Radiative Heating for Ice Giants Entries

Outcomes from the ESA Ice Giants Sensor Suite TRP

M. Lino da Silva

Space Ballistics, Lisbon, Portugal

10th Radiation of High Enthalpy Gases in Atmospheric Entry Workshop, Oxford, 9-12th Sep. 2024

Activity Modeling WP Objectives

- Identify representative peak-heating points for 45º and 60º sphere-cone capsules in Uranus and Neptune entries
- Perform CFD simulations including Ablation products injection at the wall boundary (lead: Fluid Gravity Eng.)
- Perform radiative transfer simulations based on the supplied flowfields, identify, qualitatively and quantitatively the radiative features of the flow
  - Issue recommendations for future testing and sensors development

SPACE
BALLISTICS

Methodology

- Trajectory calculations using FGE Traj6 code, peak q points from usual correlations (sutton-Graves, etc...)
- CFD simulations for max q using the TINA CFD code coupled to the FABL ablation code.
- Local radiative properties calculation + tangent-slab radiative transfer simulations using the SPARK Line-by-Line code.

Selected Trajectory Points

Geometric parameter	ESA-A and ESA-C cases	ESA-B cases
Nose radius [m]	0.45	0.45
Cone angle [°]	**45**	**60**
Shoulder radius [m]	0.45	0.45
Forebody length [m]	0.471	0.304

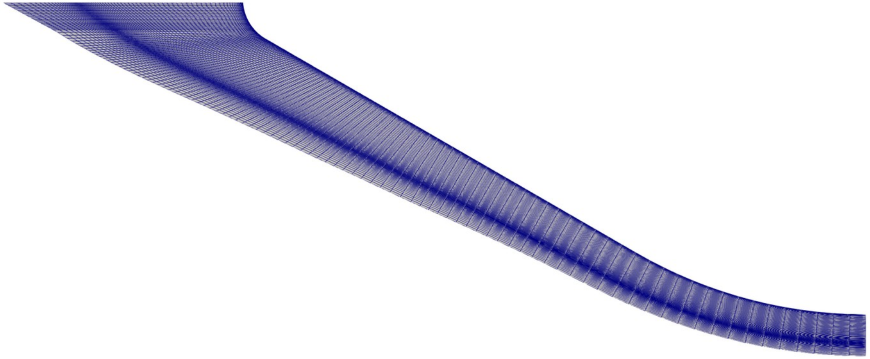
Trajectory case number	Flight path angle [°]	Entry velocity [km/s]	Entry altitude [km]
0	-15	21.25	600
1	-20	21.40	600
2	-25	21.60	600
3	-30	21.90	600
4	-35	22.75	600
5	-40	23.55	600
6	-45	23.65	600

Trajectory parameter	ESA-A-0	ESA-B-0	ESA-B-4	ESA-C-4
Air velocity [km/s]	**18.17**	**18.03**	**19.31**	**19.59**
Freestream pressure [Pa]	**192**	**145**	**377**	**501**
Static temperature [K]	52.14	52.14	52.14	52.14
Molar fraction of H_2	0.84	0.84	0.84	0.84
Molar fraction of He	0.16	0.16	0.16	0.16
Molar fraction of CH_4	**0.0**	**0.0**	**0.0**	**0.0**

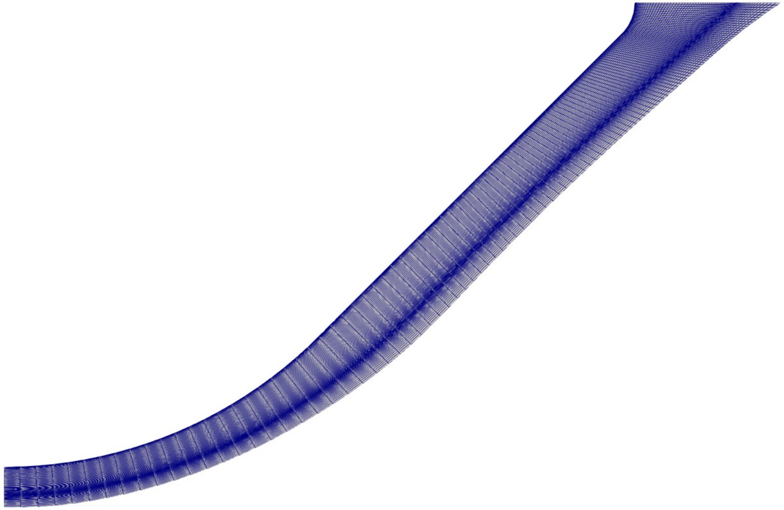
Trajectory parameter	ESA-A-0	ESA-A-6	ESA-B-0	ESA-B-6	ESA-C-6
Air velocity [km/s]	**17.67**	**19.47**	**17.74**	**19.23**	**19.50**
Freestream pressure [Pa]	**243**	**738**	**176**	**577**	**770**
Static temperature [K]	90.92	57.90	99.80	64.30	56.98
Molar fraction of H_2	0.801	0.801	0.801	0.801	0.801
Molar fraction of He	0.182	0.182	0.182	0.182	0.182
Molar fraction of CH_4	**0.016**	**0.016**	**0.016**	**0.016**	**0.016**

Meshes

60º Sphere-Cone

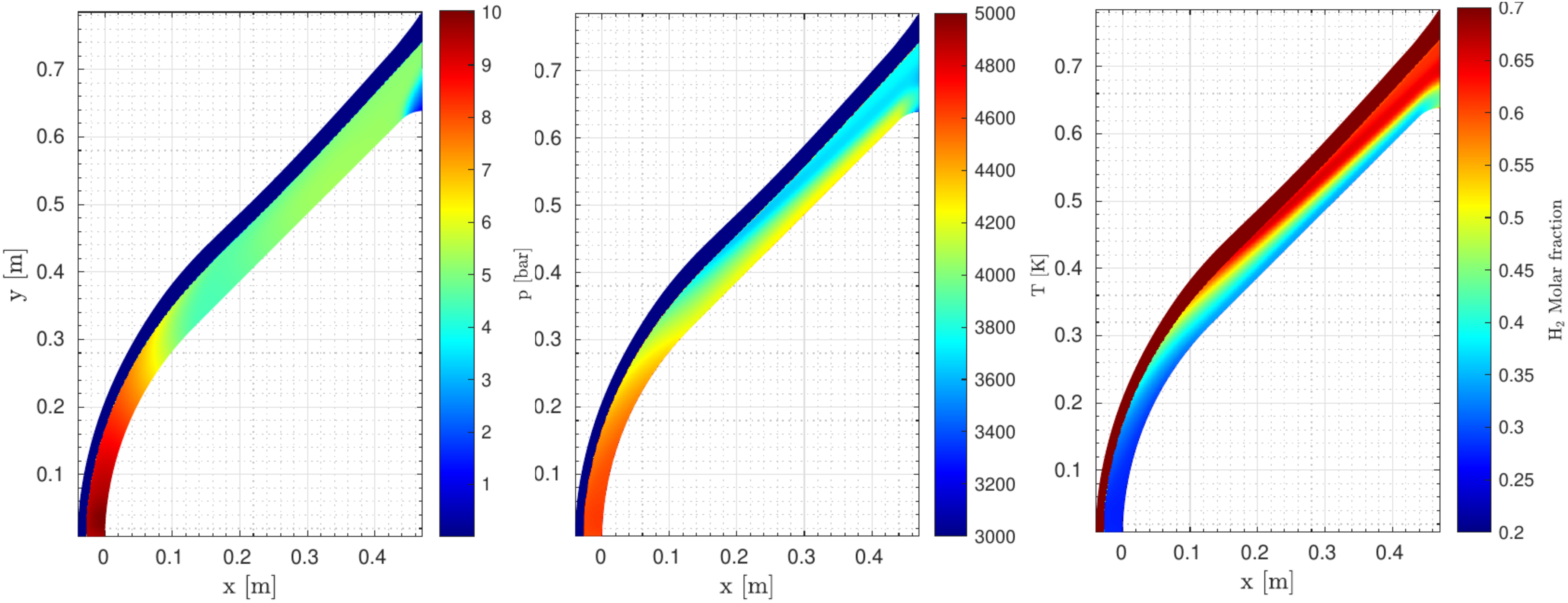


45º Sphere-Cone



Sample CFD Results

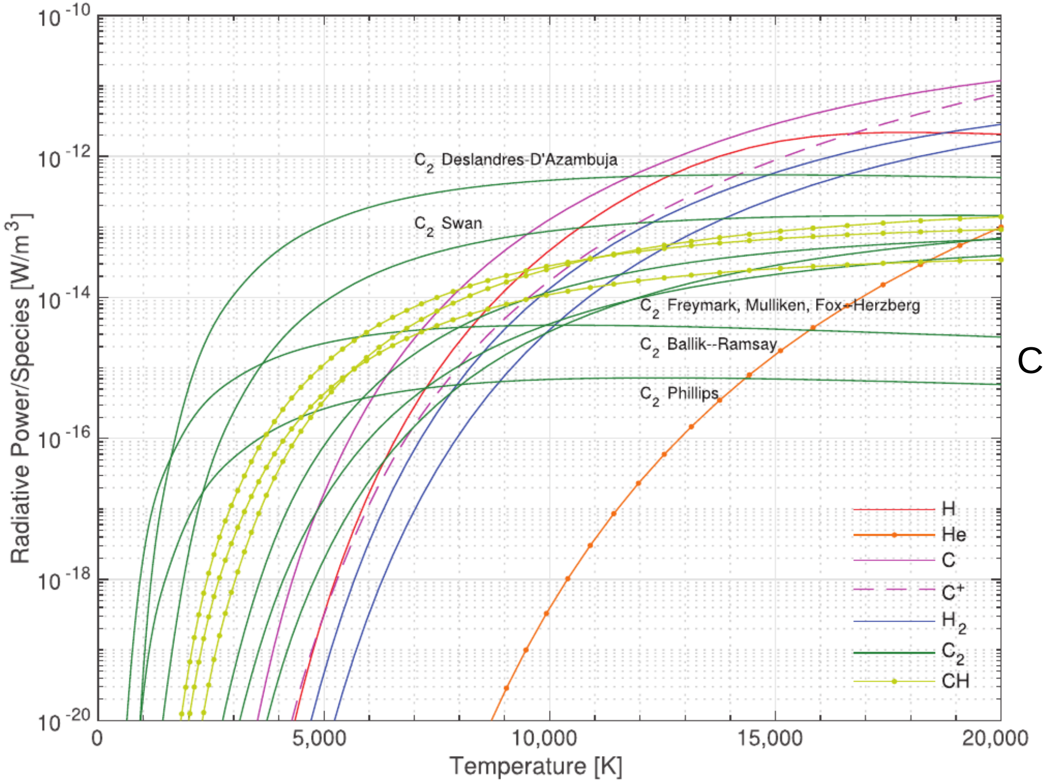
Uranus C4



- Huge post-shock pressures → tiny boundary layer
- Moderate temperatures, oblique shock does not fully dissociate H2

SPACE BALLISTICS

Radiative Power per Chemical Species

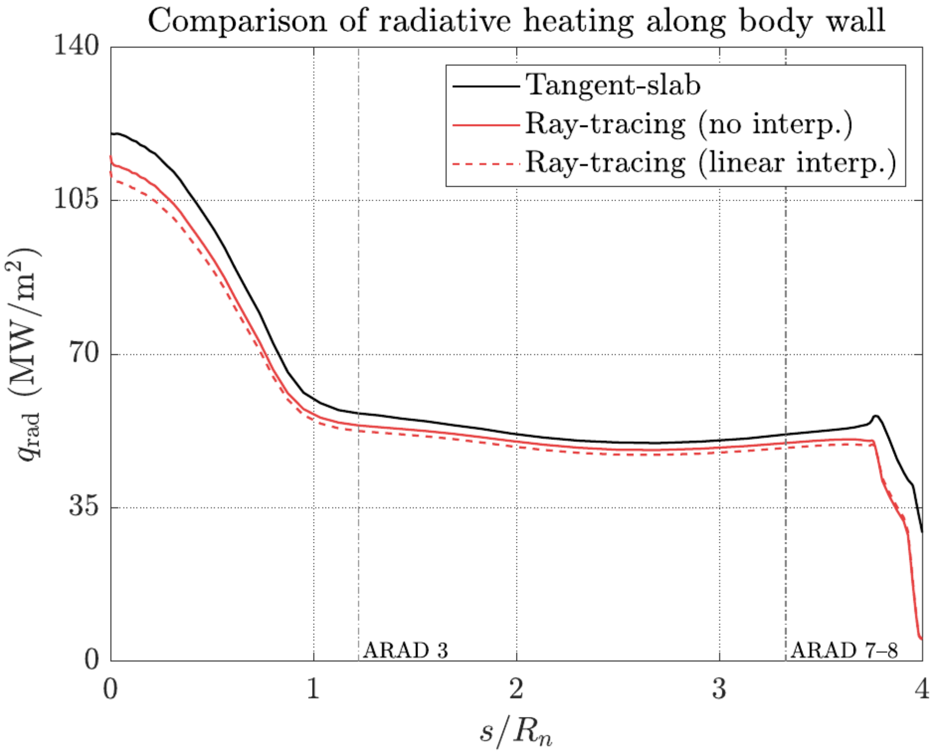


Coelho, Adv. Space Res., 2023

- C2 and CH will radiate a lot at lower equilibrium temperatures
- H2 and H only take over at higher T (equiv v>27km/s), well known.

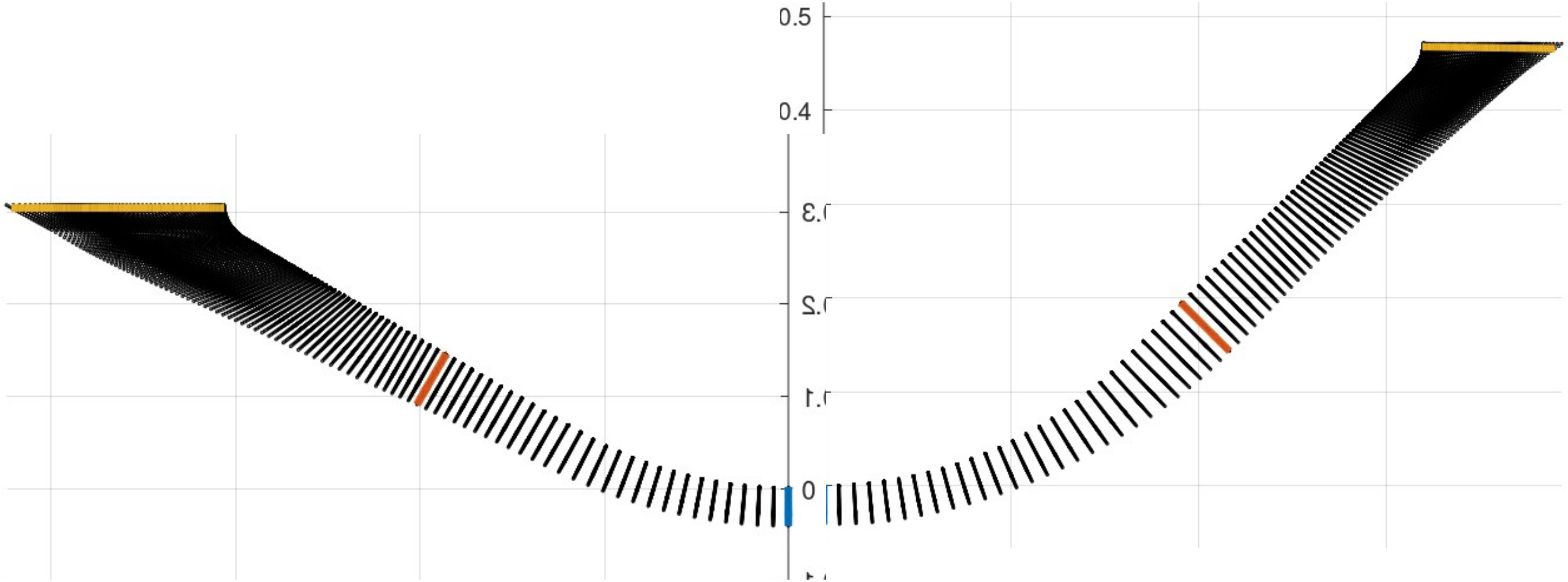
SPACE
BALLISTICS

Validity of the Tangent Slab approximation



Previous results for similar class of entries (Galileo Jupiter entry) show that the approximation is very reasonable for such high-pressure, optically thick flows (Fernandes 2019, Phys. Fluids)

Selected Grid Points for Tangent-Slab Simulations



60º Sphere-Cone

45º Sphere-Cone

Results

Main Findings

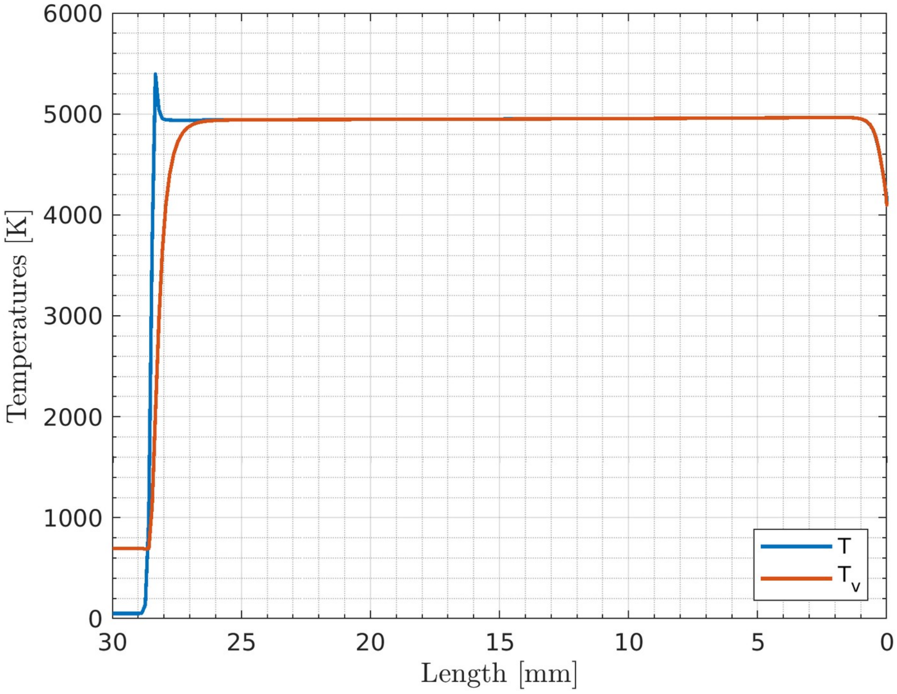
- Uranus (0% freestream CH4) radiation from the freestream negligible compared to convective heating.
  - However, increased ablation layer near the shoulder significantly enhances radiation (injection of C species)
- For Neptune (1.5% freestream CH4), radiative heating is the same order of magnitude than convective heating, and may even exceed convective heating.
- This is due to the small percentage of CH4 in the freestream which dissociates and recombines into radiative species after the shock.
- Consistent with previous predictions from Coelho, Adv. Space Res., 2023

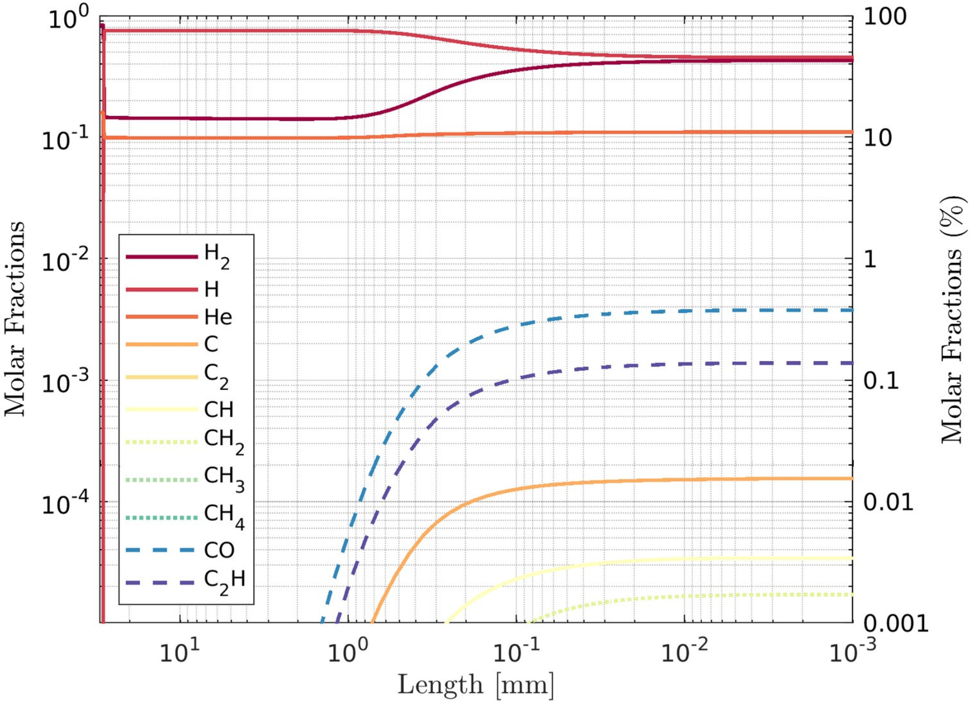
SPACE BALLISTICS

Analysis of the ablation layer

- Radiative transfer calculations carried out in three ways:
  1) Full: from the shock until the wall boundary
  2) No Ablation layer emission: from the shock until the ablation boundary, only absorption from the ablation layer considered
  3) No ablation layer emission and absorption. The ablation layer is transparent to radiation
- For Uranus, most of the radiation comes exclusively form the ablation layer
- For Neptune, the ablation layer contribution to the overall radiation is negligible
- Numerical results collated in an excel file

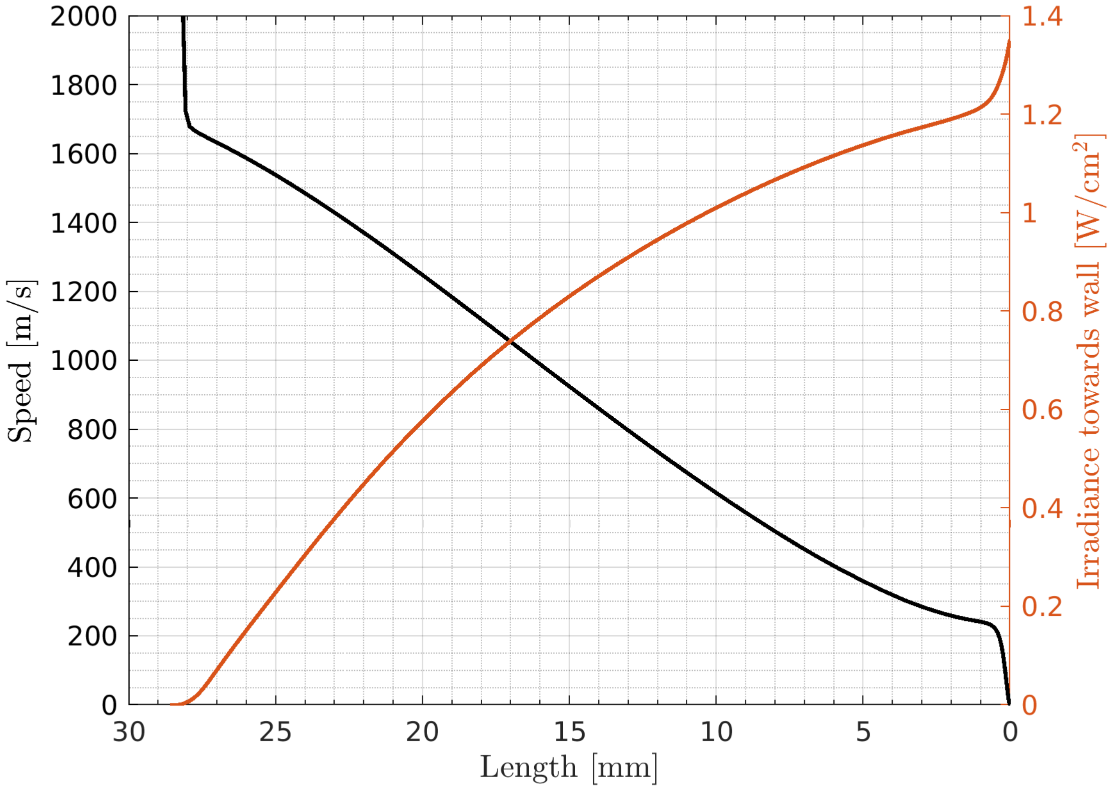
Uranus C4, LOS1 (stagnation line)



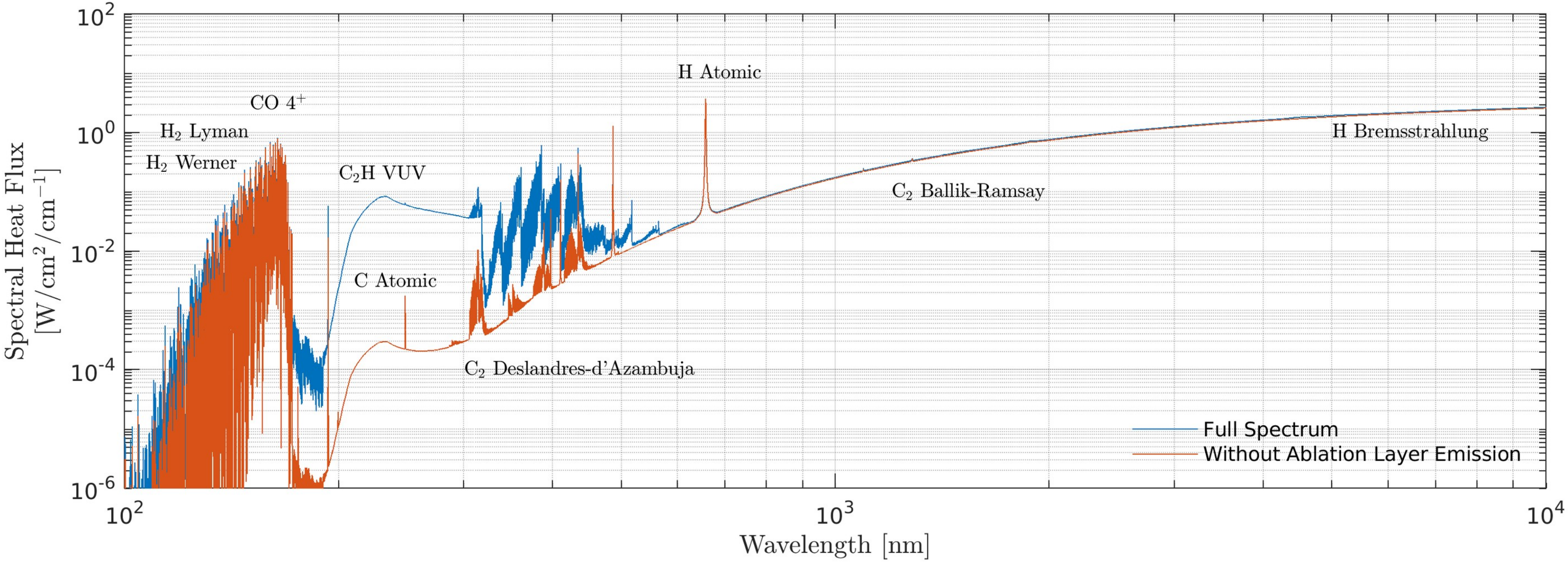


SPACE
BALLISTICS

Uranus C4, LOS1 (stagnation line, ctd.)

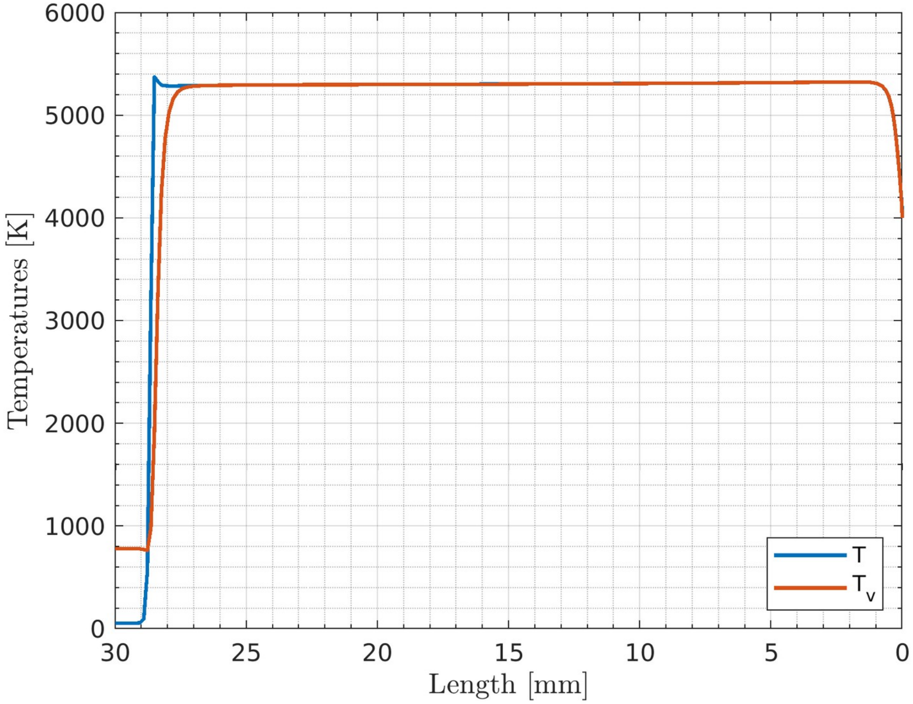


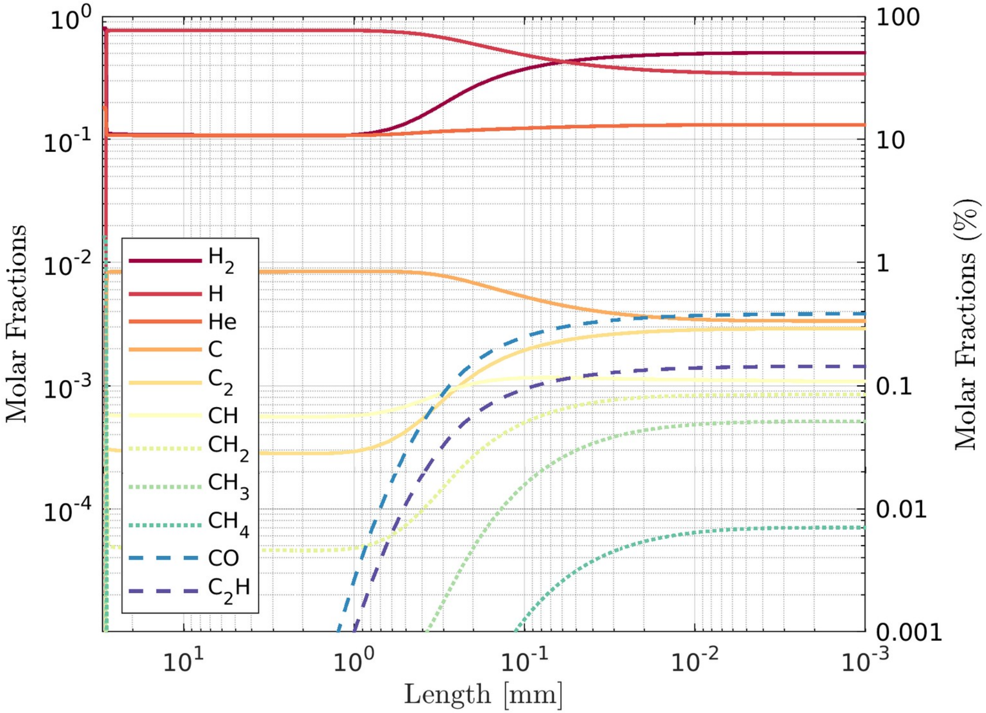
Uranus C4, LOS1 (stagnation line, ctd.)



SPACE
BALLISTICS

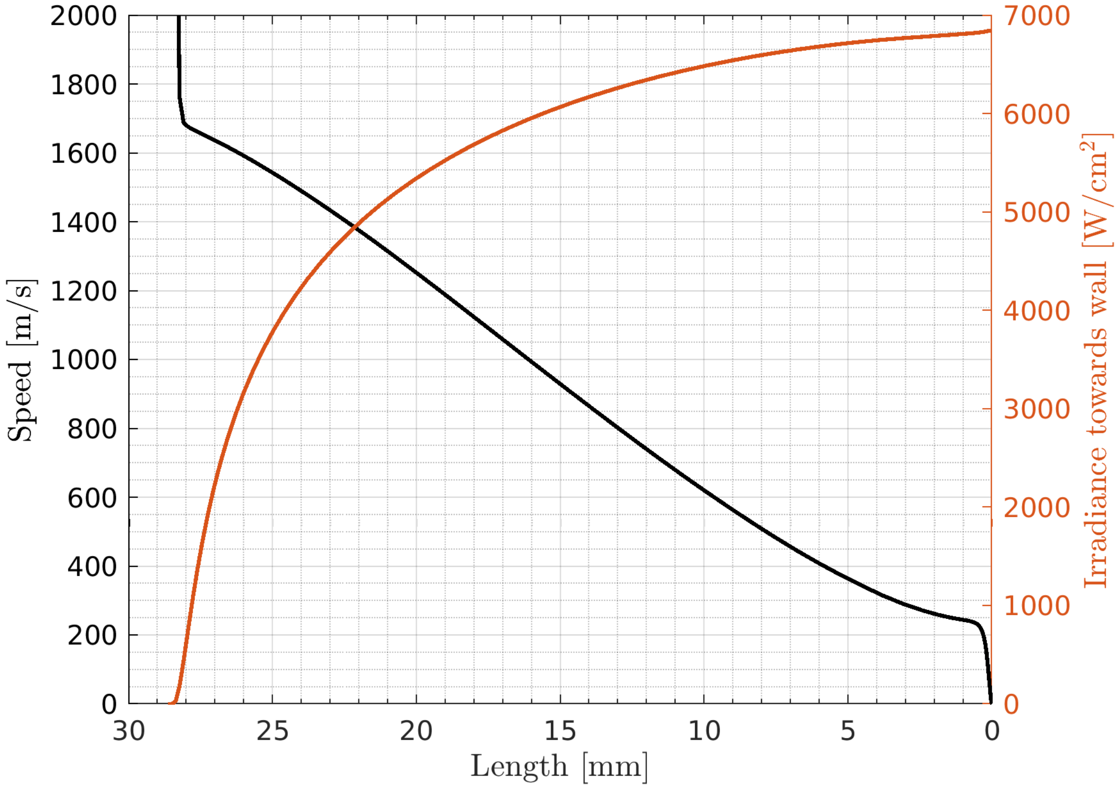
Neptune C6, LOS1 (stagnation line)



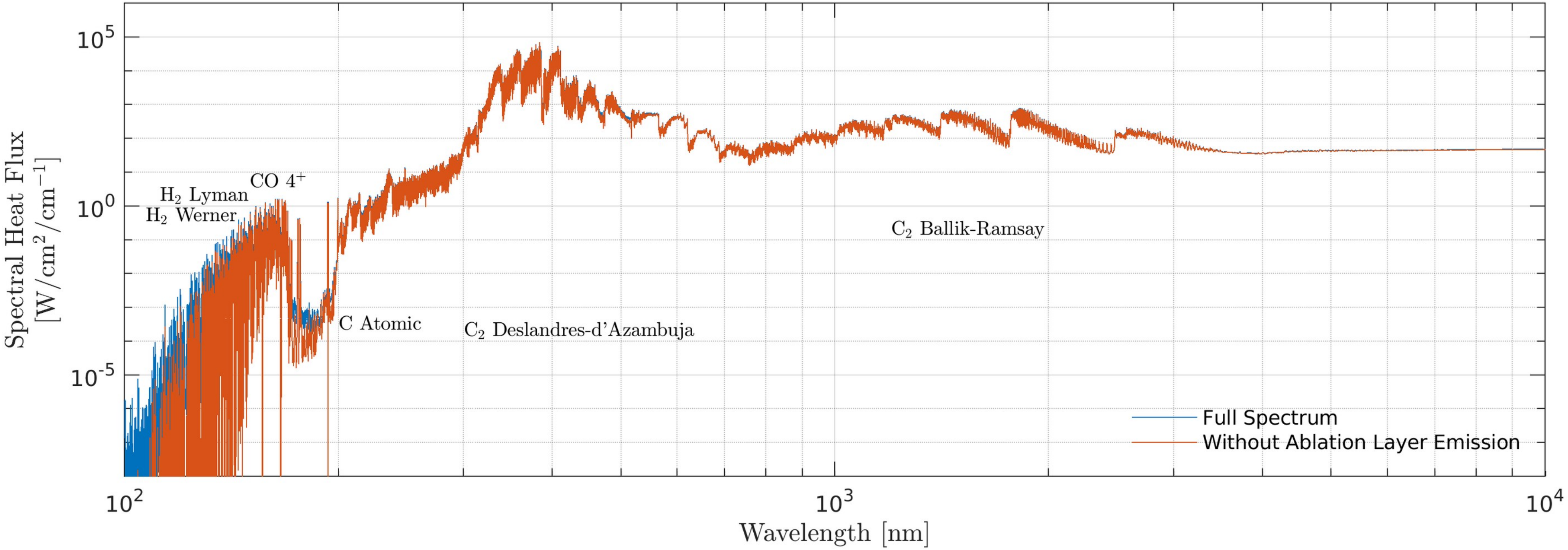


SPACE
BALLISTICS

Neptune C6, LOS1 (stagnation line, ctd.)



Neptune C6, LOS1 (stagnation line, ctd.)

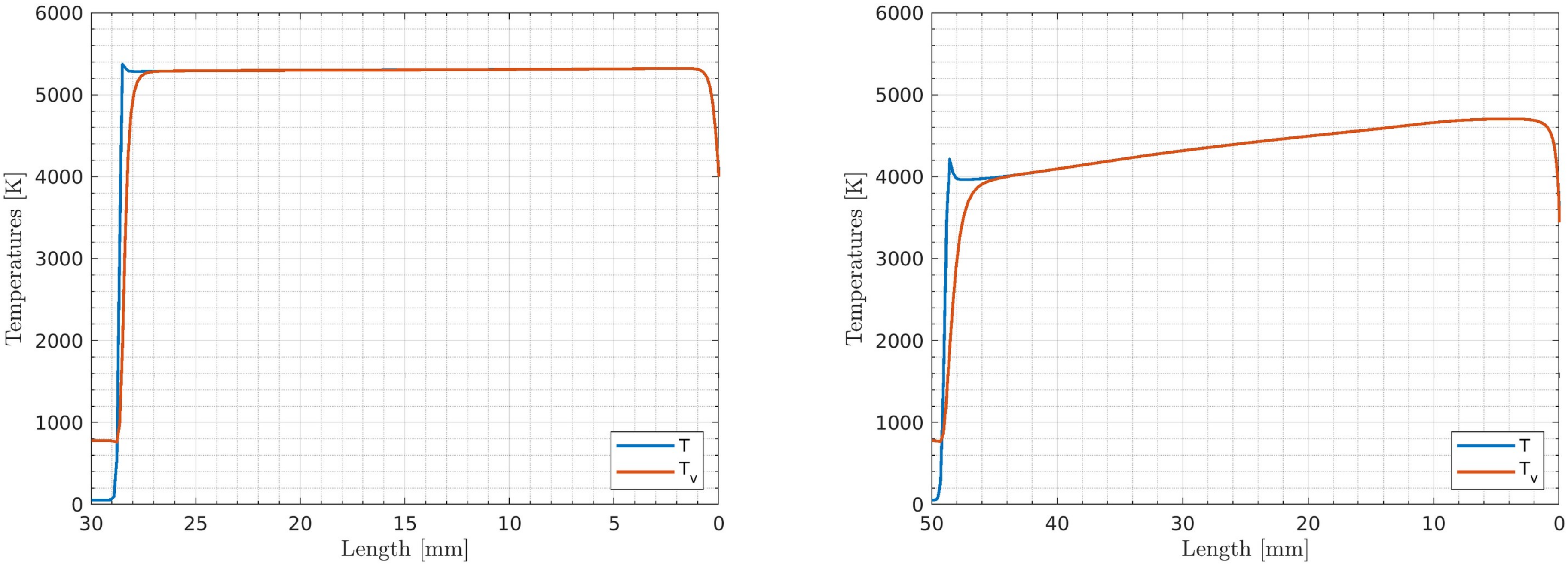


Comments on LOS2,3,4 (cone & shoulder region)

- Radiation for Uranus trajectory points no longer negligible (ranging from 3W/cm^2 to 466W/cm^2 depending on the position and trajectory point.
- For Neptune, radiative heating increases to very severe amounts (from 8kW/cm^2 to 30kW/cm^2. This is due to a thicker shock-layer, which means that more radiation is integrated
- It is useful to assess how the composition of freestream CH4 affects this, by repeating calculations for a trajectory point with 0.1% CH4 (more in line with contemporary predictions of Neptune composition) instead of 1.5%

SPACE
BALLISTICS

Neptune C6

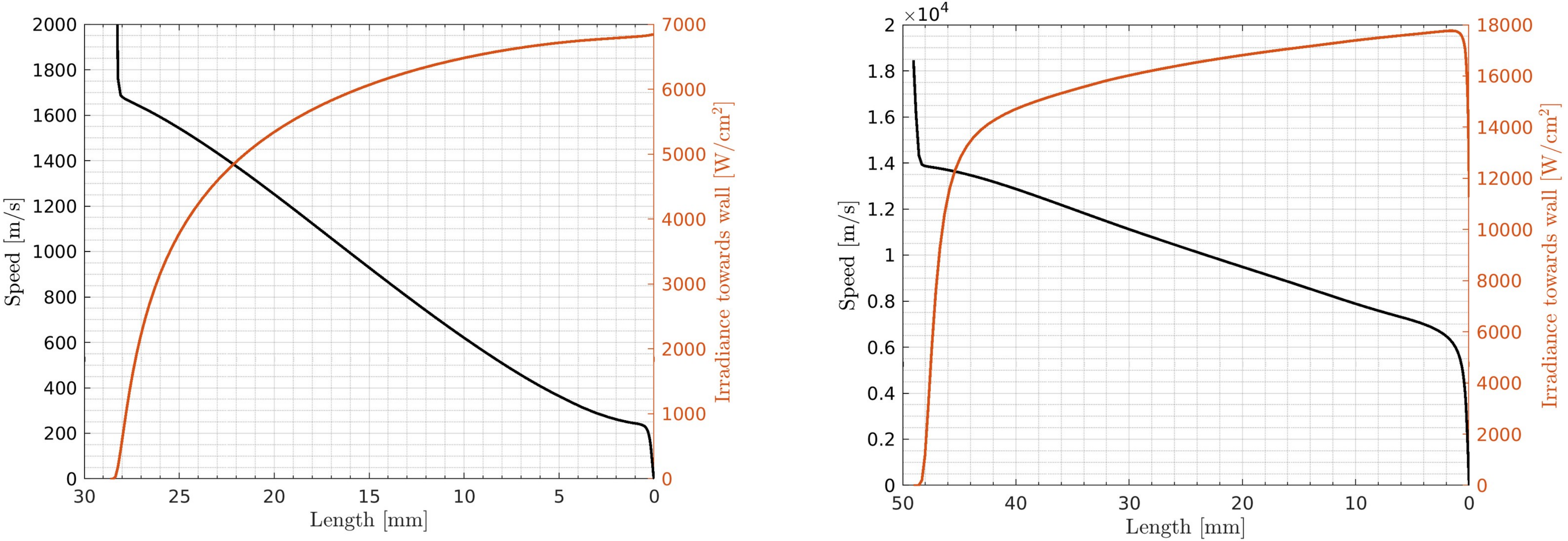


C6 point – Left: LOS1 (Stag. Line), Right LOS2

For LOS2, LOS3, LOS4, you integrate longer paths, still at very critical temperatures for radiation from C and C2 → radiation will increase a lot compared to the stagnation line

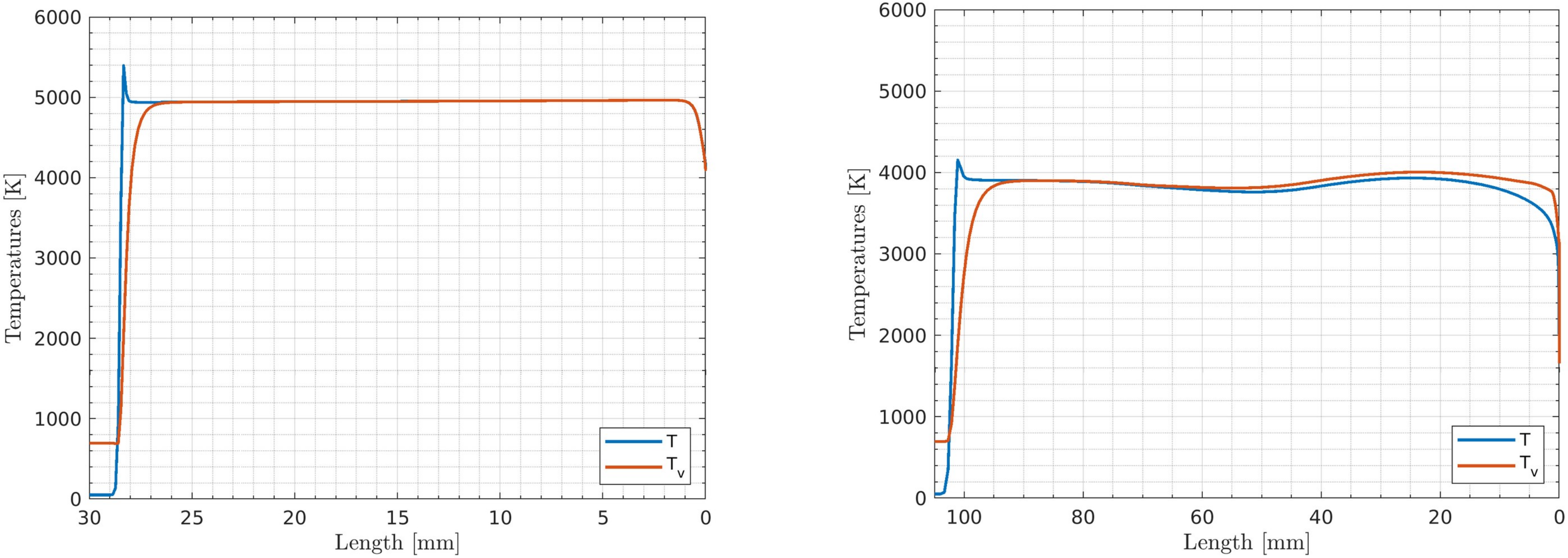
SPACE BALLISTICS

Neptune C6, ctd.



C6 point – Left: LOS1 (Stag. Line), Right LOS2

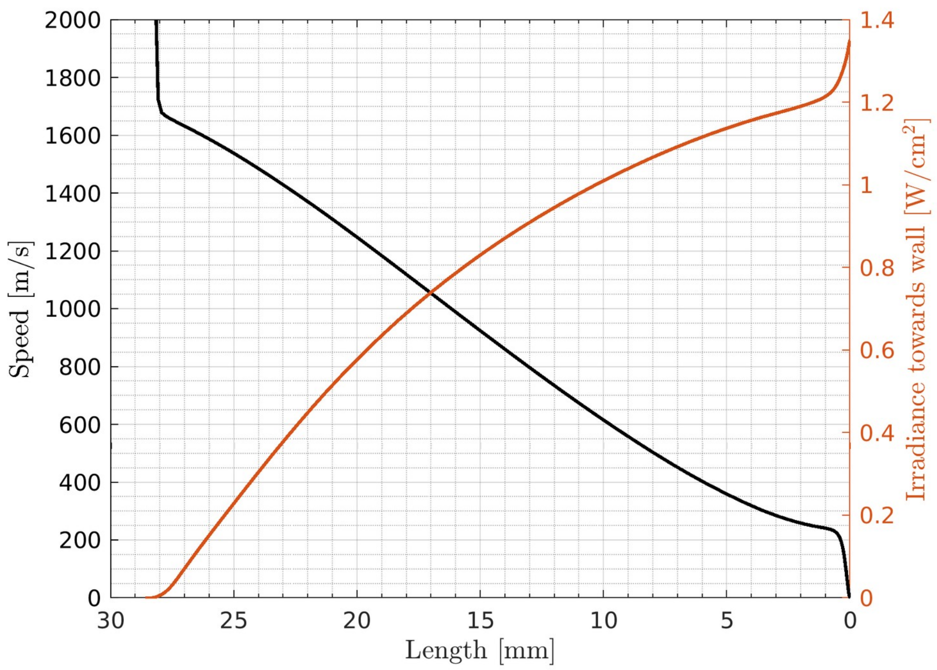
Uranus C4

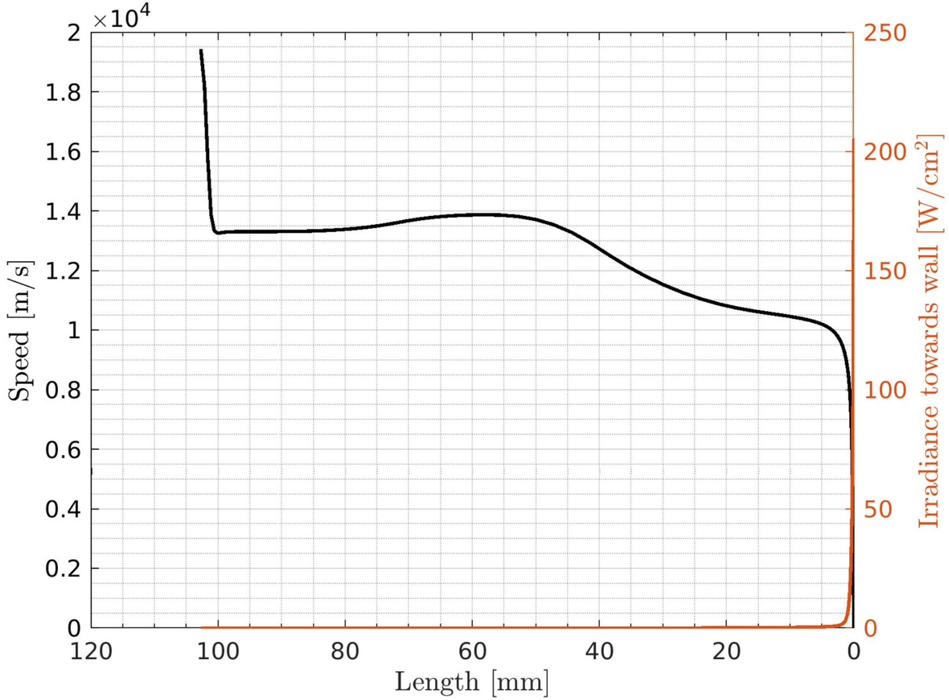


C4 point – Left: LOS1 (Stag. Line), Right LOS4

Same comment than for Neptune applies. Notice that for LOS4 we have a path of 100mm instead of 30mm, still at very high temperatures (4000K). Then the injected carbon species will radiate significantly in the edge of the ablation layer (about 3mm)

Uranus C4, ctd.

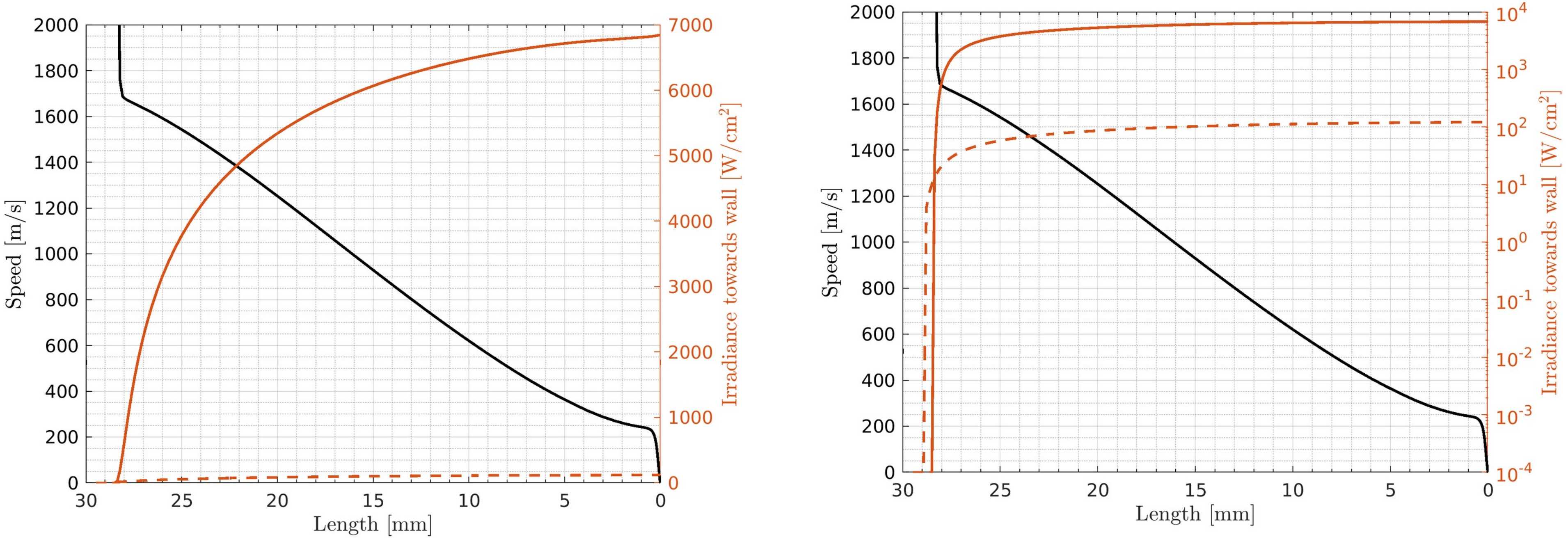




C4 point – Left: LOS1 (Stag. Line), Right LOS4

SPACE
BALLISTICS

Neptune C6, Comparison for 1.5/0.1% CH4 ratio



Neptune C6 point

SPACE
BALLISTICS

Radiative Heat Fluxes, all points

Wall Fluxes (kW/cm²)

Uranus

	LOS1			LOS2			LOS3			LOS4		
	Full	No Ablation Emission	No Ablation Emission / Absorption	Full	No Ablation Emission	No Ablation Emission / Absorption	Full	No Ablation Emission	No Ablation Emission / Absorption	Full	No Ablation Emission	No Ablation Emission / Absorption
A0	2.69E-05	7.92E-06	8.14E-06	0.014	0.000	0.001	0.044	0.001	0.002	0.010	0.001	0.001
B0	7.32E-05	4.18E-06	4.48E-06	0.025	0.000	0.001	0.017	0.001	0.001	0.003	0.000	0.000
B4	3.21E-04	3.21E-04	7.17E-04	0.110	0.002	0.005	0.097	0.004	0.007	0.047	0.001	0.002
C4	1.35E-03	1.18E-03	1.19E-03	0.124	0.002	0.039	0.466	0.002	0.007	0.204	0.005	0.006

Neptune

	LOS1			LOS2			LOS3			LOS4		
	Full	No Ablation Emission	No Ablation Emission / Absorption	Full	No Ablation Emission	No Ablation Emission / Absorption	Full	No Ablation Emission	No Ablation Emission / Absorption	Full	No Ablation Emission	No Ablation Emission / Absorption
A0	**2.35**	2.27	2.30	**20.85**	7.30	20.02	**23.72**	7.66	27.63	**32.21**	25.30	30.67
A6	**6.62**	6.46	6.57	**11.77**	0.13	18.00	**8.79**	0.01	17.70	**23.95**	8.67	29.01
B0	**1.42**	1.26	1.31	**28.90**	6.46	19.63	**28.90**	14.45	26.39	**27.54**	23.17	25.83
B6	**5.58**	4.50	5.25	**10.01**	0.06	17.64	**12.37**	0.32	20.42	**30.98**	15.27	29.44
C6	**6.85**	6.64	6.79	**11.27**	0.10	17.72	**8.36**	0.01	17.36	**22.88**	8.79	29.38
C6 0.1%CH4	0.12	0.12	0.12	**5.05**	1.61	3.45	No input flowfield data available			**7.54**	5.12	6.59

SPACE
BALLISTICS

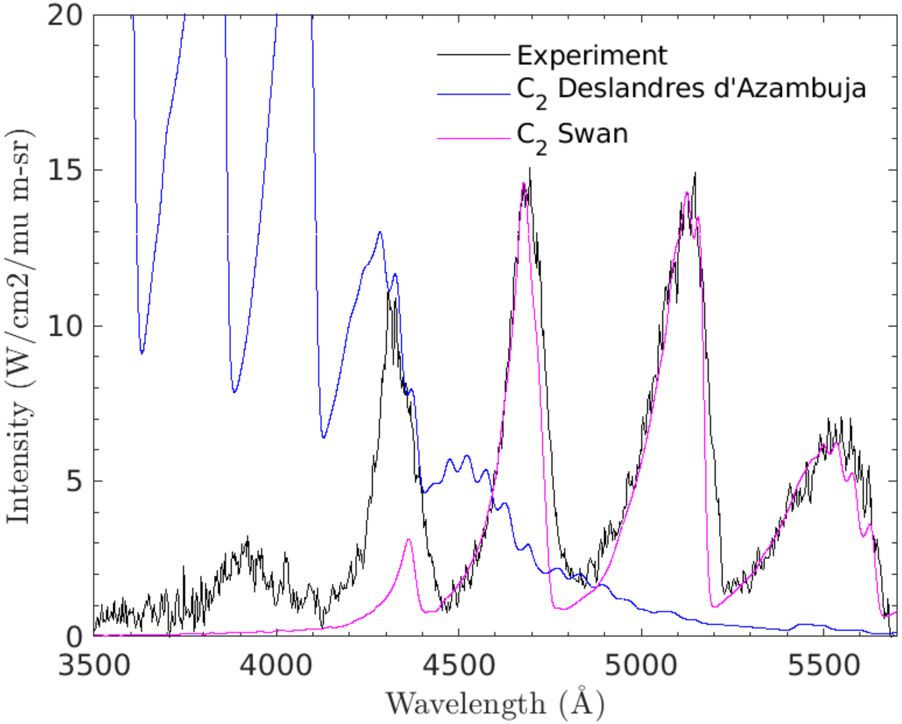
Conclusions

- Radiation heat fluxes extremely sensitive to variations of %CH4 in the freestream for Icy Giants entry conditions (v=[17.5-19.5]km/s; p_inf=[150-750]P
- For Uranus, (0% CH4), radiation is a minor contributor to the total heat fluxes, but cannot be neglected at the shoulder (because of injection of C ablation products)
- For Neptune, the radiative heat fluxes are considerable, even if minor concentrations of CH4 (0.1%) are considered. Particularly at the shoulder
- High-p, thermal equilibrium conditions. Main radiator is C2 Deslandres d'Azambuja whereas for low-p nonequilibrium conditions (experimental testing) the main radiators are C2 Swan and CH A-X, B-X.
- ...to be continued (possibly for the upcoming generation of researchers)

SPACE
BALLISTICS

Corrigendum - Monday Presentation

(I made a mistake)



Switched C2 Swan and C2 Deslandres-d’Azambuja labels!
So still no Deslandres d’Azambuja detected to date at low pressures although it is predicted to be dominant at high pressures
Will update the monday slides, please redownload tomorrow

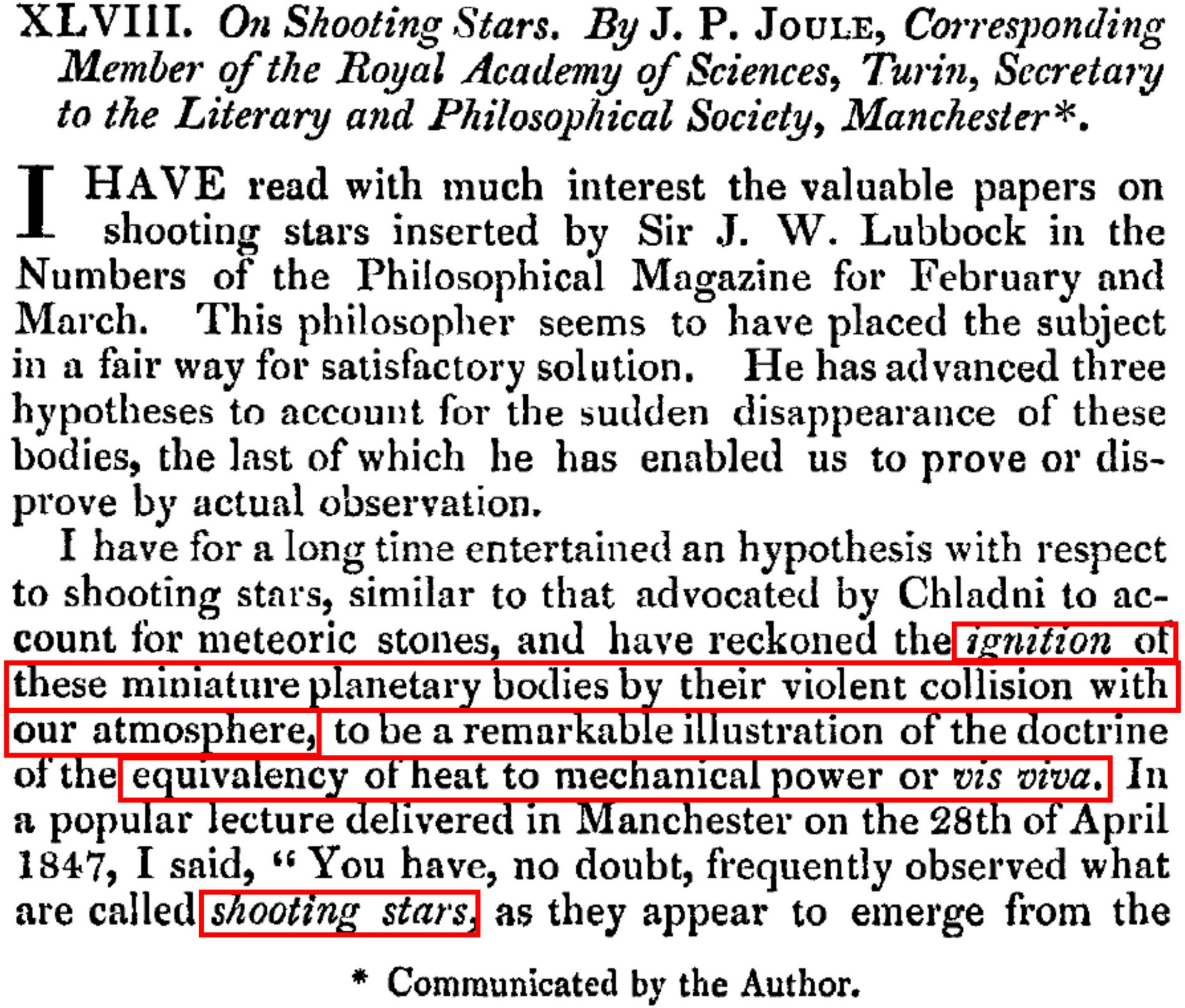
SPACE
BALLISTICS

Piggyback (mini) presentation

The First Aerothermodynamicist

Piggyback (mini) presentation

The First Aerothermodynamicist
James Prescott Joule, 1848



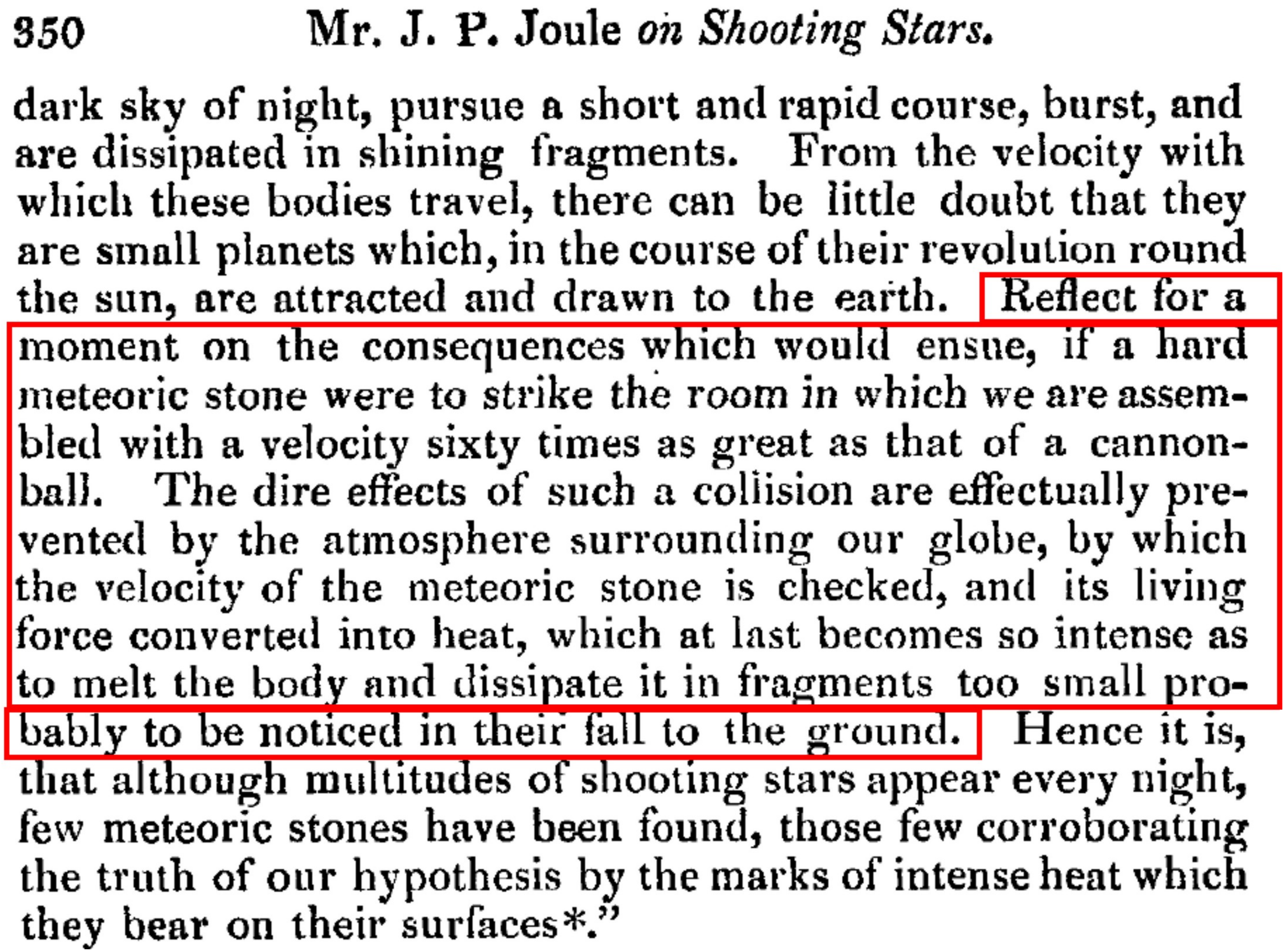
XLVIII. *On Shooting Stars. By* J. P. Joule, *Corresponding Member of the Royal Academy of Sciences, Turin, Secretary to the Literary and Philosophical Society, Manchester**.

I HAVE read with much interest the valuable papers on shooting stars inserted by Sir J. W. Lubbock in the Numbers of the Philosophical Magazine for February and March. This philosopher seems to have placed the subject in a fair way for satisfactory solution. He has advanced three hypotheses to account for the sudden disappearance of these bodies, the last of which he has enabled us to prove or disprove by actual observation.

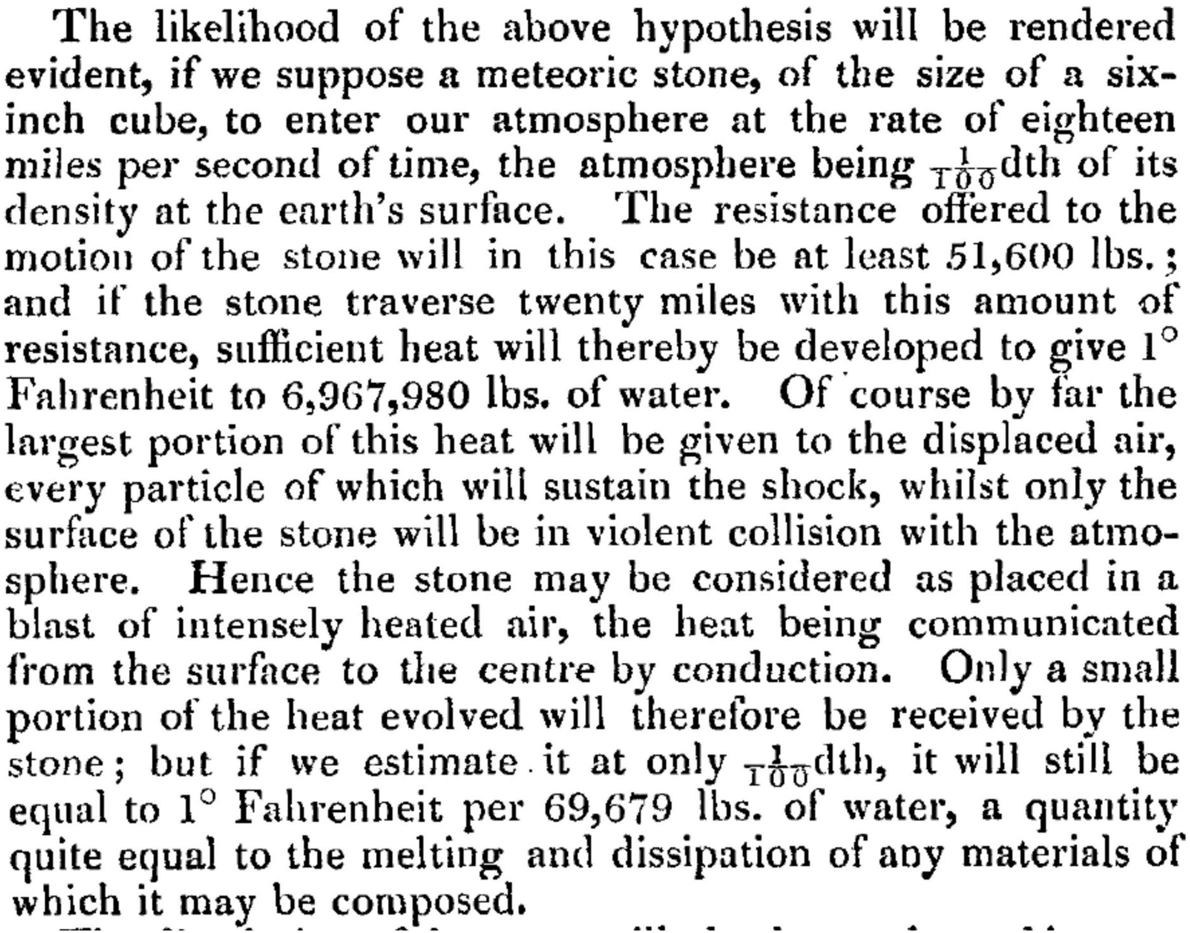
I have for a long time entertained an hypothesis with respect to shooting stars, similar to that advocated by Chladni to account for meteoric stones, and have reckoned the *ignition* of these miniature planetary bodies by their violent collision with our atmosphere, to be a remarkable illustration of the doctrine of the equivalency of heat to mechanical power or *vis viva*. In a popular lecture delivered in Manchester on the 28th of April 1847, I said, "You have, no doubt, frequently observed what are called *shooting stars*, as they appear to emerge from the

---

* Communicated by the Author.



dark sky of night, pursue a short and rapid course, burst, and are dissipated in shining fragments. From the velocity with which these bodies travel, there can be little doubt that they are small planets which, in the course of their revolution round the sun, are attracted and drawn to the earth. Reflect for a moment on the consequences which would ensue, if a hard meteoric stone were to strike the room in which we are assembled with a velocity sixty times as great as that of a cannon-ball. The dire effects of such a collision are effectually prevented by the atmosphere surrounding our globe, by which the velocity of the meteoric stone is checked, and its living force converted into heat, which at last becomes so intense as to melt the body and dissipate it in fragments too small probably to be noticed in their fall to the ground. Hence it is, that although multitudes of shooting stars appear every night, few meteoric stones have been found, those few corroborating the truth of our hypothesis by the marks of intense heat which they bear on their surfaces*."



The likelihood of the above hypothesis will be rendered evident, if we suppose a meteoric stone, of the size of a six-inch cube, to enter our atmosphere at the rate of eighteen miles per second of time, the atmosphere being $\frac{1}{100}$dth of its density at the earth's surface. The resistance offered to the motion of the stone will in this case be at least 51,600 lbs.; and if the stone traverse twenty miles with this amount of resistance, sufficient heat will thereby be developed to give 1° Fahrenheit to 6,967,980 lbs. of water. Of course by far the largest portion of this heat will be given to the displaced air, every particle of which will sustain the shock, whilst only the surface of the stone will be in violent collision with the atmosphere. Hence the stone may be considered as placed in a blast of intensely heated air, the heat being communicated from the surface to the centre by conduction. Only a small portion of the heat evolved will therefore be received by the stone; but if we estimate it at only $\frac{1}{100}$dth, it will still be equal to 1° Fahrenheit per 69,679 lbs. of water, a quantity quite equal to the melting and dissipation of any materials of which it may be composed.

3500 cm^3, 12.25 Kg

29km/s

32km altitude

223kN

7.37GJ

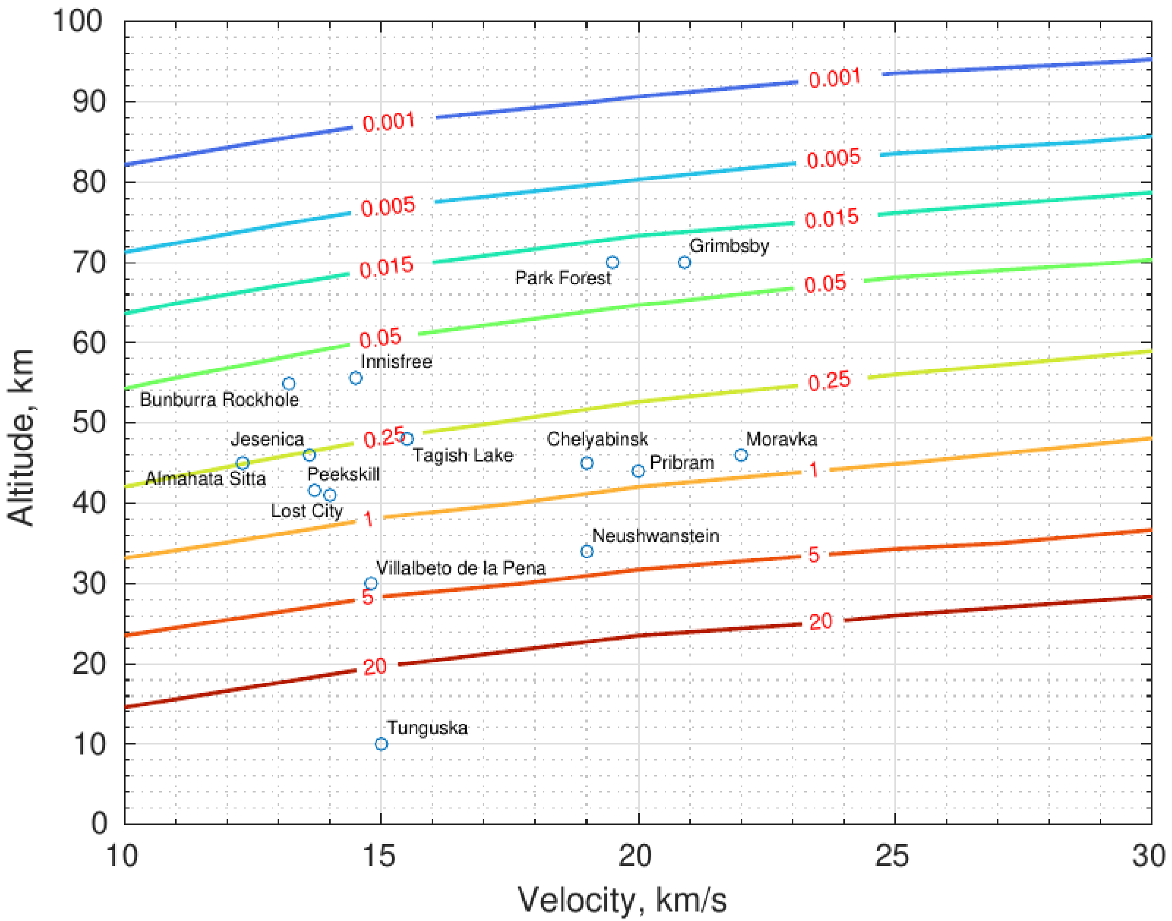
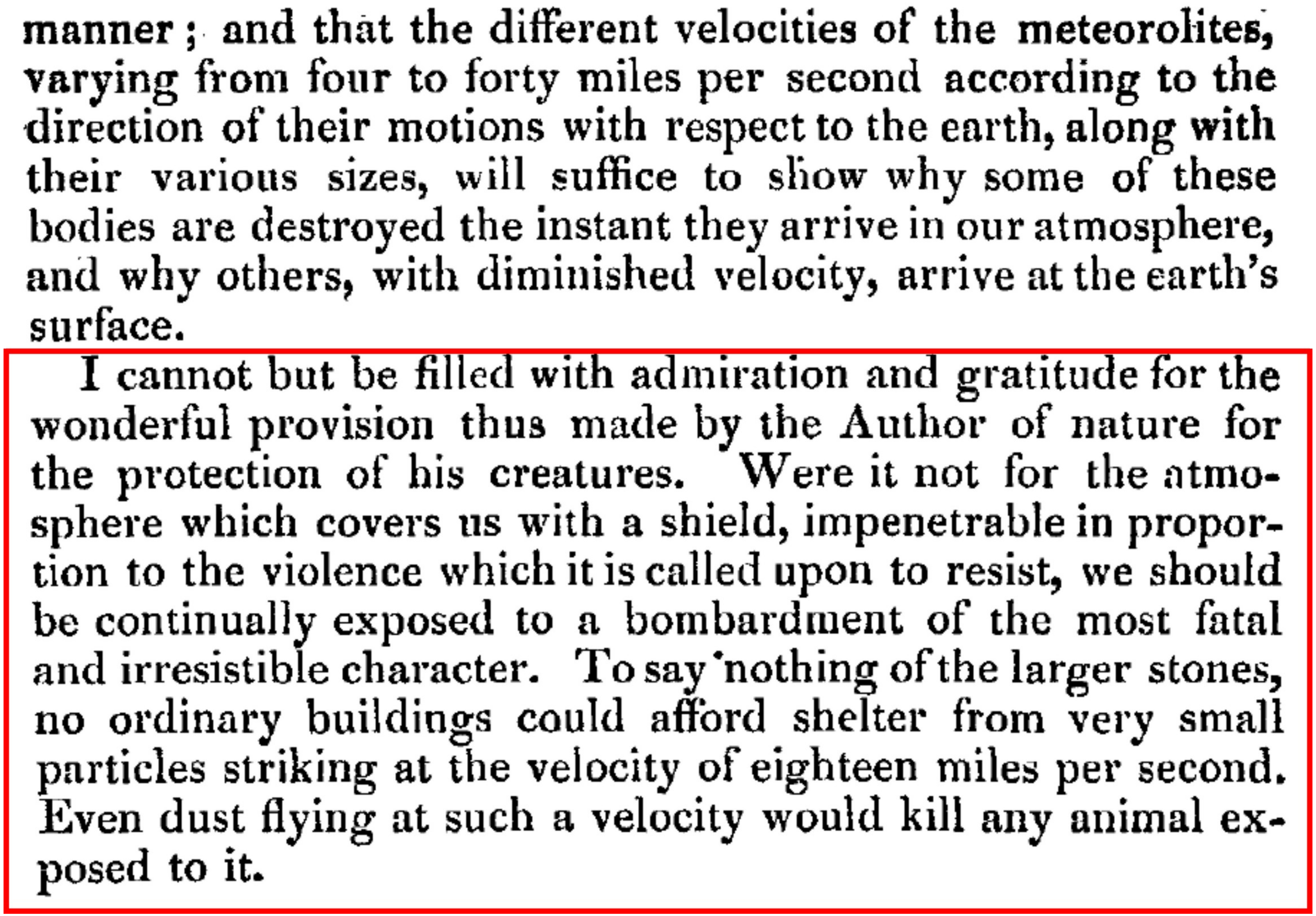


Figure 3.2: Meteoroids' points of fragmentation, with constant ram pressure curves plotted.

SPACE
BALLISTICS



manner; and that the different velocities of the meteorolites, varying from four to forty miles per second according to the direction of their motions with respect to the earth, along with their various sizes, will suffice to show why some of these bodies are destroyed the instant they arrive in our atmosphere, and why others, with diminished velocity, arrive at the earth's surface.

I cannot but be filled with admiration and gratitude for the wonderful provision thus made by the Author of nature for the protection of his creatures. Were it not for the atmosphere which covers us with a shield, impenetrable in proportion to the violence which it is called upon to resist, we should be continually exposed to a bombardment of the most fatal and irresistible character. To say nothing of the larger stones, no ordinary buildings could afford shelter from very small particles striking at the velocity of eighteen miles per second. Even dust flying at such a velocity would kill any animal exposed to it.