Stagnation-Line Simulations of Meteor Ablation

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Annual BRAIN-BE meeting : METRO

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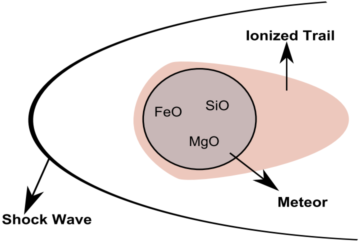
Outline

Outline

Meteors in earth's atmosphere

Perseid Meteor Shower 2013 [Jeff Sullivan]

Artistic View Meteor [MidnightWatcher's]



50 tonnes of meteor enter in the earth's atmosphere per day

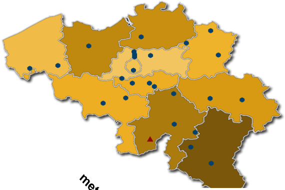
- **Velocity**: 11.2-72.5 km/s
- **Composition**: (FeO;MgO;Ca;SiO)
- **Size**: radius 1 μm - 10 m

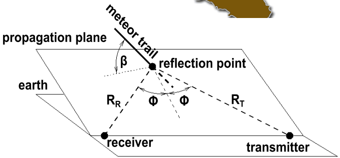
BRAMS (Belgian RAdio Meteor Stations)

How can the ablation products influence the composition of the upper atmosphere? What is the physics of the meteor phenomenon?

- BRAMS, project of the Belgian Institute for Space Aeronomy, uses radio stations all over Belgium

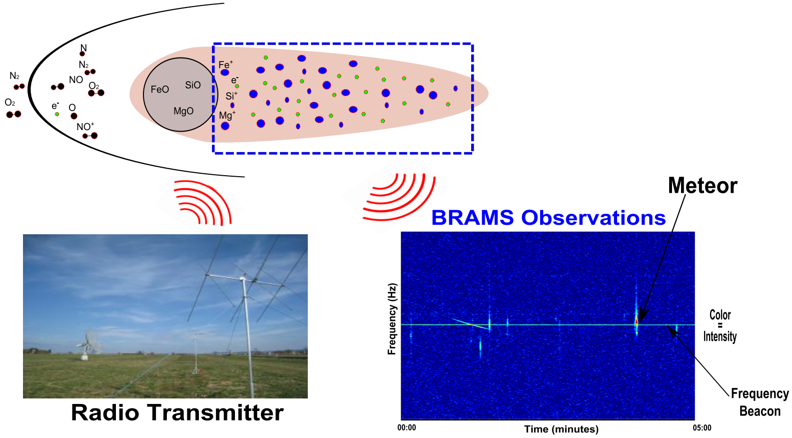
- Detect the meteor trail using radio waves **(Forward Scattering technique)**





Geometry of specular radio reflections

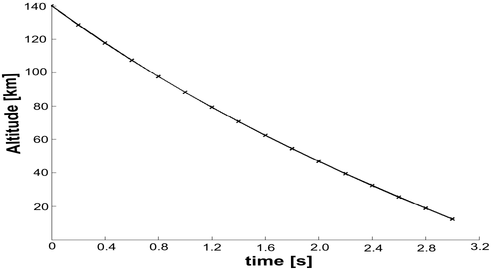
(BRAMS)



Ionized trail reflection signal from multiple stations $\Longrightarrow$ velocity and trajectory of the meteor **but not the size!!**

$$\text{Trajectory} \quad : \quad \frac{dV}{dt} = -\Gamma V^2 \frac{3\rho_a}{4\rho_m R} + \rho_m g$$

Vondrak et al, Atmos. Chem. Phys., 2008



State-of-the-art model for meteor entry phenomena

$$\text{Trajectory} \quad : \quad \frac{dV}{dt} = -\Gamma V^2 \frac{3\rho_a}{4\rho_m R} + \rho_m g$$

$$\text{Mass Balance} \quad : \quad \frac{dm_i}{dt} = \gamma p_i S \sqrt{\frac{\mu_i}{2\pi k_B T}}$$

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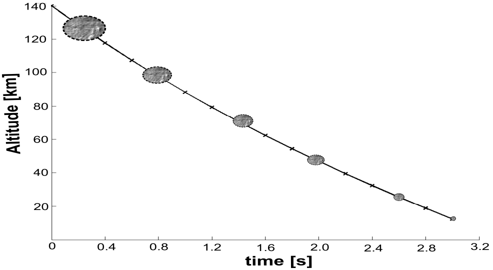

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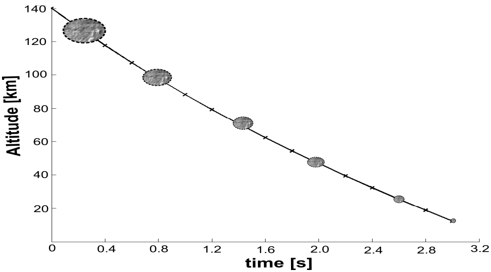
$$\text{Energy Balance} \quad : \quad \frac{1}{2}\pi R^2 V^3 \rho_a \Lambda = 4\pi R^2 \varepsilon\sigma(T^4 - T_{env}^4) + \frac{4}{3}\pi R^3 \rho_m C \frac{dT}{dt} + L\frac{dm}{dt}$$

Vondrak et al, Atmos. Chem. Phys., 2008



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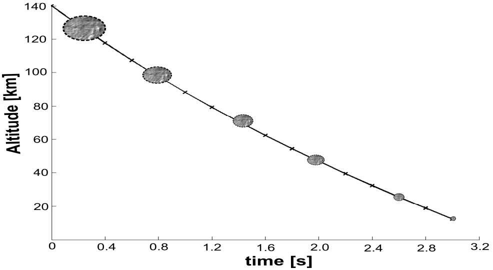


Model too simple ⇒ no predictions of the electron concentration ...

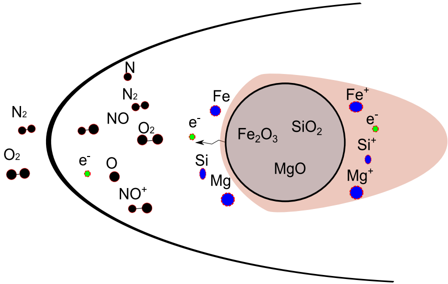
Simulate the ablation of the meteors during the entry of Earth′s atmosphere similar to the models of gas-surface interaction used by aerospace community

I Development of boundary condition for ablation

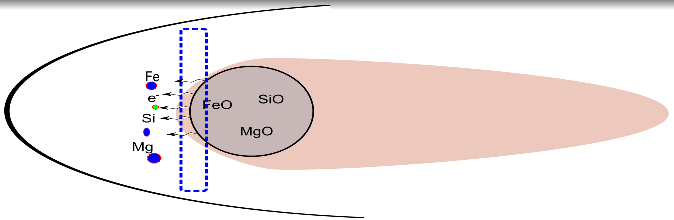
II Meteor species database for thermodynamic and transport properties

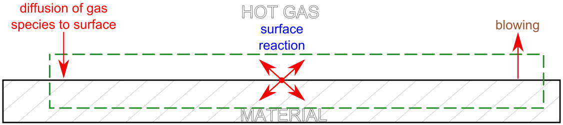
Assumptions:

- Continuum flow
- Atmospheric Gas reactions: non equilibrium
- Ablations products: frozen
- Single fragment meteor
- Geometry: sphere
- Forward stagnation streamline



Outline

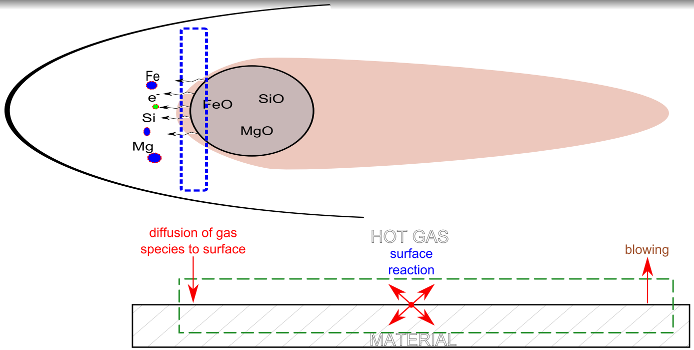




- Species i Mass Balance[1] (O_2, N_2, ..., FeO, Fe, SiO_2, MgO...):

$$J_{i,w} + \sum_{r=1}^{N_r} \omega_i^r = (\rho v)_w y_{i,w} \quad \text{k=1,...,}N_s \tag{1}$$

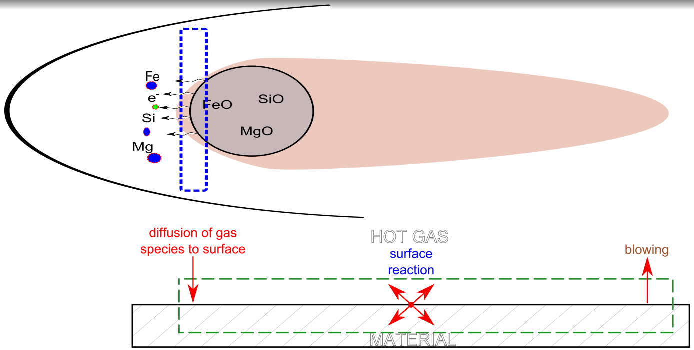
[1] *Turchi et al*, AIAA 2014-2125 (2014)



- Elements k Mass Balance (O, N, Fe, Si, Mg):

$$\sum_{i=1}^{Ns} \sigma_{i,k} \frac{M_k}{M_i} (1) \Rightarrow J_{i,k} + \dot{m}\ y_{k,s} = (\rho v)_w\ y_{k,w} \quad \text{k=1,...,}\epsilon$$

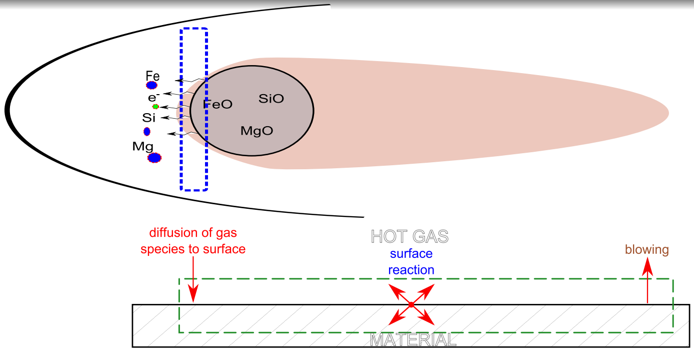
Ablation Model Surface Mass Balance (SMB)



- Elements k Mass Balance (O, N, Fe, Si, Mg):

$$\sum_{k=1}^{\epsilon} \left(J_{i,k} + \dot{m} \; y_{k,s} = (\rho v)_w \; y_{k,w} \right) \Rightarrow \dot{m} = (\rho v)_w$$

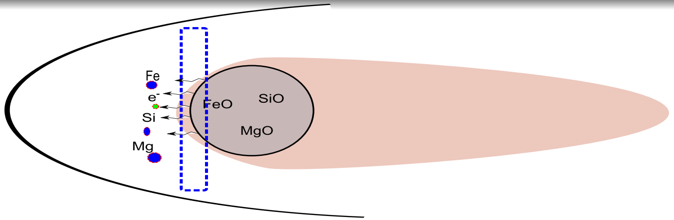
Ablation Model Surface Mass Balance (SMB)

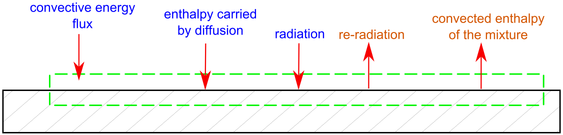


- mass blowing rate, $\dot{m}$:

$$\dot{m} = \frac{J_{i,k}}{(y_{k,w} - y_{k,s})}$$

- $y_{k,w}$: gaseous mixture at the wall computed by chemical equilibrium
- $J_{i,k}$: elemental mass diffusion computed by CFD





- Energy Balance[1]:

$$\lambda \nabla T_w + \sum_{i=1}^{N_s} h_i \rho_i V_i + q_{rad,in} = q_{rad,out} + \dot{m} h_w \quad (1)$$

[1] *Turchi et al*, AIAA 2014-2125 (2014)

A surface composed by multiple constituents

Classification	Composition		Elemental composition	
Simplify Ordinary Chondrite	SiO_2	0.606	Si	0.232
	MgO	0.394	Mg	0.152
			O	0.616

Meteors surface properties

How to compute $y_{k,w}$ for a multi element surface?[2]

Multiphase Equilibrium solver [3]

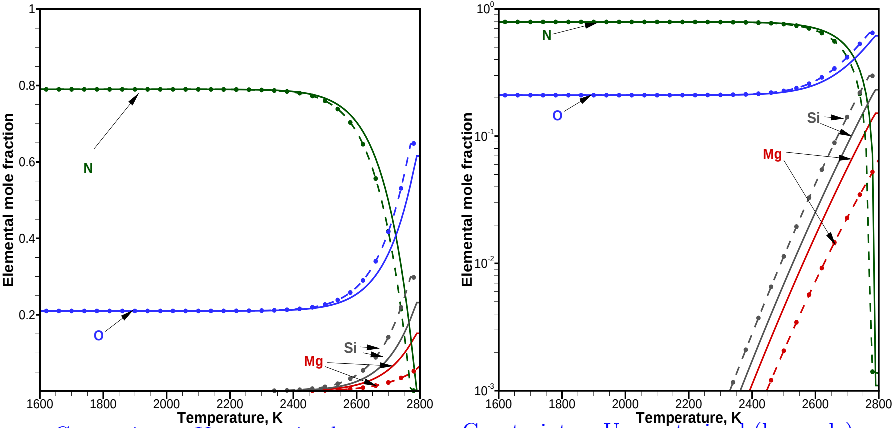
- Multiphase Gibbs function continuation (MPGFC)[4]
- Impose any linear constraint to the system:

$$\frac{x_{\mathrm{Si}}}{x_{\mathrm{Mg}}} = \mathbf{const};$$

[2] First addressed by *Milos et al*, AIAA 97-0141 (1997)

[3] Developed by *Scoggins et al*, (under review, 2015)

[4] Extension Gibbs Function Continuation(GFC) by *Pope et al*, FDA 03-02 (2003)

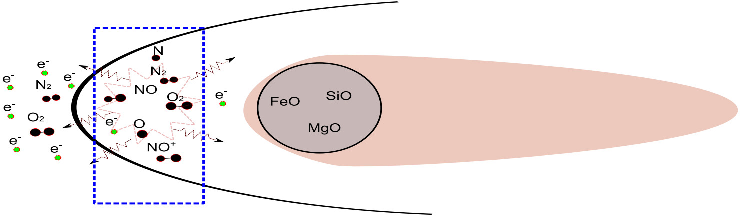


Constraint vs Unconstrained

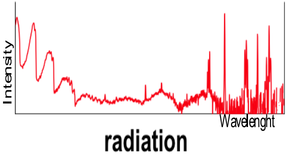
Constraint vs Unconstrained (log scale)

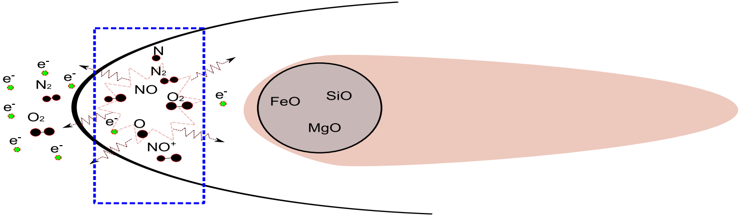
Gaseous Elemental mole fraction vs Temperature, 0.09 atm; —— constrained, – • – unconstrained equilibrium

Outline



- High entry velocity (11.2–72.5 km/s)
- High temperatures (*e.g.* 120.000 K): complex thermodynamic properties
- High radiative field: computational expensive





- High entry velocity (11.2–72.5 km/s)
- High temperatures (*e.g.* 120.000 K): complex thermodynamic properties
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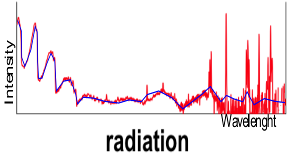
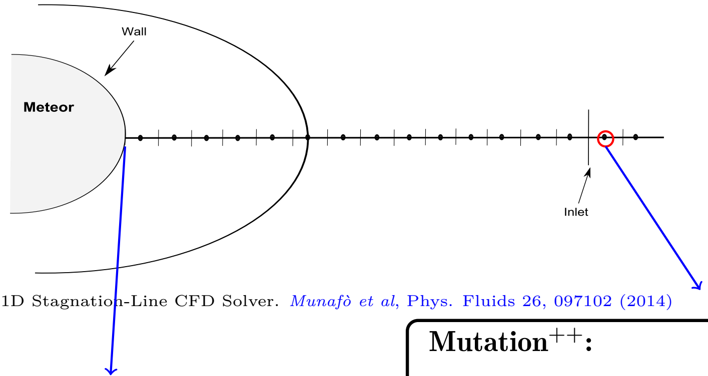
Statistical narrow band (SNB) method:

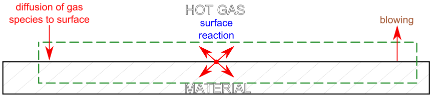
- Accurate Description
- Low CPU Cost for coupling



Meteor Ablation Methodology



1D Stagnation-Line CFD Solver. *Munafò et al*, Phys. Fluids 26, 097102 (2014)



Gaseous species mass fluxes over a generic ablating material.

↔

Mutation^{++}:

- Thermodynamic Properties
- Transport Properties
- Chemistry
- Multiphase Equilibrium Solver
- Radiation

Developed by *Scoggins et al,* AIAA 2014-2966 (2014)

Numerical Tools specifications

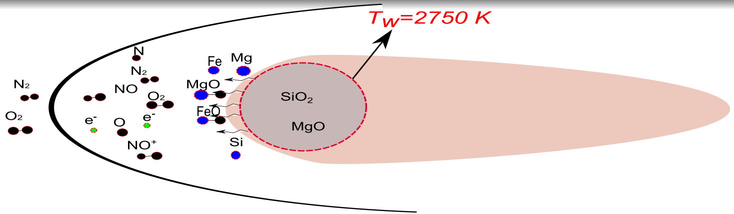
Stagnation-Line Code CFD Solver

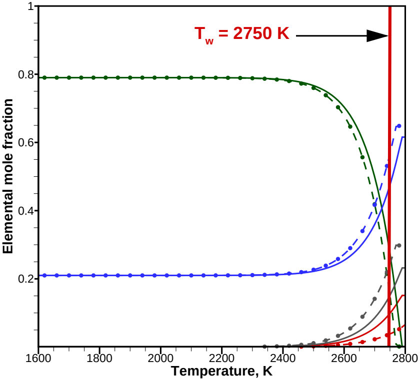
- 1D Stagnation-Line solver in spherical coordinates
- Cell-centered finite volume
- Roe′s Riemann solver
- Fully implicit time-integration

$$\frac{\partial}{\partial t}\mathbf{U} + \frac{\partial}{\partial r}\mathbf{F}^{\mathbf{inv}} + \frac{\partial}{\partial r}\mathbf{F}^{\mathbf{vis}} + \frac{\mathbf{G}^{\mathbf{inv}} + \mathbf{G}^{\mathbf{vis}}}{r} = \mathbf{S}$$

MUlticomponent Thermodynamic And Transport properties for IONized plasmas in C++ (Mutation^{++})

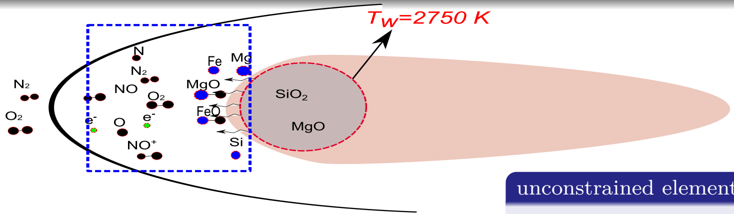
- Thermodynamic properties : NASA database
- Transport properties : rigorous Chapman-Enskog expansion derived from Kinetic Theory
- Air chemistry : Arrhenius law (reaction rates obtained from *Park et al,* J Thermophys Heat Tr Vol.15, No.1 (2001))
- Multiphase Equilibrium Solver : minimization Gibbs free energy (continuation method)

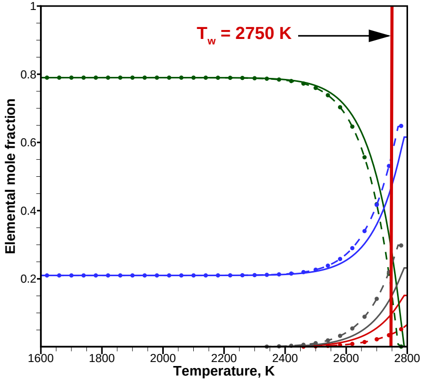




– • – unconstrained, —— constrained Mutation^{++}

Lets analyze the flow with ablation products using Mutation^{++}...





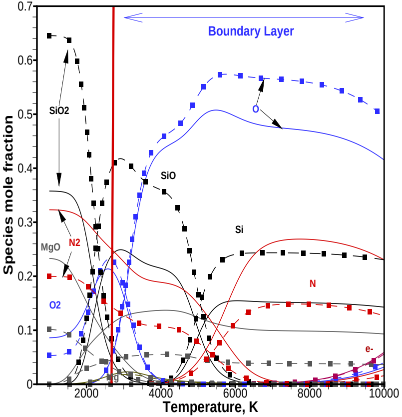
unconstrained elemental composition:

- N : 0.1510
- O : 0.5666
- Mg: 0.0384
- Si: 0.2440

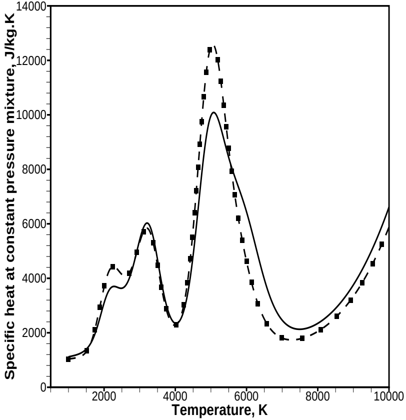
constrained elemental composition:

- N : 0.2740
- O : 0.4752
- Mg: 0.0989
- Si: 0.1517

– • – unconstrained, —— constrained Mutation^{++}

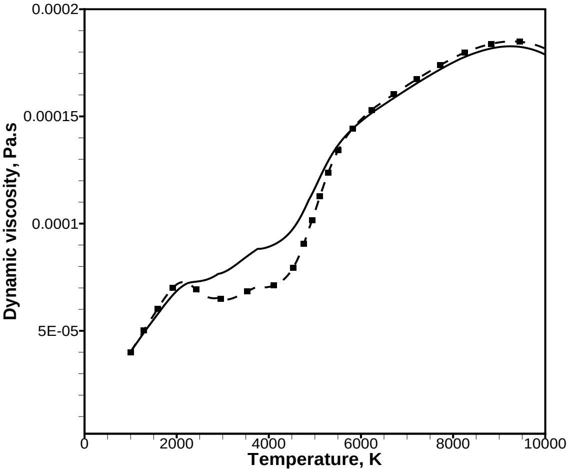


Gases equilibrium composition, 0.09 atm



Specific heat at constant pressure, 0.09 atm

—— constrained vs –■– unconstrained equilibrium (Mutation^{++})



—— constrained vs –■– unconstrained equilibrium (Mutation^{++})

Dynamic Viscosity, 0.09 atm

Outline

Stagnation-Line CFD Calculations

Simulation conditions:

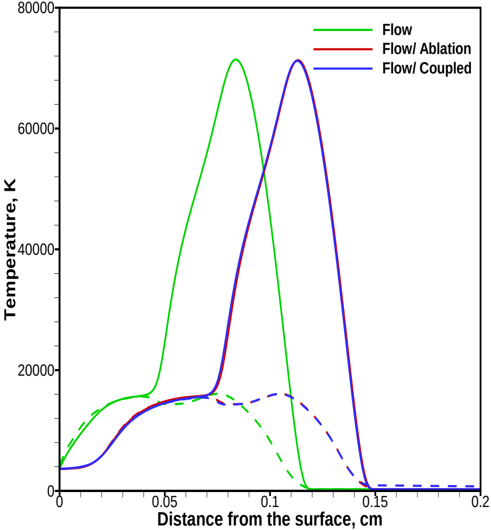
- Meteor composition in the atmosphere:
  - Simplify Ordinary Chondrite meteor, 1 cm radius
- Boundary conditions:
  - Supersonic inlet
  - Ablative wall

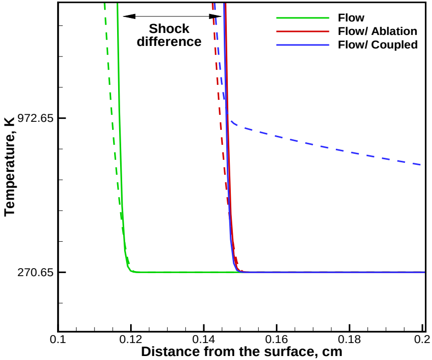
Trajectory analysis:

- Entry velocity: 15 km/s
- Altitude: 50 km

Altitude=50 Km

Translation temperature —— and Internal temperature (- -)

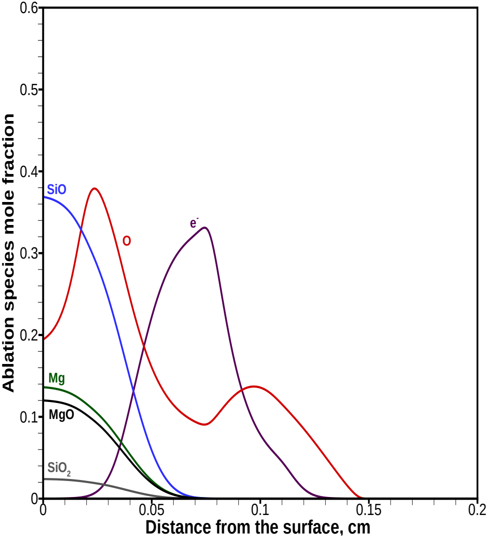


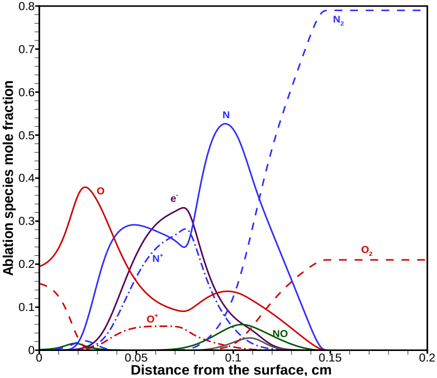


$$T_w = 3645 \text{ K}$$

Altitude=50 Km

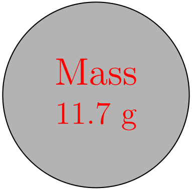
Species diffusion





$$\dot{m} = 9.54\ \text{kg/m}^2/\text{s}$$

To summarize the ablation properties:



r = 1 cm

$$\rho = 2800 \text{ kg/m}^3$$

$$\dot{m} = 9.54 \text{ kg/m}^2\text{/s} \rightarrow \text{mass lost} = 11.9 \text{ g/s}$$

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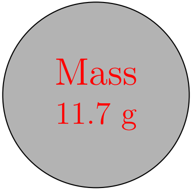

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Meteor destroyed

Outline

Conclusion

- Tools developed at VKI for spacecraft entries have been adapted and applied to meteor entry applications:
  - The **ablative boundary condition** was developed with an approach similar to re-entry vehicles
- Important results have been obtained using engineering tools:
  - The **ablation product concentration** diffuse sharply in the shock layer at higher altitude
  - The **electron mole fraction** in the shock layer is large
  - The **high entry velocity** leads to a large mass blowing rate
  - At 50 km high a ordinary chondrite is completely ablated

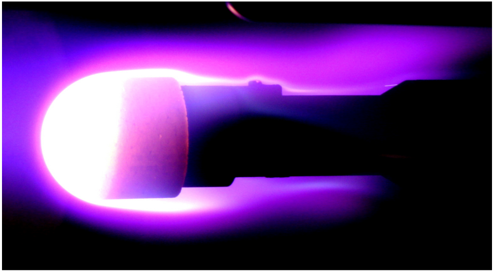
Validation of the physical-chemical models:

Comparison of ARGO solver with plasma wind tunnel experiments

Porous medium approach by Schrooyen, 2015

Experimental observations:

- Surface recession and temperature
- Surface melting
- Species radiation



Thank You for Your Attention!

Questions?

Comments?

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Acknowledgment:

- J.B. Scoggins (VKI)
- Alessandro Turchi (VKI)
- Johan De Keyser and Hervé Lamy (BIRA)
- Philippe Chatelain (UCL)

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A Model for A Model for Inductive Plasma Wind Tunnels
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Atmospheric Chemistry and Physics, 2008

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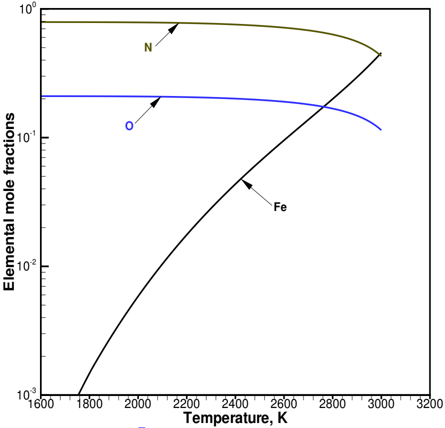
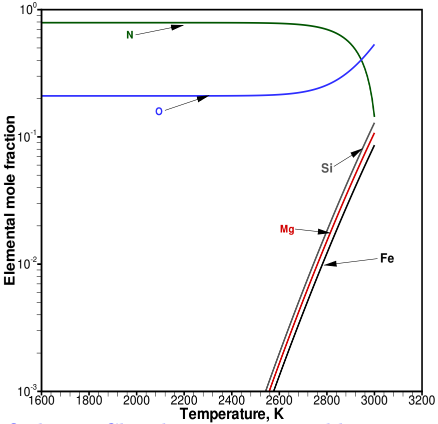
PhD Thesis, Univ. Sapienza

Multi species surface equilibrium



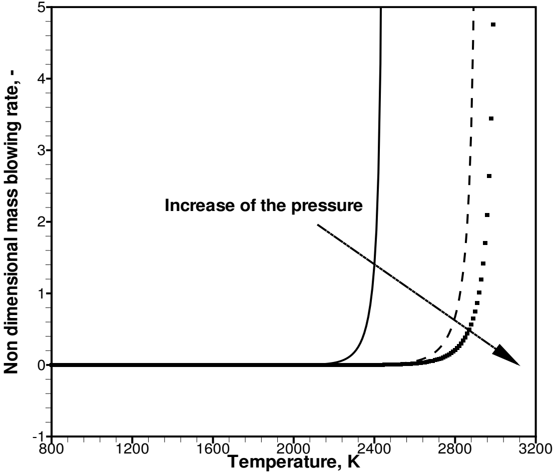
Iron meteor



Ordinary Chondrite meteor equilibrium constraint

Gaseous Elemental mole fraction vs Temperature, 1 atm

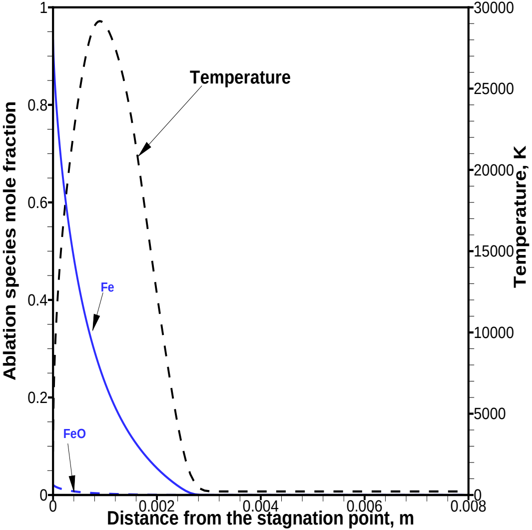
Non dimensional mass blowing rate constraint equilibrium composition



Iron meteor; —— 0.01 atm, - - - 0.5 atm, ■ 1 atm

Altitude=70 Km

Species Diffusion and Temperature (- -)

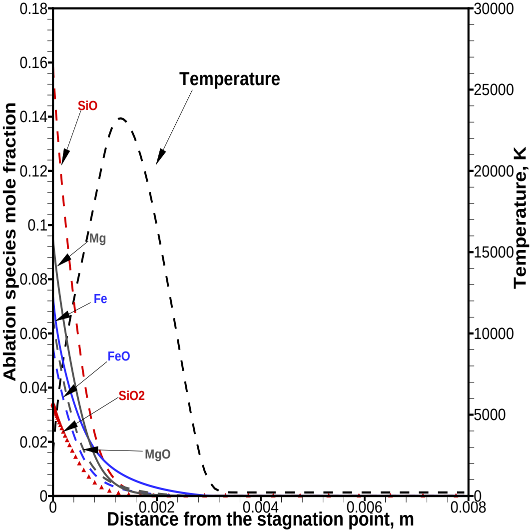


$\dot{m} = 2.625\ \mathrm{kg/m^2s}$
weight $= 32.96$ g
$\mathrm{U}_\infty = 11500$ m/s

Radius 1cm
$K_n = 0.0151$

Altitude=70 Km

Species Diffusion and Temperature (- -)



$\dot{m} = 0.705$ kg/m^{2}s

weight = 8.38 g

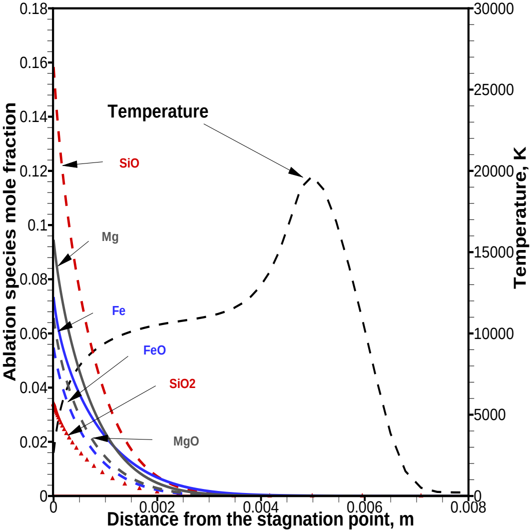
$U_\infty = 11500$ m/s

Radius 1cm

$K_n = 0.0151$

Altitude=70 Km

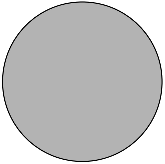
Species Diffusion and Temperature (- -)



$\dot{m}$ = 0.550 kg/m^{2}s

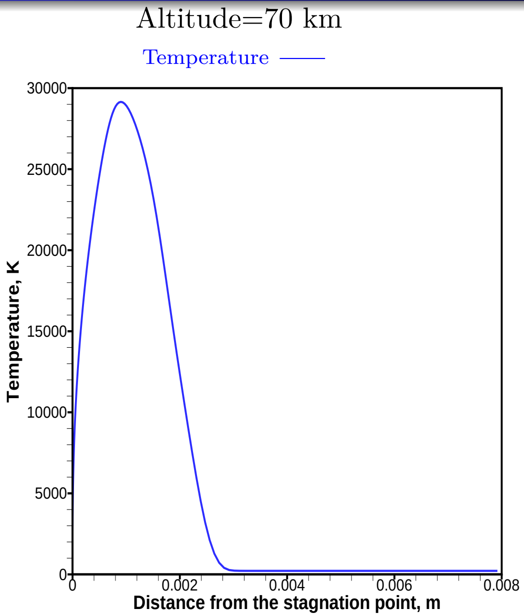
weight = 8.38 kg

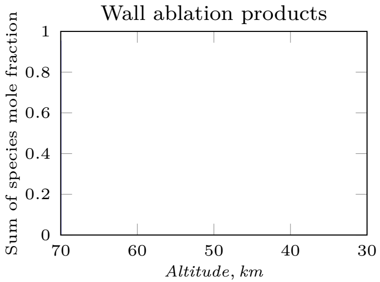
U_∞ = 11500 m/s

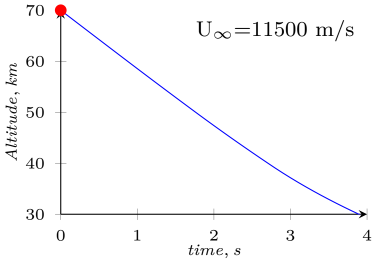


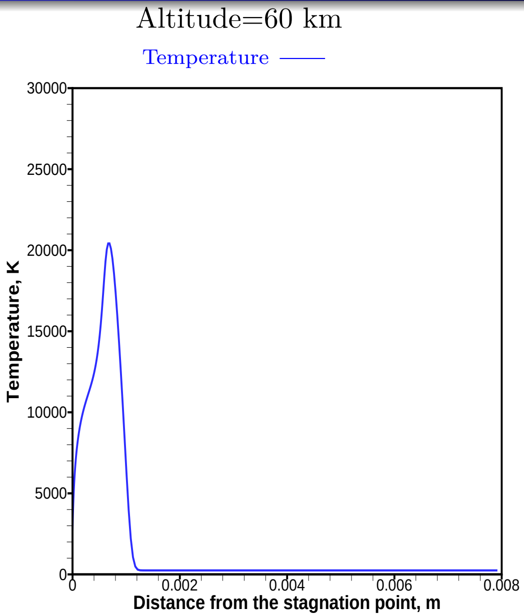
Radius 10cm

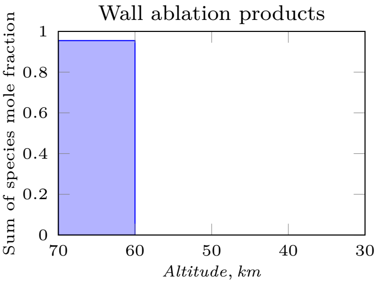
K_n=0.0015

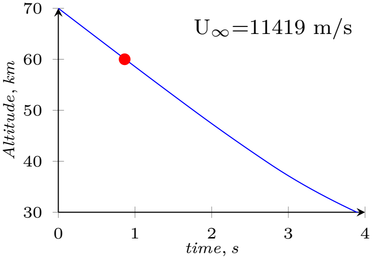

Altitude=70 km
Temperature
30000
25000
20000
15000
10000
5000
0
Temperature, K
0
0.002
0.004
0.006
0.008
Distance from the stagnation point, m


Wall ablation products
Sum of species mole fraction
1
0.8
0.6
0.4
0.2
0
70
60
50
40
30
Altitude, km

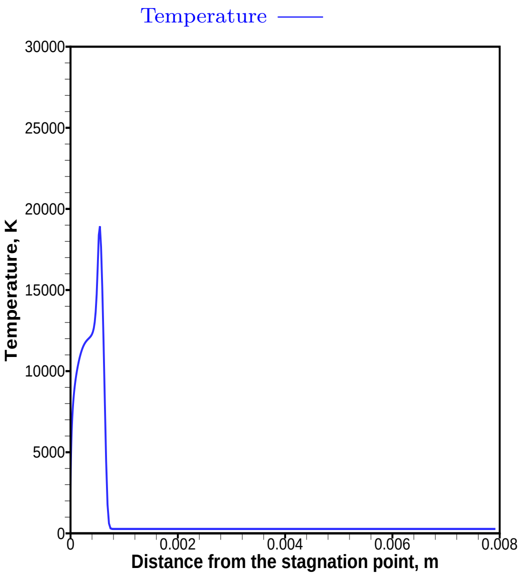

U∞=11500 m/s
Altitude, km
70
60
50
40
30
0
1
2
3
4
time, s

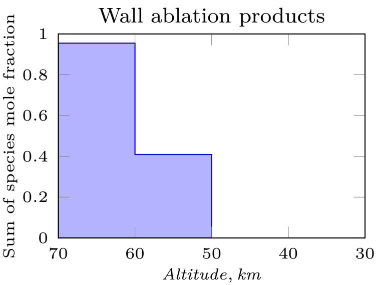

Altitude=60 km
Temperature
30000
25000
20000
15000
10000
5000
0
Temperature, K
0
0.002
0.004
0.006
0.008
Distance from the stagnation point, m

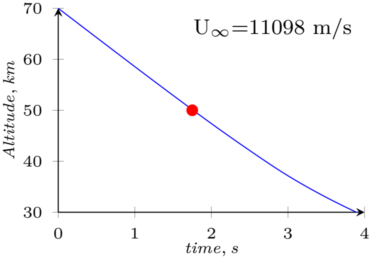

Wall ablation products
Sum of species mole fraction
1
0.8
0.6
0.4
0.2
0
70
60
50
40
30
Altitude, km

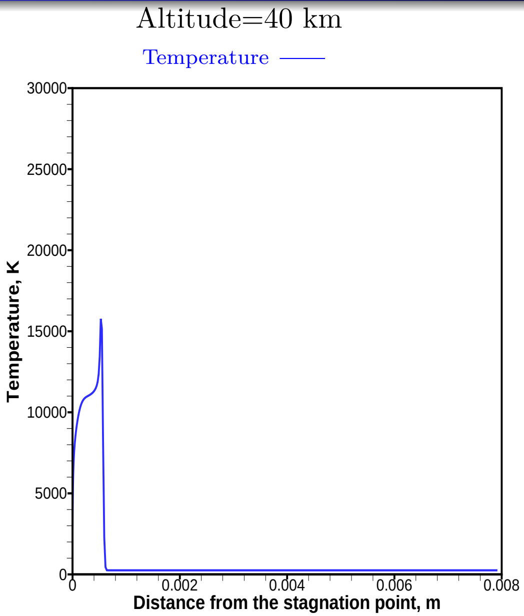

U∞=11419 m/s
Altitude, km
70
60
50
40
30
0
1
2
3
4
time, s

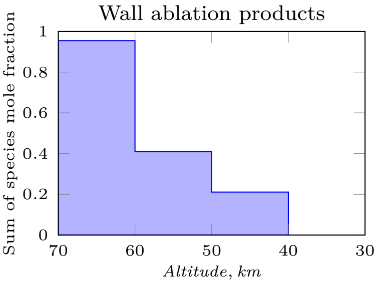
Altitude=50 km

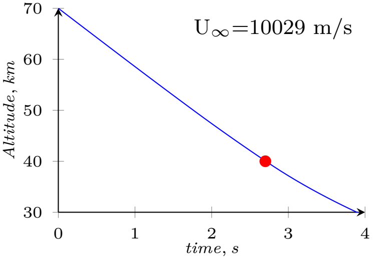




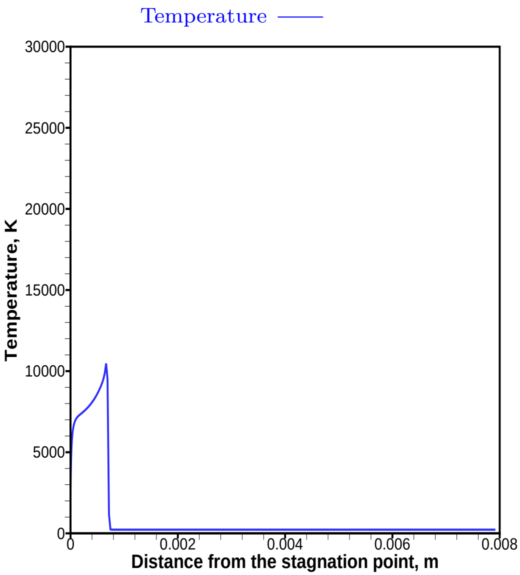


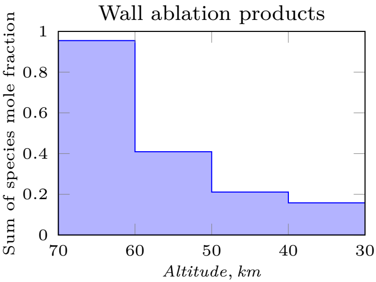

Altitude=40 km
Temperature
30000
25000
20000
15000
10000
5000
0
Temperature, K
0
0.002
0.004
0.006
0.008
Distance from the stagnation point, m

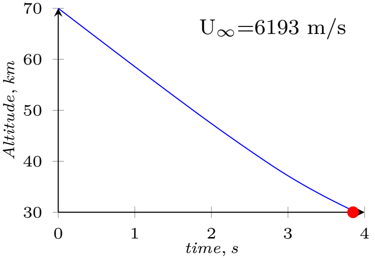

Wall ablation products
Sum of species mole fraction
1
0.8
0.6
0.4
0.2
0
70
60
50
40
30
Altitude, km


U∞=10029 m/s
Altitude, km
70
60
50
40
30
0
1
2
3
4
time, s

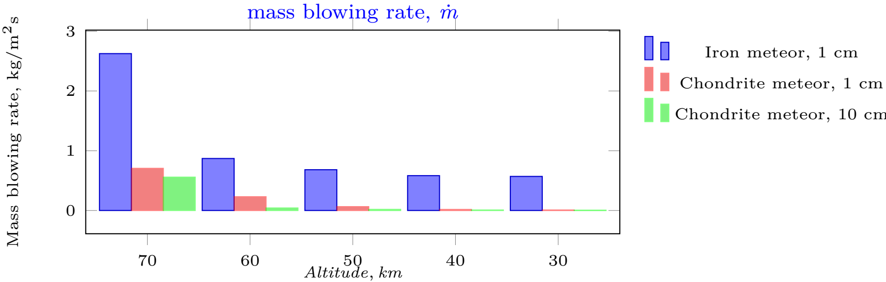
Altitude=30 km

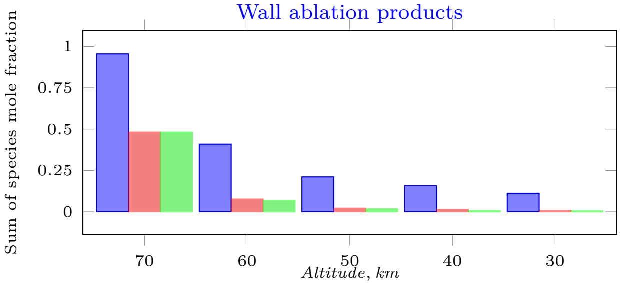


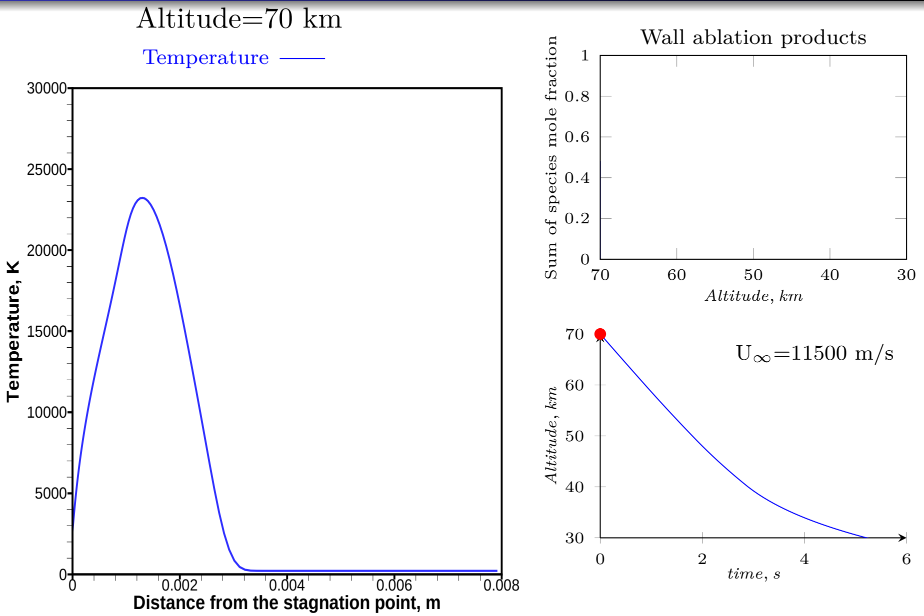




To summarize the ablation properties:

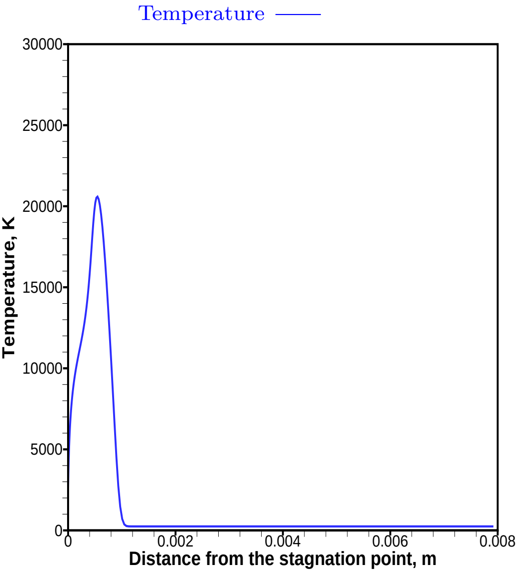


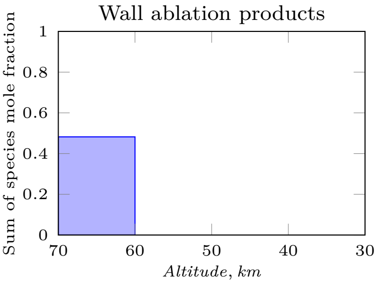


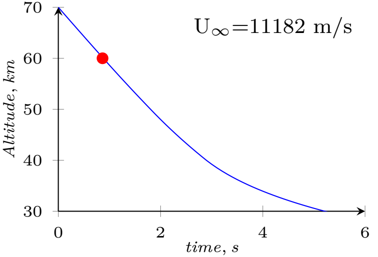

Altitude=70 km
Temperature
30000
25000
20000
15000
10000
5000
0
Temperature, K
0.002
0.004
0.006
0.008
Distance from the stagnation point, m
Wall ablation products
Sum of species mole fraction
1
0.8
0.6
0.4
0.2
70
60
50
40
30
Altitude, km
U∞=11500 m/s
Altitude, km
time, s
2
4
6

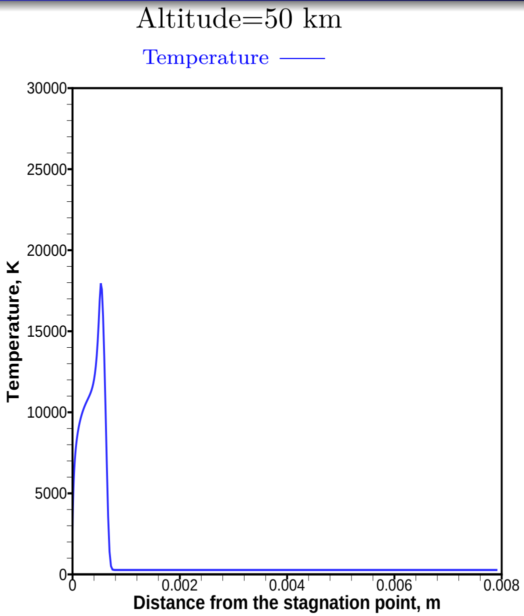
Trajectory of Ordinary Chondrite meteor, radius = 1 cm

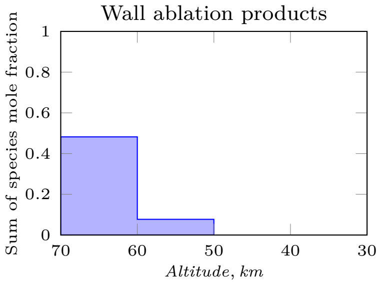
Altitude=60 km

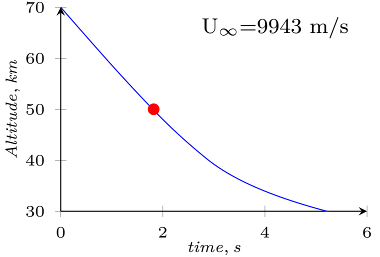






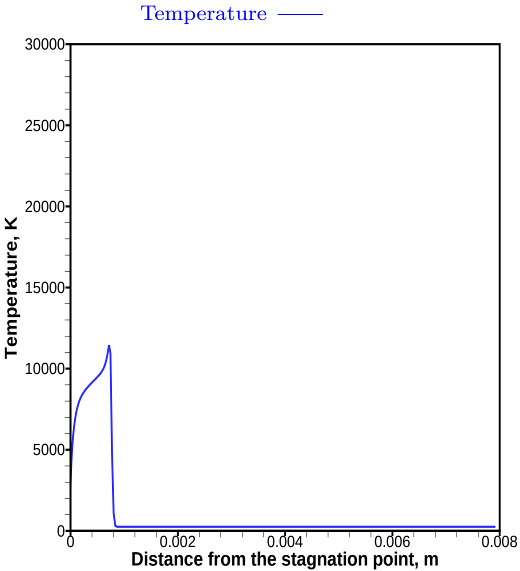

Altitude=50 km
Temperature
30000
25000
20000
15000
10000
5000
0
0.002
0.004
0.006
0.008
Temperature, K
Distance from the stagnation point, m

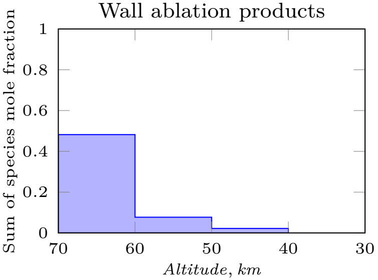

Wall ablation products
Sum of species mole fraction
1
0.8
0.6
0.4
0.2
0
70
60
50
40
30
Altitude, km

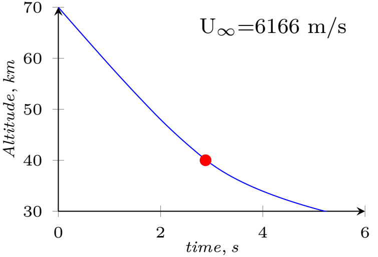

U∞=9943 m/s
Altitude, km
70
60
50
40
30
0
2
4
6
time, s

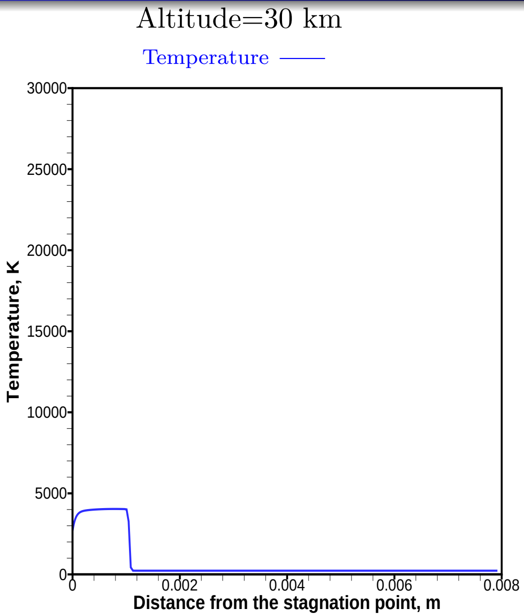
Trajectory of Ordinary Chondrite meteor, radius = 1 cm

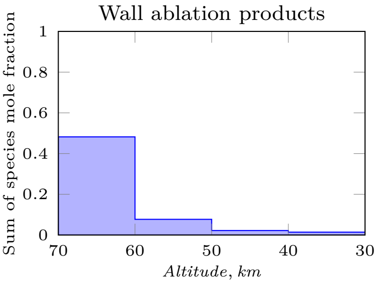
Altitude=40 km

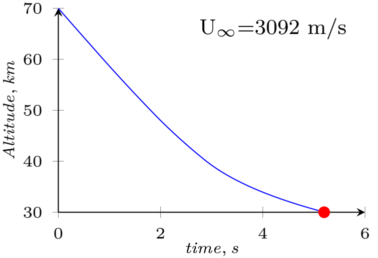


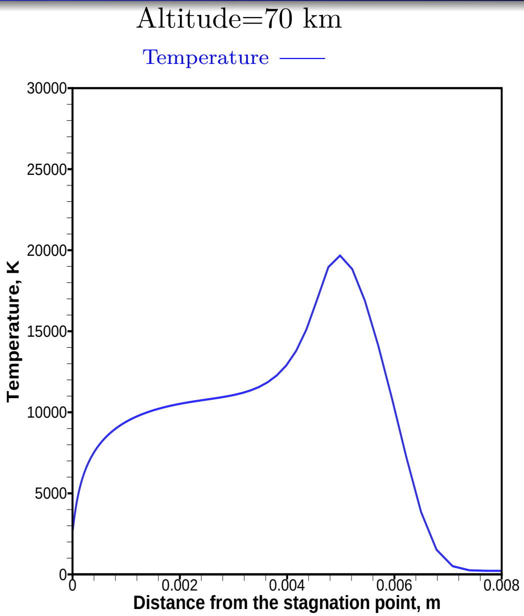


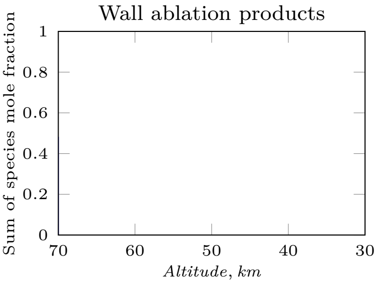


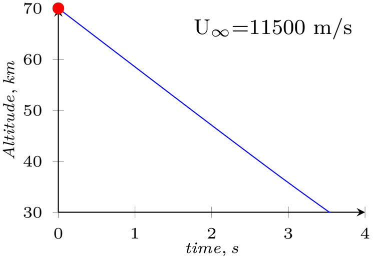

Altitude=30 km
Temperature
30000
25000
20000
15000
10000
5000
0
Temperature, K
0
0.002
0.004
0.006
0.008
Distance from the stagnation point, m

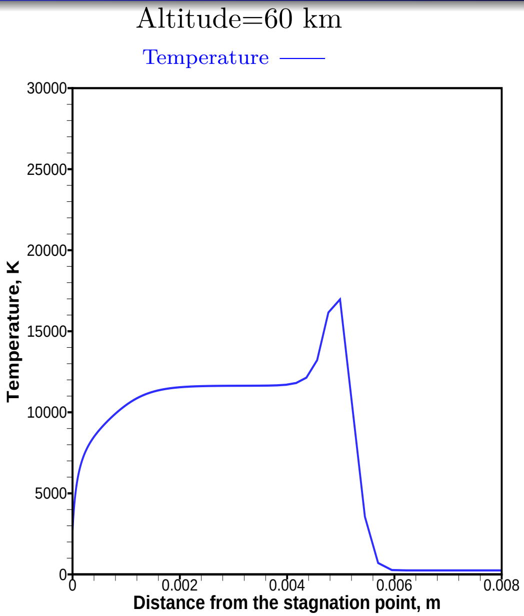

Wall ablation products
1
0.8
0.6
0.4
0.2
0
Sum of species mole fraction
70
60
50
40
30
Altitude, km

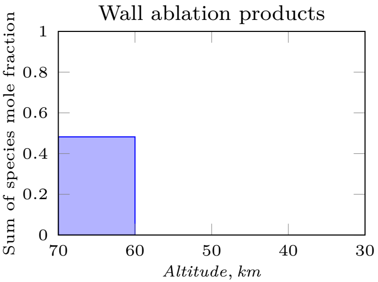

70
60
50
40
30
Altitude, km
U∞=3092 m/s
0
2
4
6
time, s

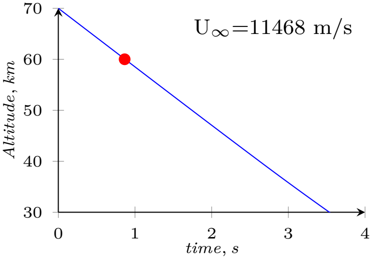

Altitude=70 km
Temperature
30000
25000
20000
15000
10000
5000
0
Temperature, K
0
0.002
0.004
0.006
0.008
Distance from the stagnation point, m

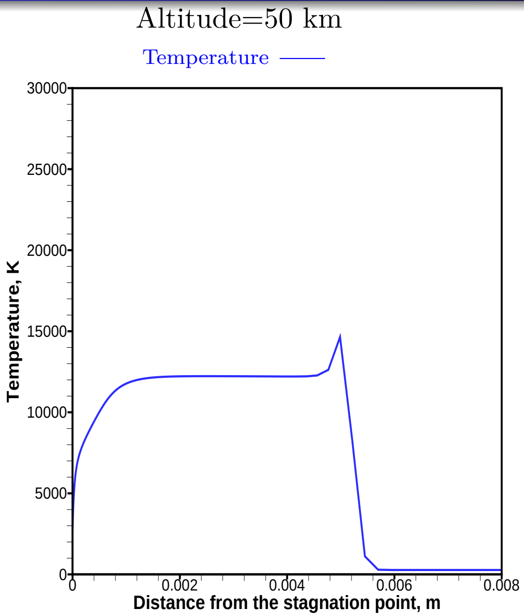

Wall ablation products
Sum of species mole fraction
1
0.8
0.6
0.4
0.2
0
70
60
50
40
30
Altitude, km

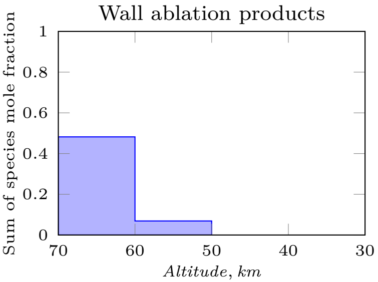

U∞=11500 m/s
Altitude, km
70
60
50
40
30
0
1
2
3
4
time, s

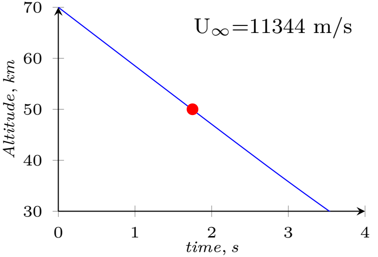

Altitude=60 km
Temperature
Temperature, K
Distance from the stagnation point, m
30000
25000
20000
15000
10000
5000
0
0.002
0.004
0.006
0.008

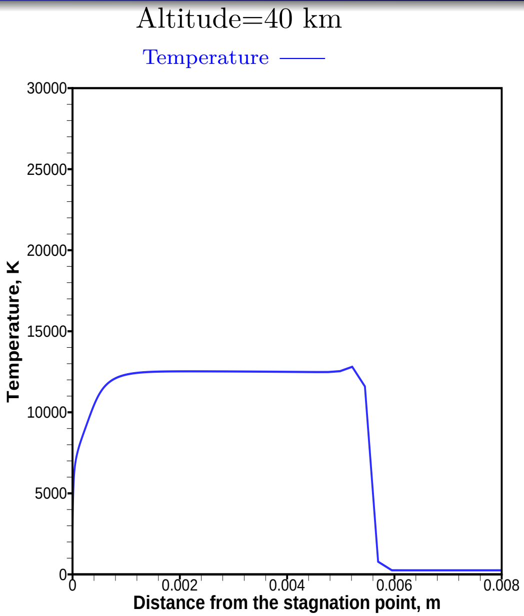

Wall ablation products
Sum of species mole fraction
Altitude, km
1
0.8
0.6
0.4
0.2
0
70
60
50
40
30

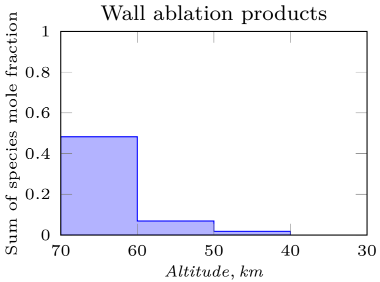

U∞=11468 m/s
Altitude, km
time, s
70
60
50
40
30
0
1
2
3
4

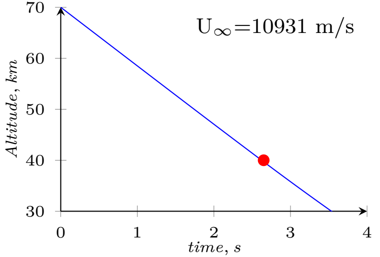

Altitude=50 km
Temperature
Temperature, K
30000
25000
20000
15000
10000
5000
0
0.002
0.004
0.006
0.008
Distance from the stagnation point, m

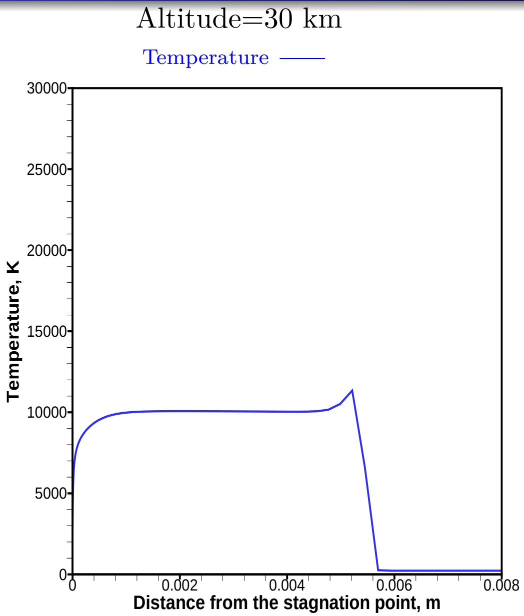

Wall ablation products
Sum of species mole fraction
1
0.8
0.6
0.4
0.2
0
70
60
50
40
30
Altitude, km

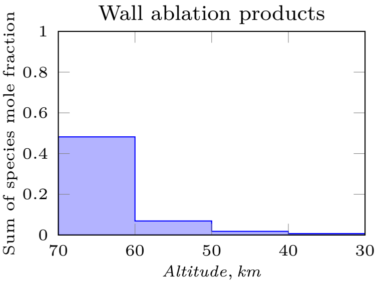

U_∞=11344 m/s
Altitude, km
70
60
50
40
30
0
1
2
3
4
time, s

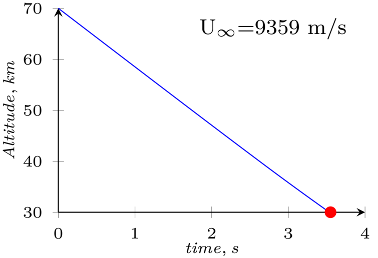

Altitude=40 km
Temperature
30000
25000
20000
15000
10000
5000
0
Temperature, K
0
0.002
0.004
0.006
0.008
Distance from the stagnation point, m

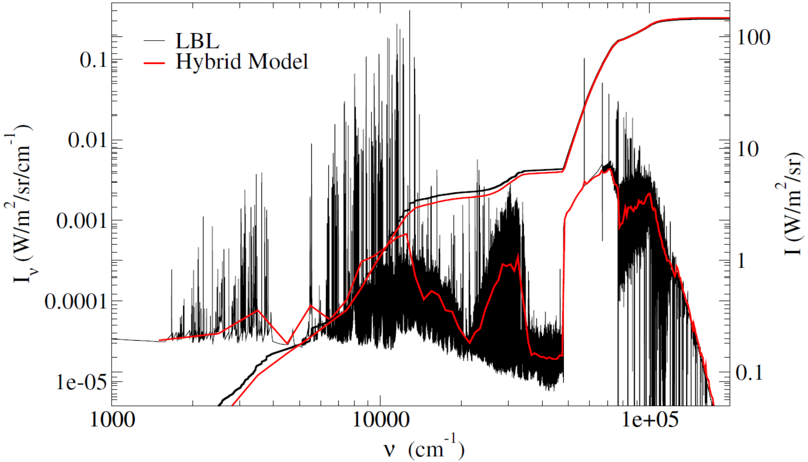

Wall ablation products
Sum of species mole fraction
1
0.8
0.6
0.4
0.2
0
70
60
50
40
30
Altitude, km


70
60
50
40
30
Altitude, km
U∞=10931 m/s
0
1
2
3
4
time, s


Altitude=30 km
Temperature
30000
25000
20000
15000
10000
5000
0
0.002
0.004
0.006
0.008
Temperature, K
Distance from the stagnation point, m


Wall ablation products
Sum of species mole fraction
1
0.8
0.6
0.4
0.2
0
70
60
50
40
30
Altitude, km

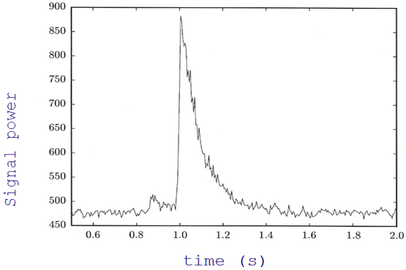

U∞=9359 m/s
Altitude, km
70
60
50
40
30
0
1
2
3
4
time, s



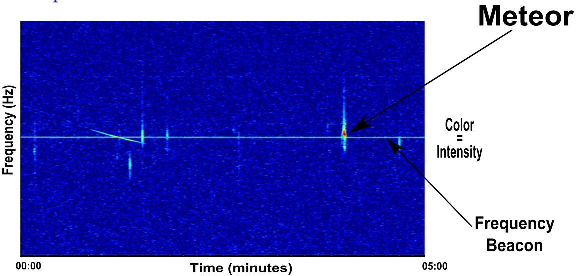
Soucasse et al, 2010

Radio Waves Detection by BRAMS network

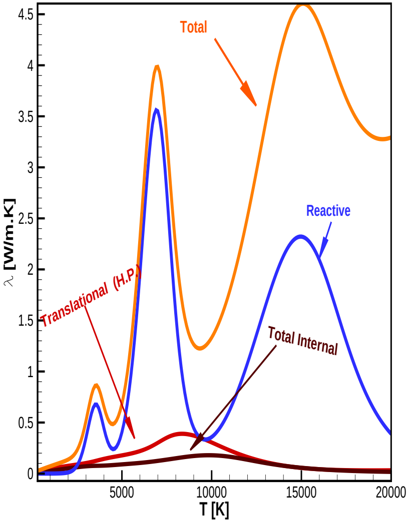
Receiver Signal Power



Spectrum of Meteors in One Hour



Thermal conductivity of Air 11 at 1 atm



$$q_h = -(\lambda^F + \lambda^E)\nabla T + \sum_i \rho_i V_i h_i$$

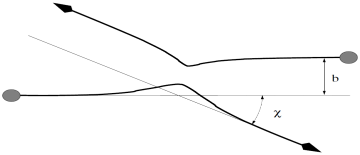
- Generalized Fick law:

$$\rho_i V_i = \sum_j -D_{ij} \nabla x_j$$

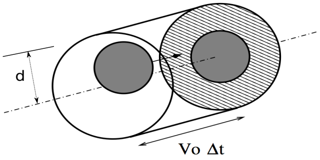
$$\nabla x_j = \frac{\partial x_j}{\partial T} \nabla T \;\; in \;\; LTE$$

- Diffusion of Enthalpy:

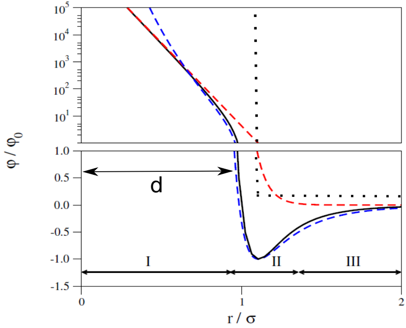
$$\sum_i \rho_i V_i h_i = -\lambda^R \nabla T$$



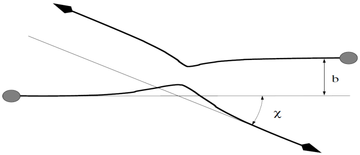
Elastic Collisions



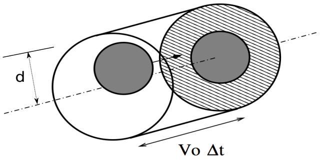
Collision Cylinder $\bar{Q}_{ij}^{(2,2)} \approx \pi d^2$



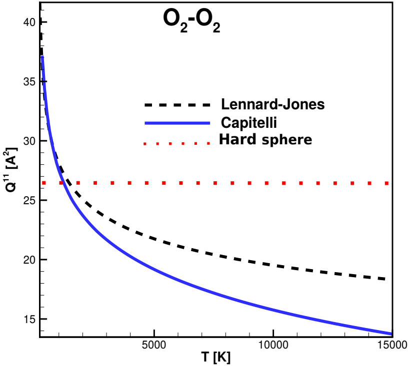
Potentials models for the O2-O2, —— Tang-Toennies, - - Born-Mayer, - - (m,6) and ■ Hard sphere model



Elastic Collisions

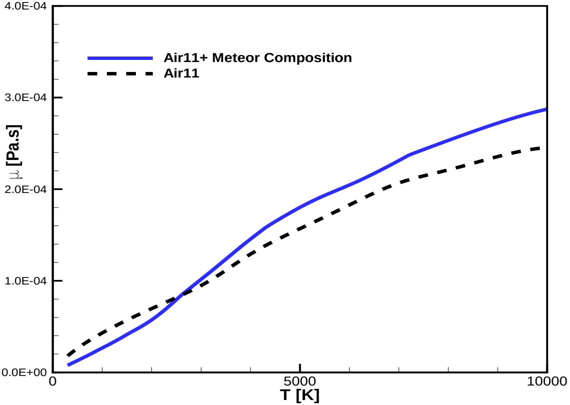


Collision Cylinder $\bar{Q}_{ij}^{(2,2)} \approx \pi d^2$



Comparison Lennard-Jones Potential vs Capitelli Model vs Hard Sphere $O_2 - O_2$

Comparison μ Air 11 with Air 11+Meteor Species at 1 atm Mutation++



—— Air11 + Meteor Composition, - - Air11

- Phenomenological Transport

$$\mu \propto \frac{\sqrt{\pi k_b T m_i}}{\pi d^2}$$

- Rigorous Chapman Enskog transport ($\sim$ 160 interactions)

Fe-*O*, *FeO*-O_2, ...