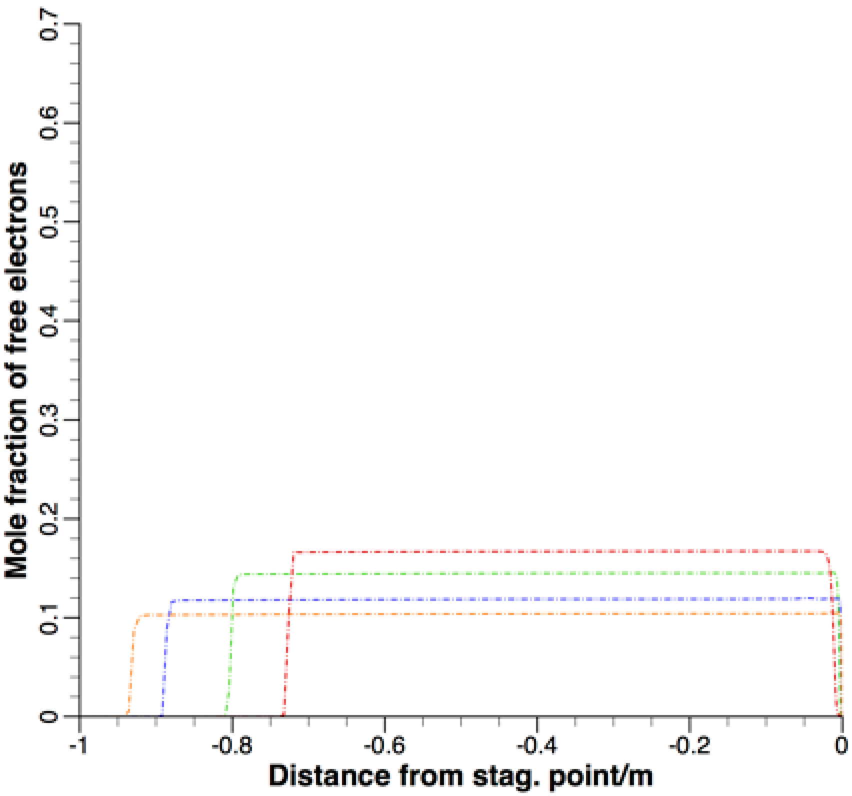
- Shock-layer temperature increases with increasing stag. pressure (altitude ↓)
  - Rapid increase up to about 10-30 bar, almost linear thereafter
  - Results based on extrapolated enthalpy past 20,000 K
- Free electron mole fraction decreases with increasing stag. pressure
- Fully-ionized plasma for velocities > 20 km/s

Flow Characteristics (3/3)

Shock-layer temperature



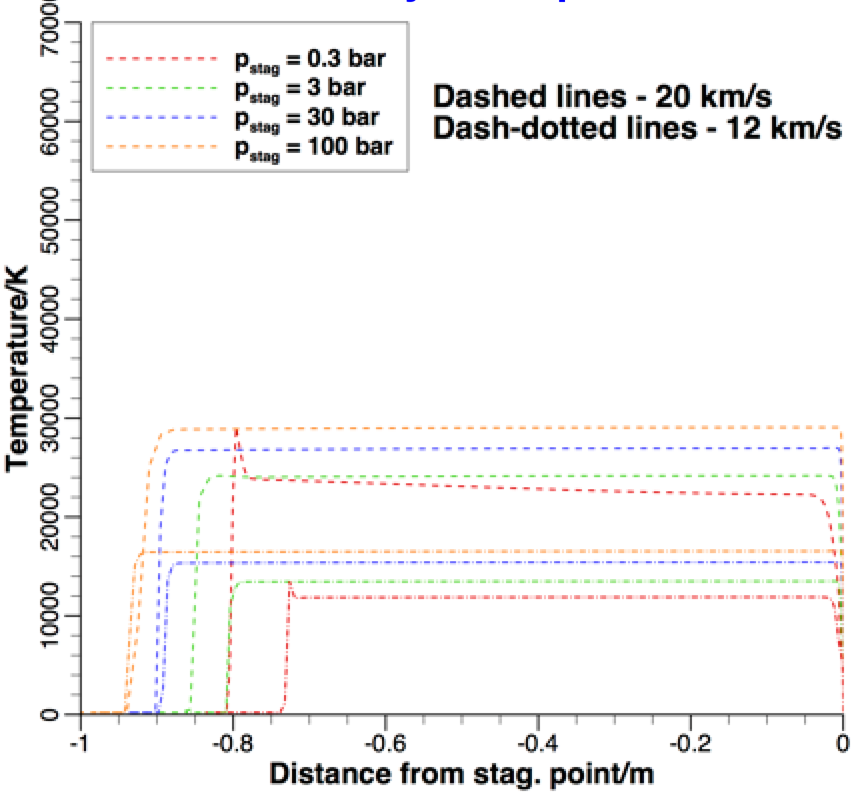
Free electron mole fraction



- Chemical overshoot at low pressures, between 0.3 and 3 bar
  - Kinetics of second stage ionization needed for high altitudes and velocity > 20 km/s
- Highest shock layer compression at lowest pressure
  - Larger radiating volume at higher pressures
- Without radiation coupling, one would infer blackbody radiation (at low gas emissivity)

Flow Characteristics (3/3)

Shock-layer temperature



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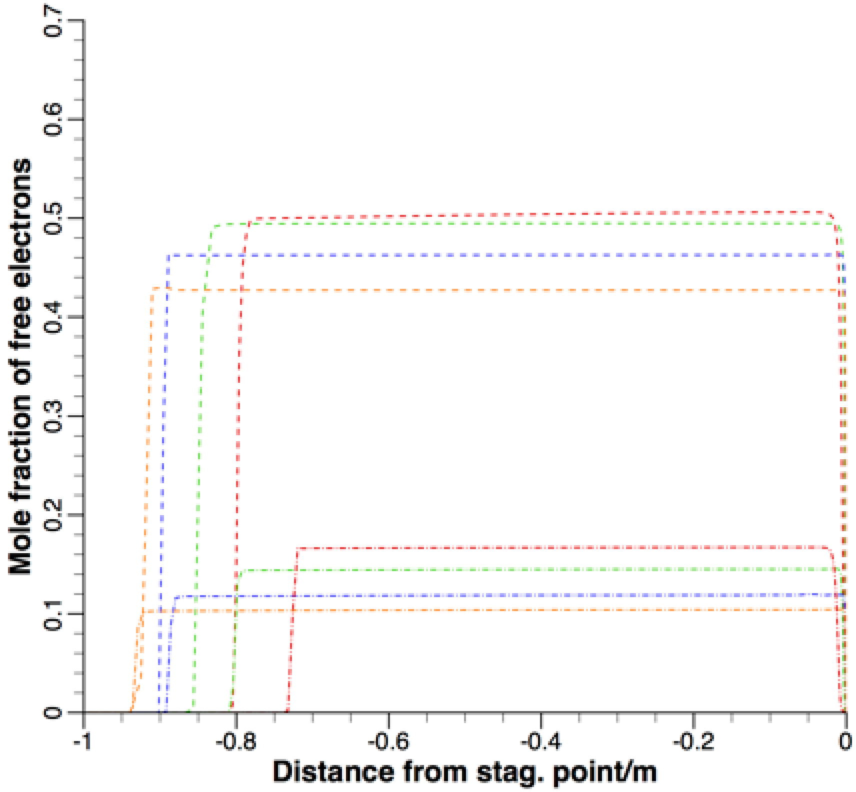

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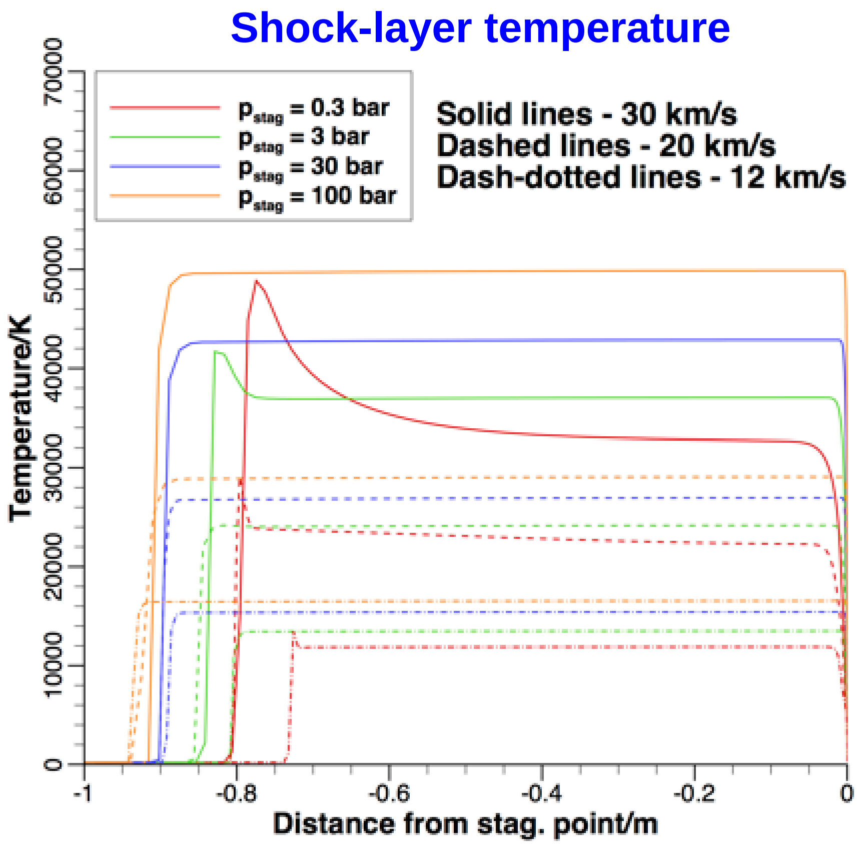

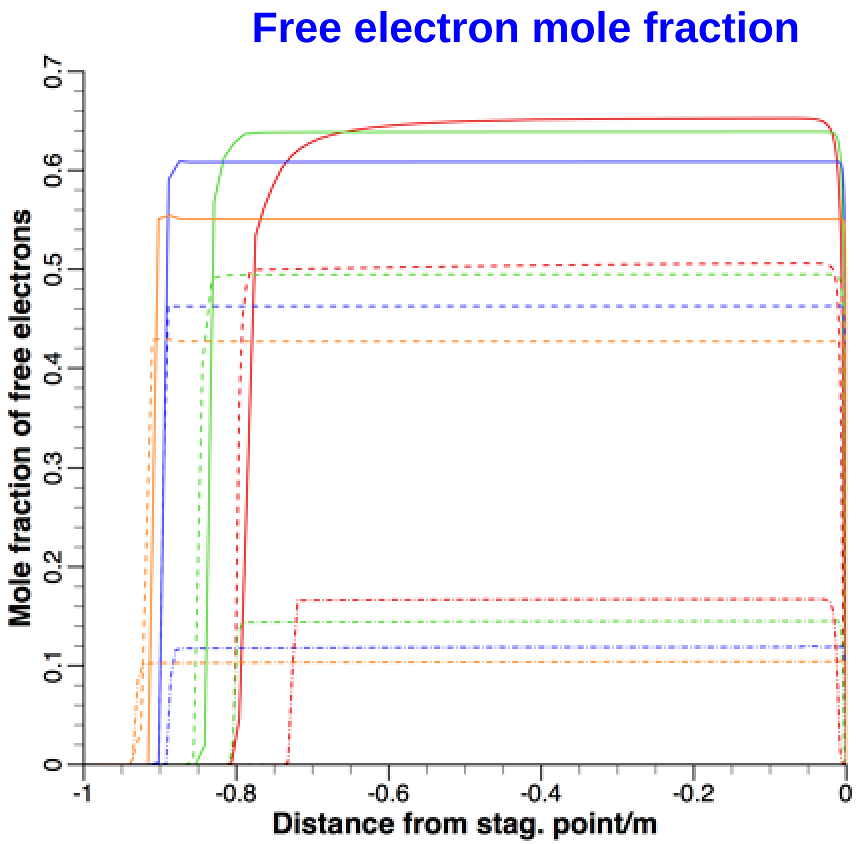

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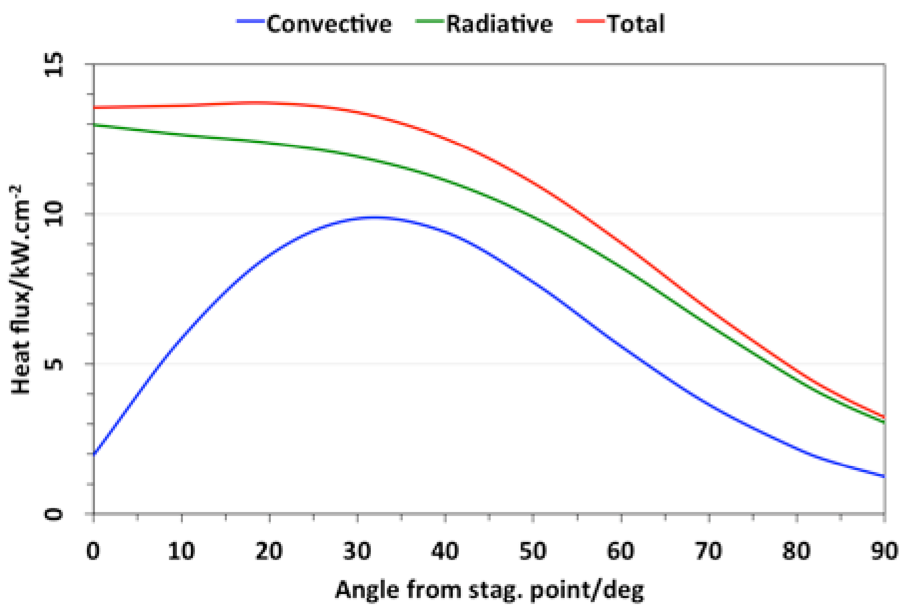
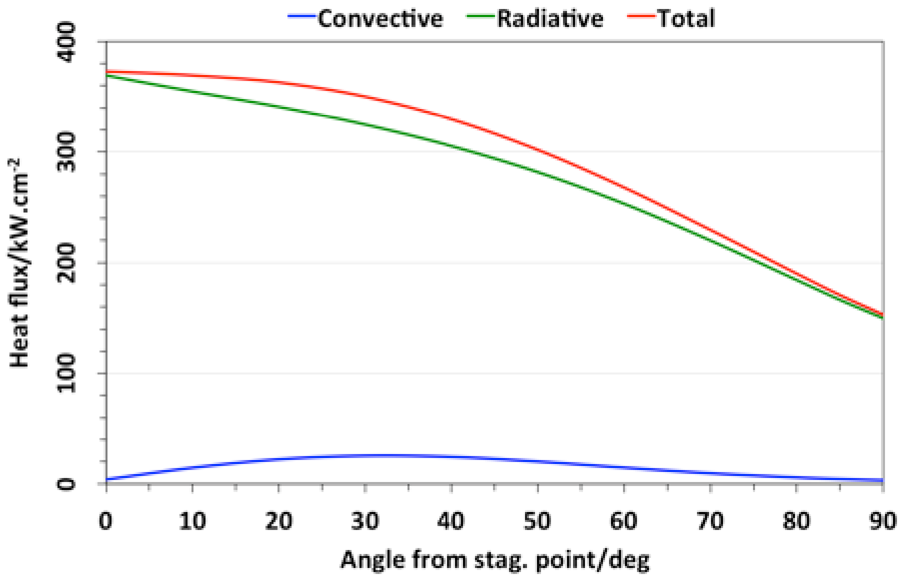
Convection *vs.* Radiation

Sample surface heat flux distribution (u = 20 km/s, p_{stag} = 1 bar, R = 15 m)



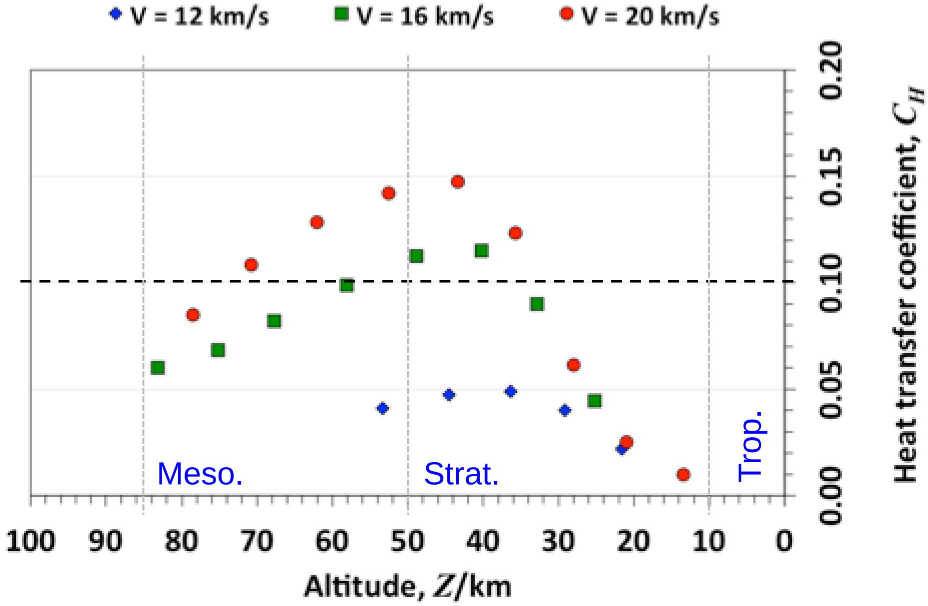
Sample surface heat flux distribution (u = 20 km/s, p_{stag} = 30 bar, R = 15 m)



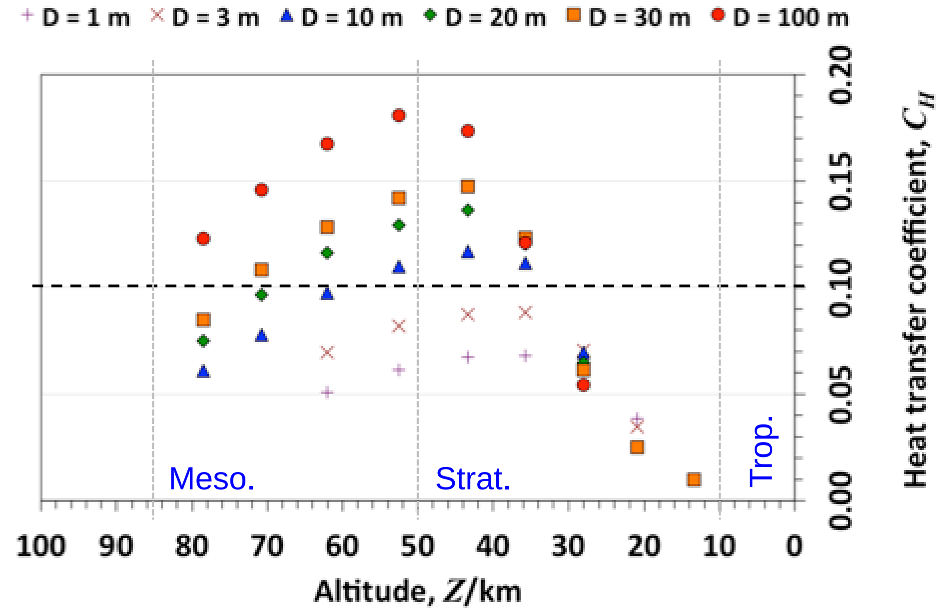
- Surface heating completely dominated by shock-layer radiation
  - True across all velocities and hemisphere diameters, except for small (1 m diameter) hemispheres at high altitudes when convection and radiation become comparable
- Radiative heat flux is from Tauber-Wakefield correlation
  - Radiation does not drop rapidly past sonic line attachment (≈40° from stag. point)

Heat Transfer Efficiency, C_H

30 m diameter, Velocity variation

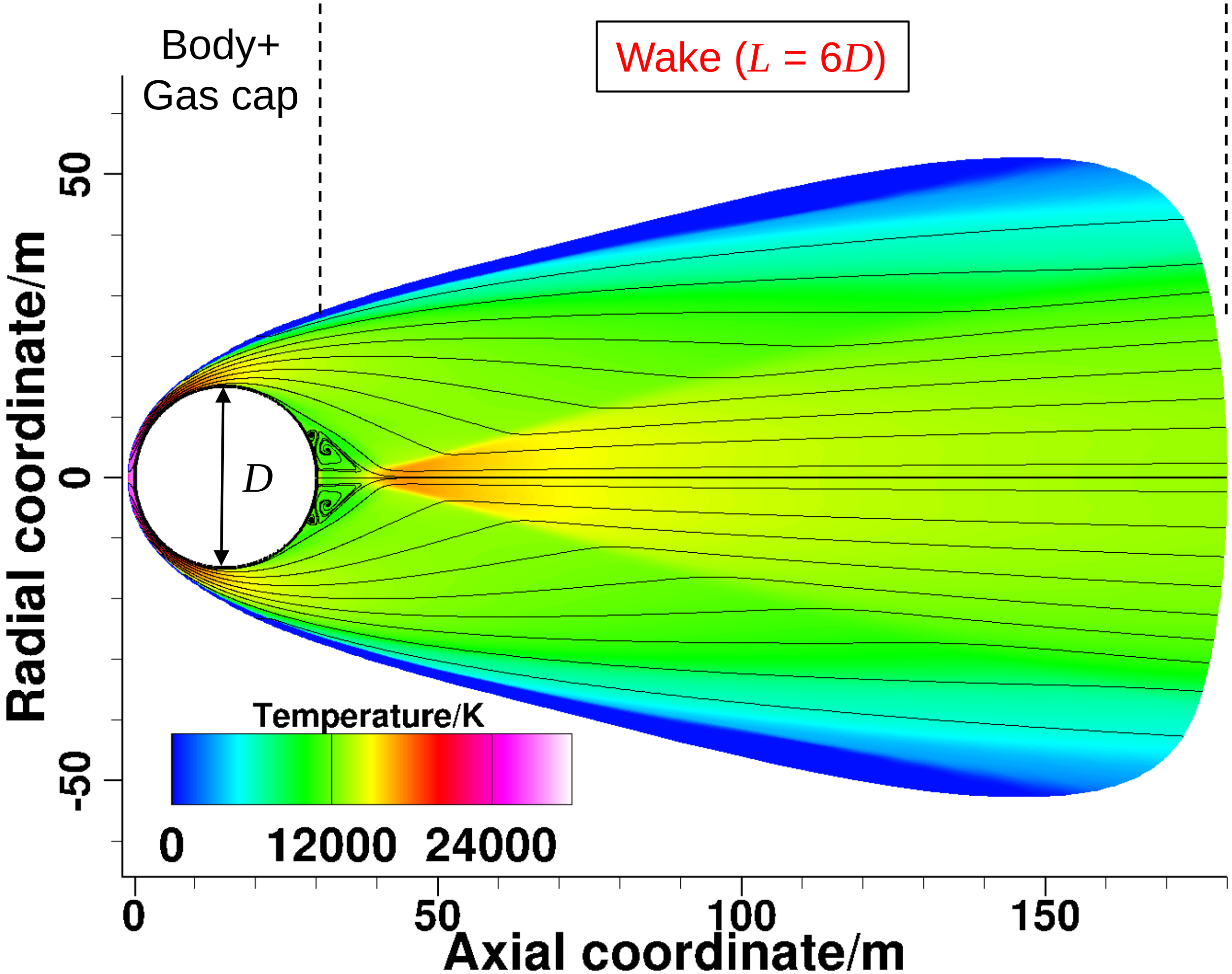


20 km/s Velocity, Diameter variation



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

Radiation Energy Deposition
(Methodology [1])



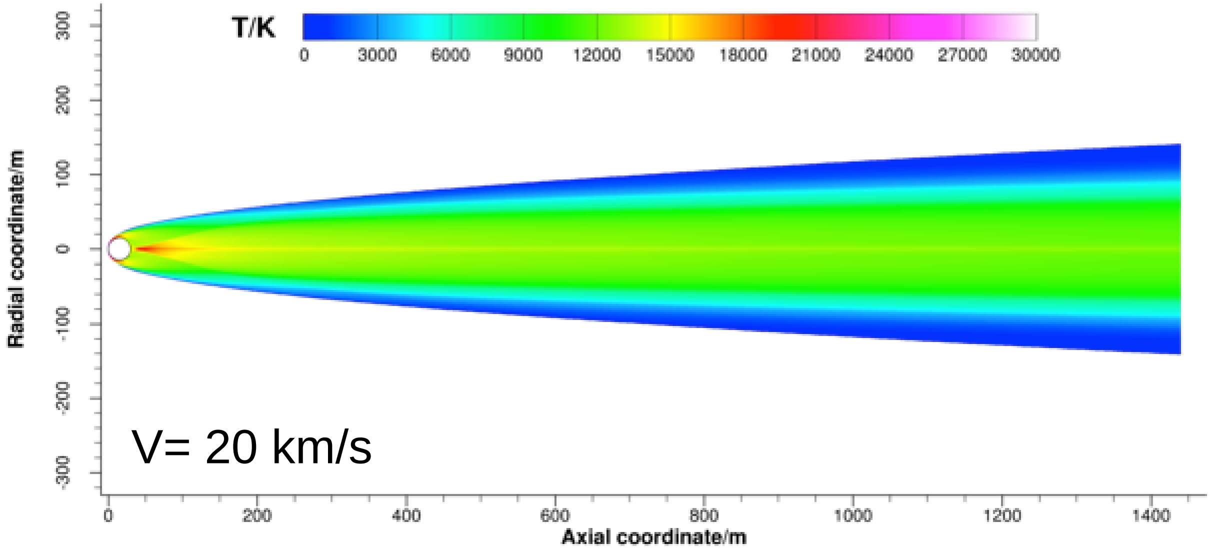
- 3 groups of lines of sight
  - nosecap, body, and wake
- Wavelength range
  - 85 nm to 4 μm
- Radiance integrated over *projected* area
  - Area same as pitch plane shock-layer geometry
- Two applications:
  - Near-field radiation energy deposition
  - Transmission through atmosphere to detector 100 km away for magnitude (light curve)

Reference:

1. **Liu, Y., Prabhu, D., Trumble, K. A., Saunders, D., & Jenniskens, P.,** "Radiation Modeling for the Reentry of the Stardust Sample Return Capsule," *Journal of Spacecraft and Rockets,* Vol. 47, No. 5, 2010, pp. 741–752.

Extended Wake

- Wake extended to 48*D* for two cases – 12 and 20 km/s, 30 m diameter, and 100 bar stagnation pressure



	$V/km.s^{-1}$	Wake L = 6D	Wake L = 48D	Multiplier
$I/W.sr^{-1}$	12	1.87×10^{11}	3.17×10^{11}	1.7
$I/W.sr^{-1}$	20	5.07×10^{12}	2.66×10^{13}	5.2

Inconclusive without additional expensive calculations
Multiplier probably goes as the square of the velocity

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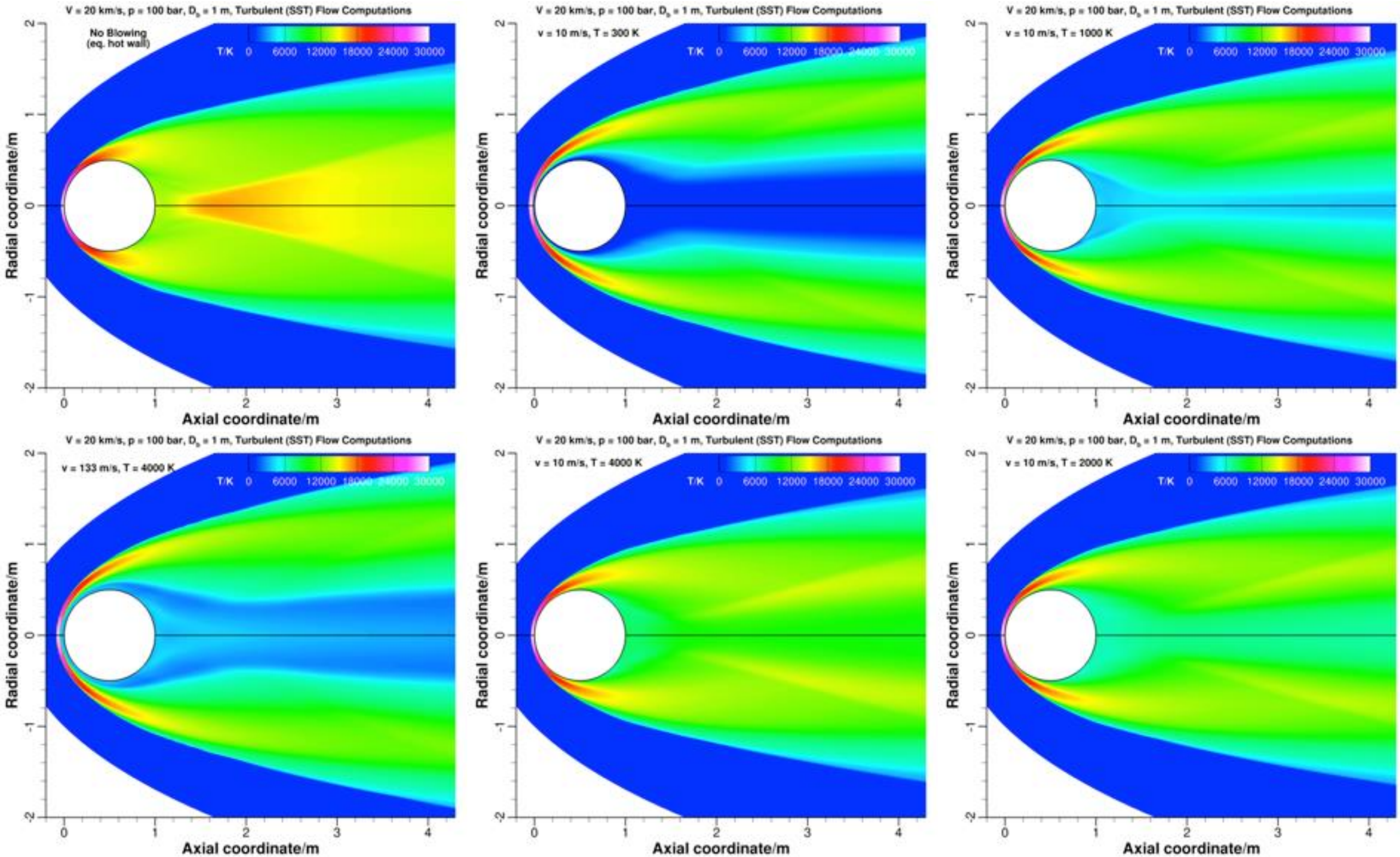
Wall Blowing (1/2)
(V=20 km/s, P=100 bar)



Wall Blowing (2/2)

(Temperature variation of blown air)

Case	Mass flux $kg.m^{-2}.s^{-1}$	CD	I (wake) W/sr^{-1}
No blowing, cold wall	0	0.868	1.35 $\times 10^9$
No blowing, eq. hot wall	0	0.873	1.21 $\times 10^9$
v_w = 10 m/s, T_w = 300 K	1162.4	0.974	4.56 $\times 10^8$
v_w = 10 m/s, T_w = 1000 K	348.7	0.914	
v_w = 10 m/s, T_w = 2000 K	174.4	0.892	4.68 $\times 10^8$
v_w = 10 m/s, T_w = 4000 K	87.2	0.879	5.75 $\times 10^8$
v_w = 133 m/s, T_w = 4000 K	1162.4	0.952	4.22 $\times 10^8$

Very little evidence of mixing of blown gas and plasma – turbulence model?
Only wake contribution to intensity shown
Inclusion of blowing reduces radiation from wake
Inclusion of meteoritic species (gas phase only) is possible
Scattering by solid phase has to be developed
Changes in C_D are quite modest – C_D is still O(1) quantity!

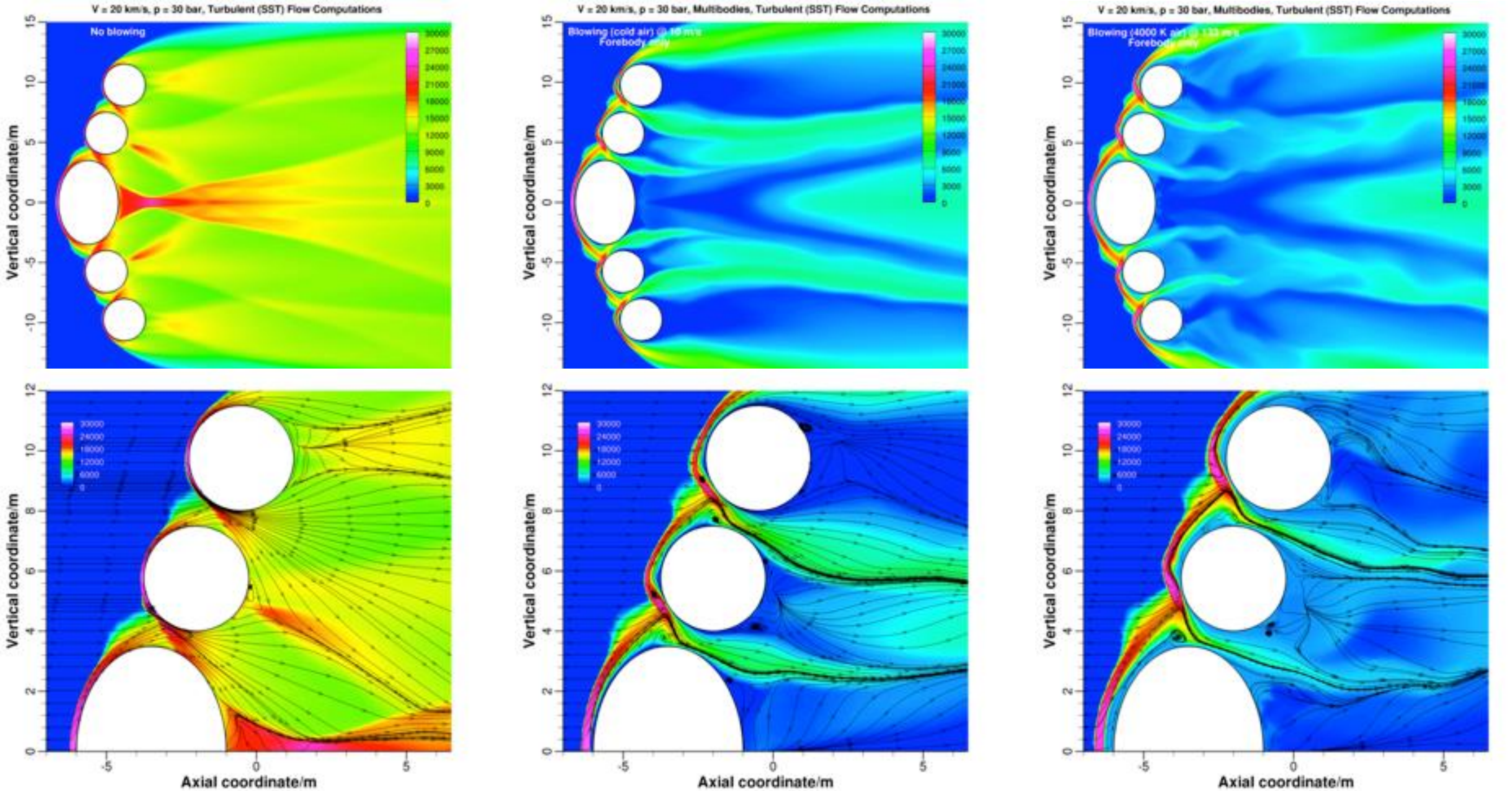
Some Open Issues

- Problem formulation might have to be revisited
  - Weakly ionized flow assumption is the basis for current CFD model
- What is the role of pre-cursor (if any) heating?
- Is a two-temperature, T_{ion}-$T_{electron}$, formulation needed for the wake?
  - Thermal nonequilibrium is not an issue for the forebody
- Wake closure is an issue, esp. in an axisymmetric formulation
  - 6D is generally used for entry vehicles, but > 48D necessary for meteors?
- Line-by-line computations are expensive, esp. for 3D flows
  - Would a Rosseland mean opacity approach be more efficient?
    - High stagnation pressures favor such an approach
    - Can pre-compute opacity tables (including ablation products) using line-by-line method
- Tighter coupling of flow, radiation, and ablation fields
  - Ablation models for silicates under development – variation with meteoroid types?
  - Transport properties for blown species
- Handling multiple body dynamics
  - Current approach is limited to static arrangements of multiple bodies

Backup

Where we would like to be

Blowing velocity = 0 m/s | Blowing velocity = 10 m/s | Blowing velocity = 133 m/s



Blowing limited to "exposed" faces of the collection of objects
Shock interactions completely altered by blowing