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Modeling of an Aerosol Capture Probe during Venus Atmospheric Entry

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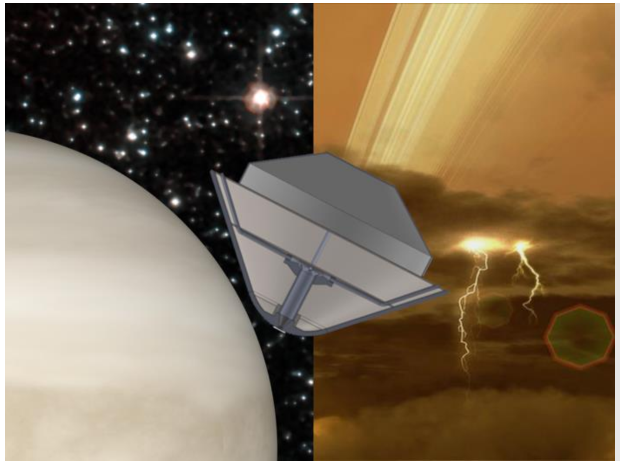
Introduction & Motivation

Aerosols are key to planetary science

- Surface chemistry and mass transportation processes.
- Heat, chemical, and kinetic energy transfer.
- Planetary climate evolution: green house effect, etc.
- Clouds expected on rocky planets with water.
- Many moons also have aerosols, and not just water!
- Difficult to study remotely (e.g., opacity).
- Highly dynamic in space and time.

A suite of modeling tools was developed at NASA Ames for the analysis of in-situ aerosol capture probes entering atmosphere using a single-body aeroshell.

Nephele[1] Venus mission concept as use case



Mission Objective:
Determine whether high molecular weight hydrocarbons are responsible for the UV absorption of Venus cloud aerosols.

Key Operational Objectives:

1. Demonstrate collection of atmospheric aerosols compatible with bulk and trace chemical analyses.

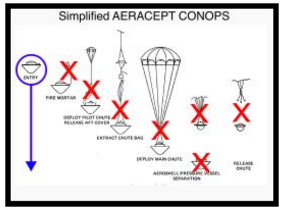
Key Science Objectives:

1. Inform what chemical and microphysical processes govern the clouds and hazes in Venus' atmosphere.
2. Extend knowledge of organic chemistry in non-Earth-like planetary environments, and its impact on habitability.

Combined entry and aerocapture probe technology

AERACEPT[2] fits in-situ aerosol science into small spacecraft.

AErosol
Rapid
Analysis
Combined
Entry
Probe/sonde
Technology

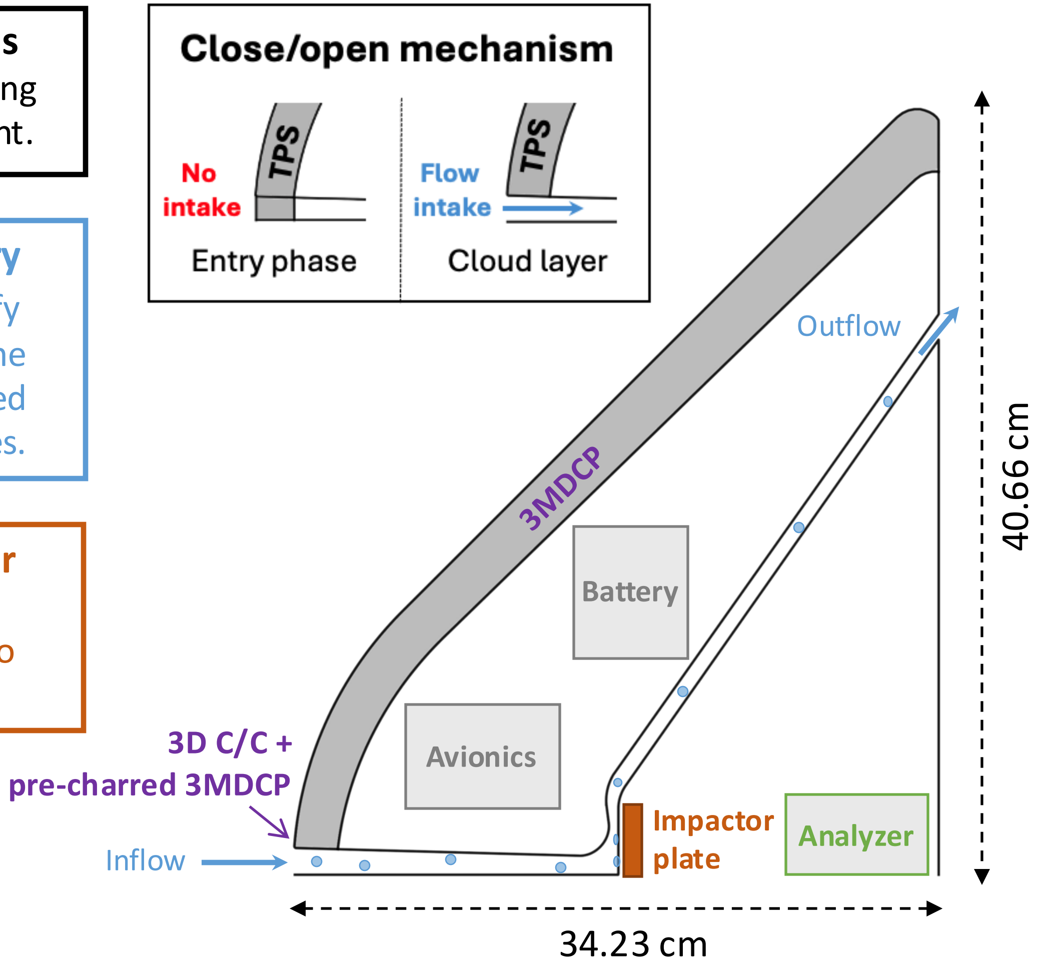


Embedded inlets aspire aerosols during atmospheric descent.

Internal geometry is designed to satisfy the collection volume requirements defined by science objectives.

Interior impactor capture aerosols and deliver them to optical analysis.

Gas and particle flow driven by probe descent.



TPS materials (3D C/C, 3MDCP)[3] allow rapid descent in small footprint, without parachutes or separation.

Compact optical analysis (LIBS, SERS, etc.)[4] can identify elements and molecules with cadence matching rapid descent speeds.

Aerosol capture efficiency depends on size, shape, and speed.

Venus atmospheric entry: Trajectory and Hypersonic CFD

Ballistic entry trajectory of the probe: *Traj*[5]

Probe mass [kg]	Altitude [km]	Entry angle [deg]	Velocity [km/s]
95	200	-10	11

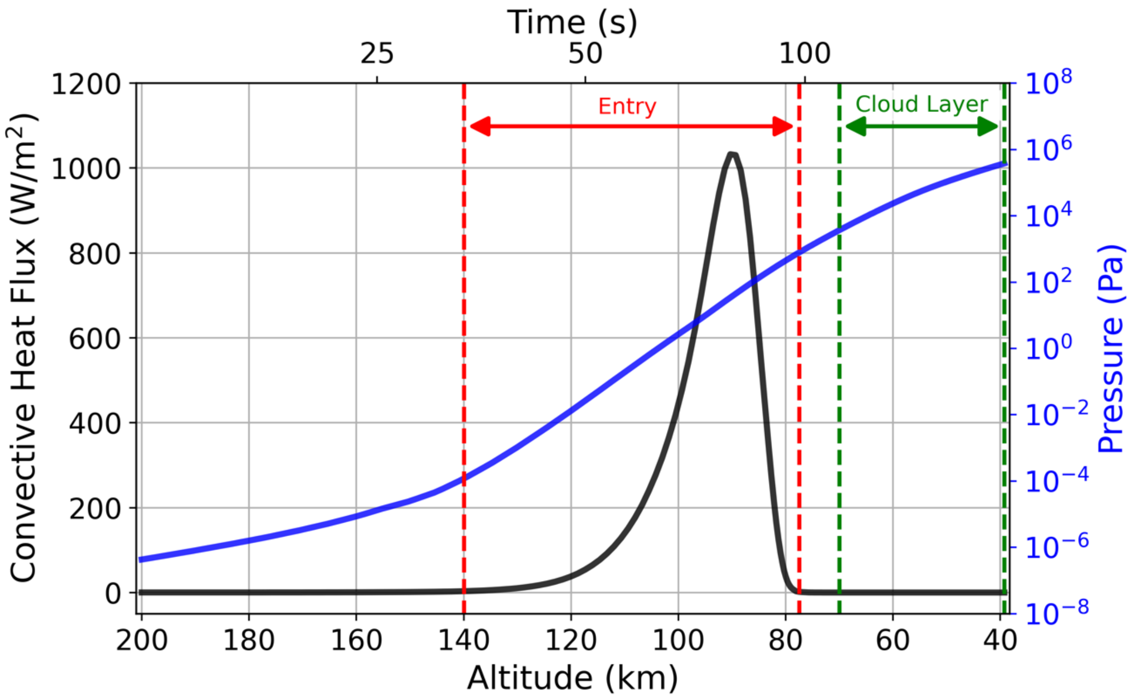


Fig. 1 Pressure & heat flux evolution at the stagnation point.

Aerothermal environment: *DPLR*[6]

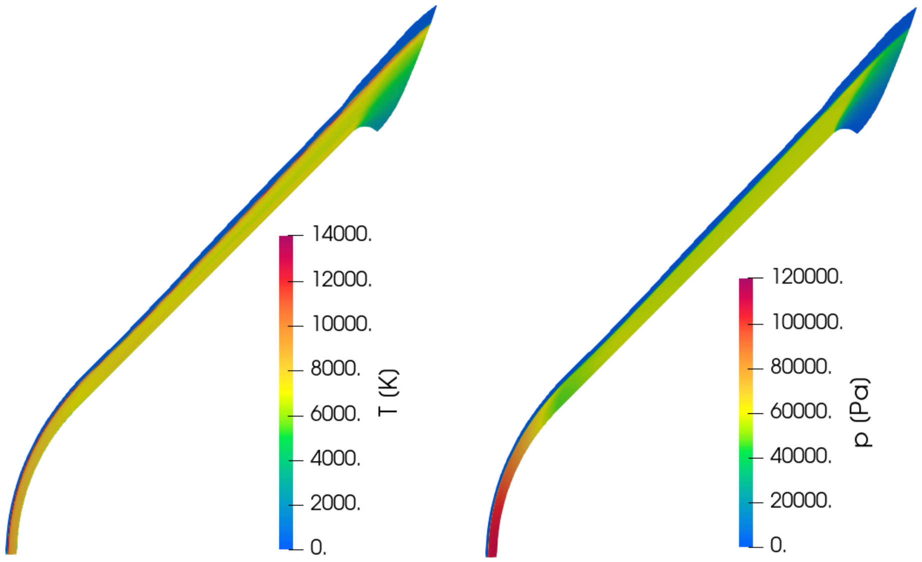


Fig. 2 Temperature and pressure at peak heating.

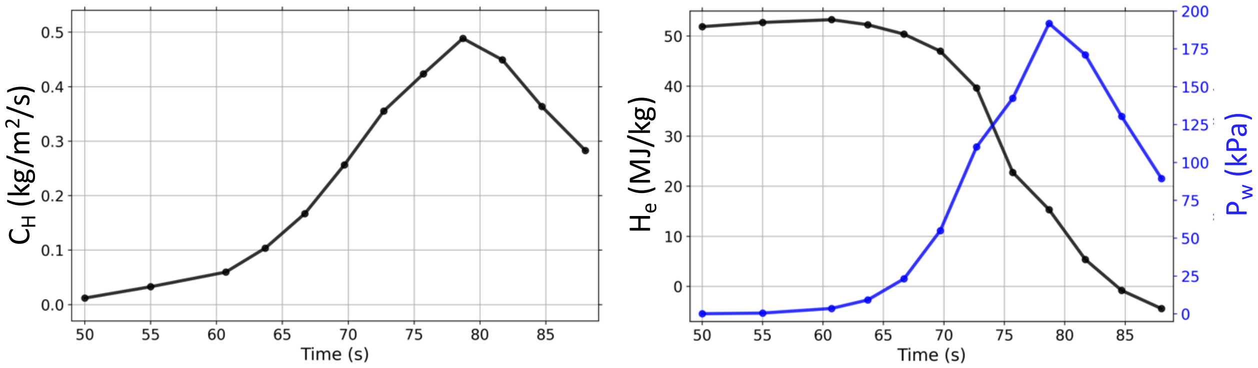


Fig. 3 Aerothermal environment at the heatshield front surface.

TPS thermal evolution: Material Response

TPS material thickness estimation: *FIAT*[7]

Nose 3D C/C	**Nose** pre-charred 3MDCP	**Flank** 3MDCP
3 mm	10.81 mm	13.81 mm

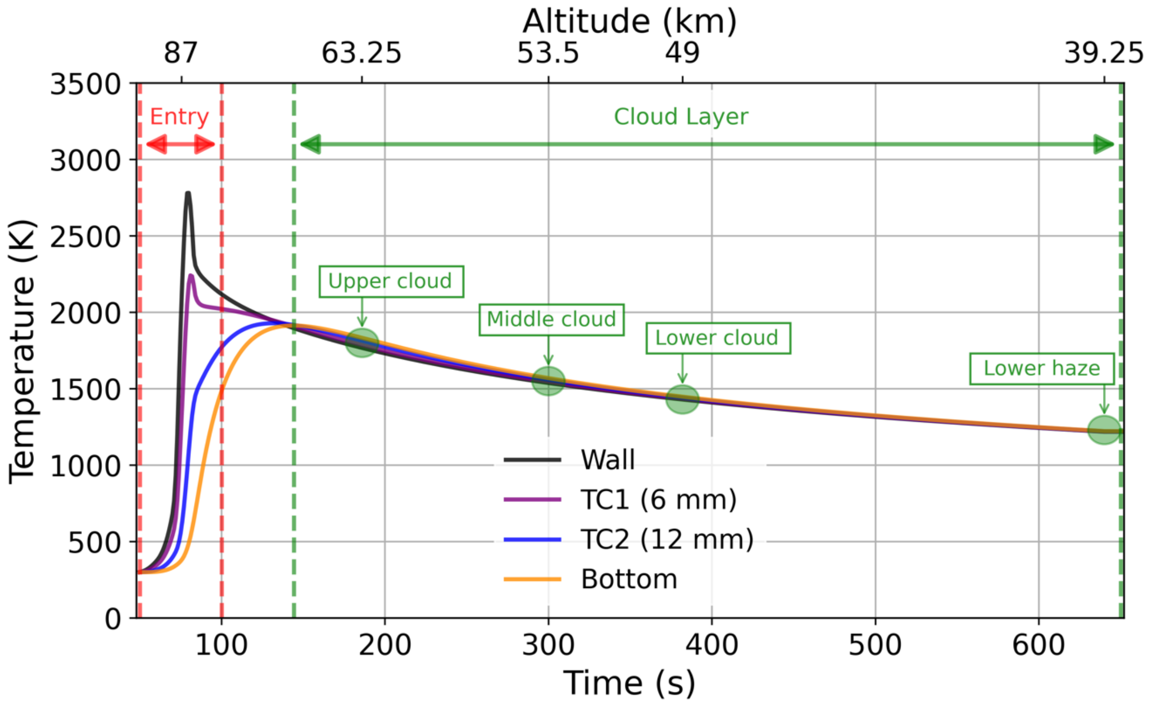


Fig. 1 Temperature evolution at the stagnation point.

TPS material temperature and recession: *PATO*[8]

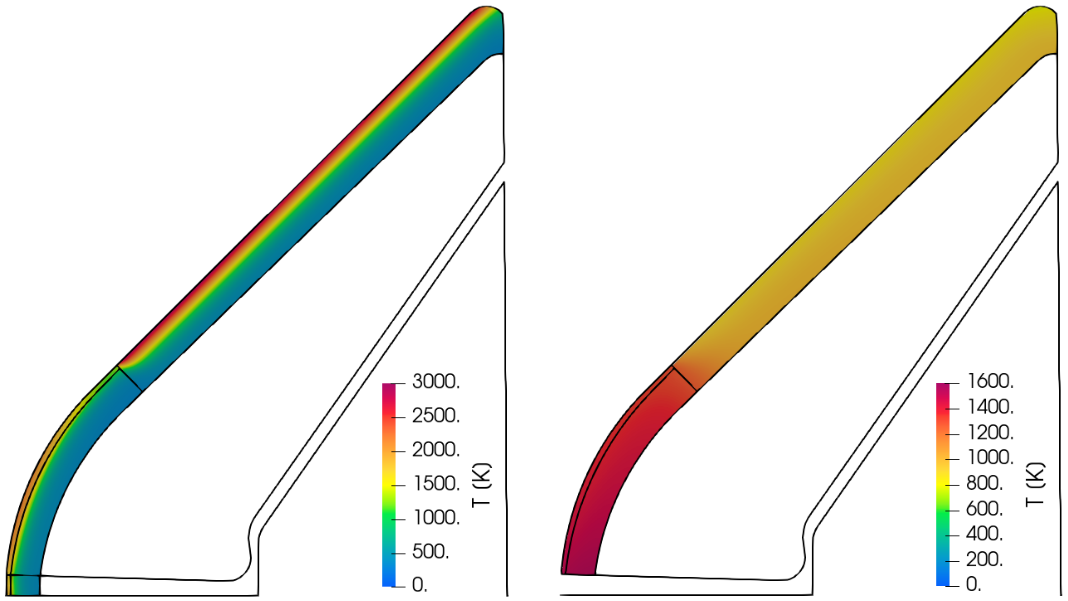


Fig. 2 In-depth temperature at 89.6 km (left) and 63.25 km (right).

Region Name	Upper Cloud	Middle Cloud	Lower Cloud	Lower Haze
h [km]	63.25	53.5	49.0	39.25

Flow dynamics in the cloud layer: Subsonic CFD

Internal and external flow fields estimation: *rhoPimpleFoam* from *OpenFOAM*[9]

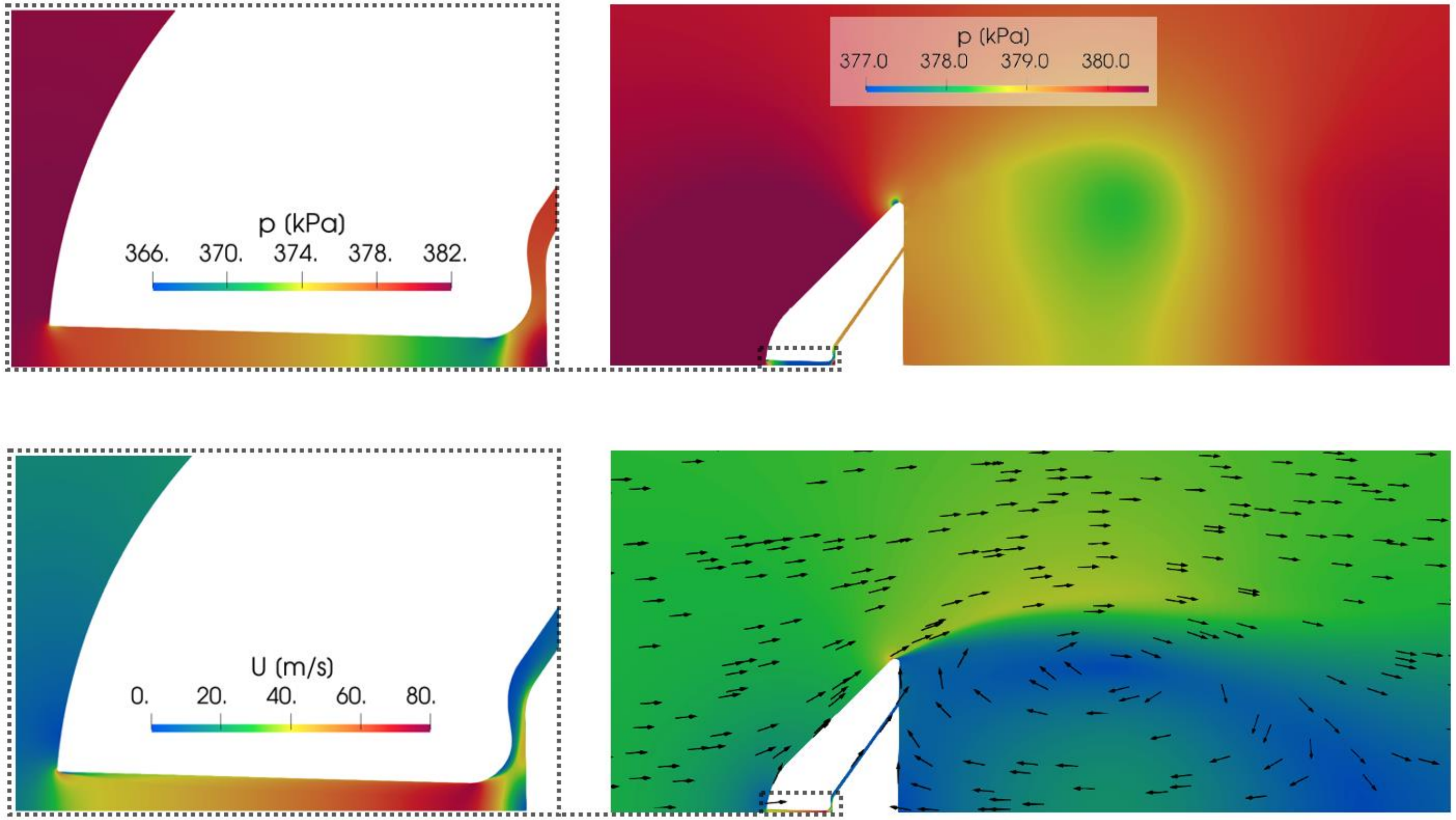


Fig. 1 Pressure (top) and velocity (bottom) fields in the lower haze (39.25 km).

h [km]	$\mathbf{d_p}$ [μm] 50% **aspiration** efficiency	$\mathbf{d_p}$ [μm] 50% **capture** efficiency
63.25	1.8	4.8
53.50	2.2	7.0
49.00	2.5	7.8
39.25	3.6	11.1

$$Stk = \frac{C_c\,\rho_p\,(d_p)^2\,|\boldsymbol{v}_g|}{18\,\mu_g\,d_{in}} \qquad d_p = \sqrt{\frac{Stk\;18\,\mu_g\,d_{in}}{C_c\,\rho_p\,|\boldsymbol{v}_g|}}$$

A compromise is needed during the internal geometry design: particles should be directed into the probe (low Stk) while retaining sufficient inertia to impact the plate (high Stk).

Collected sample quantification: Particle Tracking

Accumulated volume & aspiration/capture efficiencies: *denseParticleFoam* from *OpenFOAM*[9]

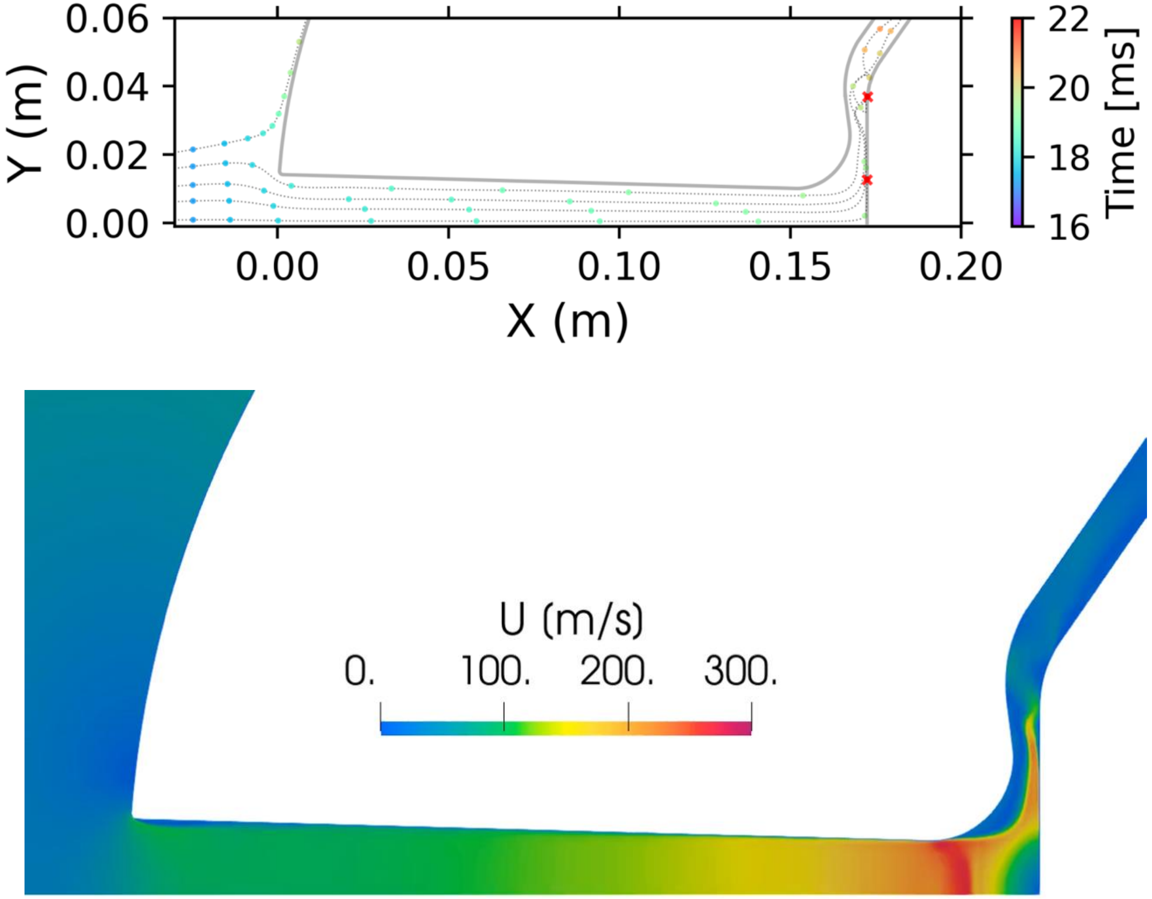
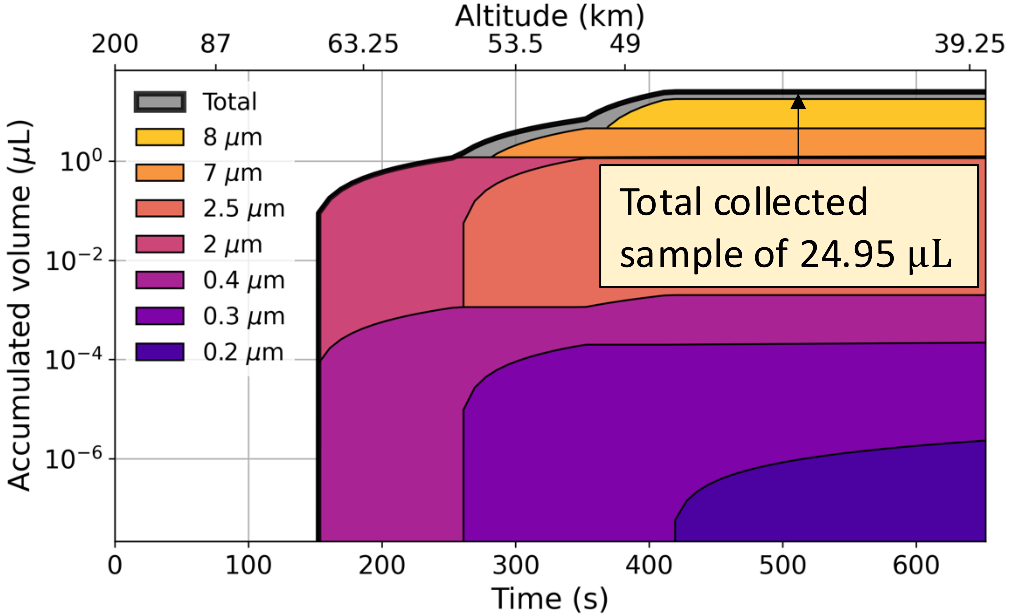


Fig. 1 Tracking of 0.4µm-diameter particles at 63.25 km.

h [km]	63.25		53.5			49			39.25		
d_p [µm]	0.4	2	0.3	2.5	7	0.4	2	8	0.2	0.3	2
η_{in} [%]	4.88	5.01	5.83	5.94	5.4	6.1	6.2	5.7	5.6	5.6	5.6
η_p [%]	0.04	100	1.72	100	100	1.5	6.7	100	0.9	0.9	1.8



Total collected sample of 24.95 µL

Fig. 2 Accumulated volume of collected particles at the impactor.

Collected sample integrity: Thermal Analysis

Particle temperature estimation: *rhoPimpleFoam*[9] and PATO[8]

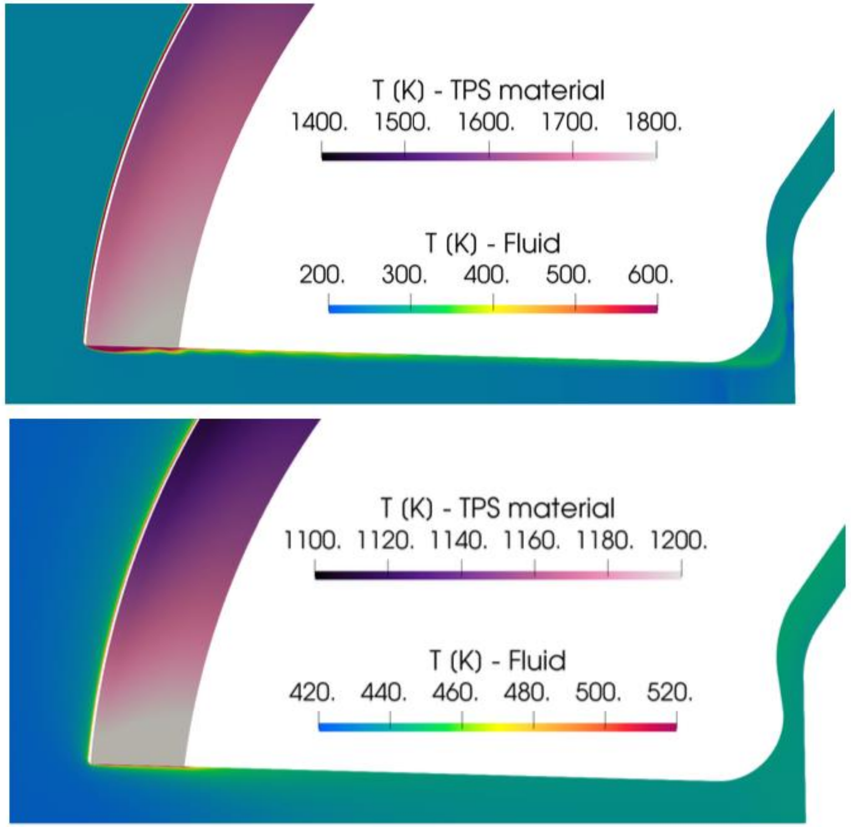
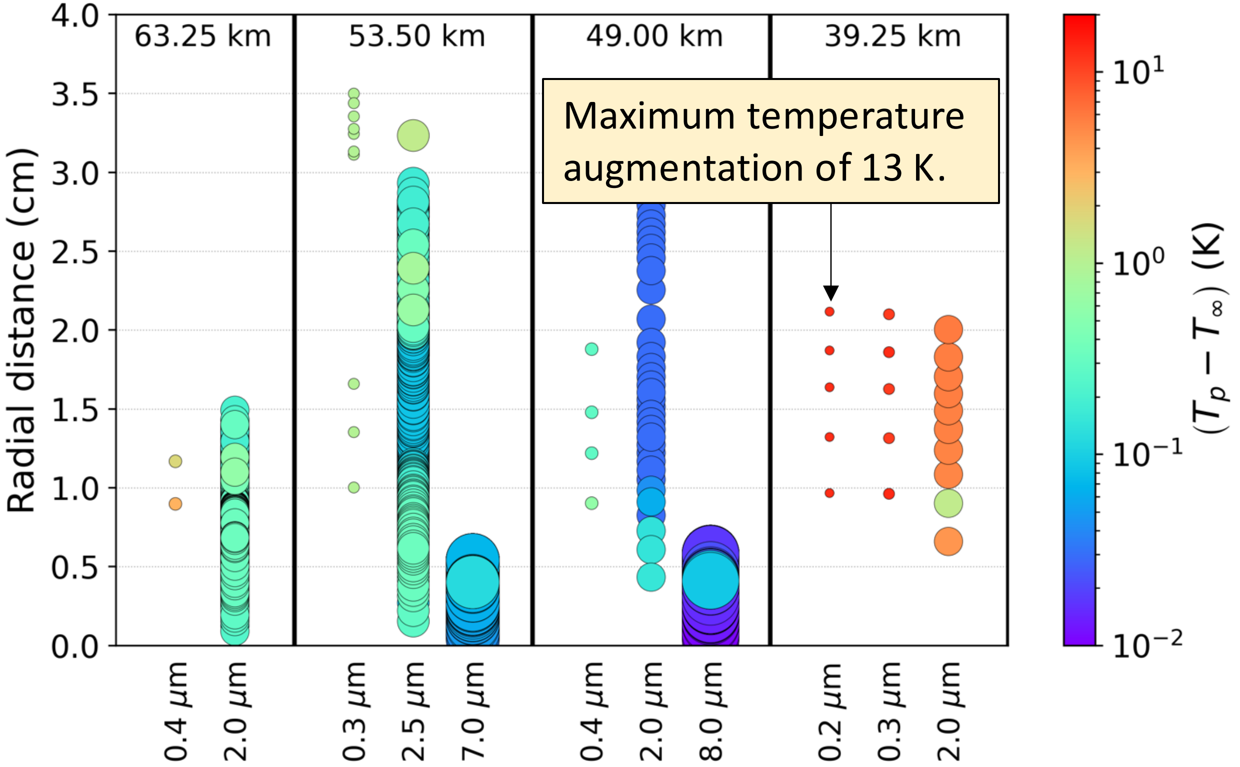


Fig. 1 TPS thermal response and gas temperature in the Venus cloud layer at 63.25 km (top) and 39.25 km (bottom) using a TPS wall thermal BC.

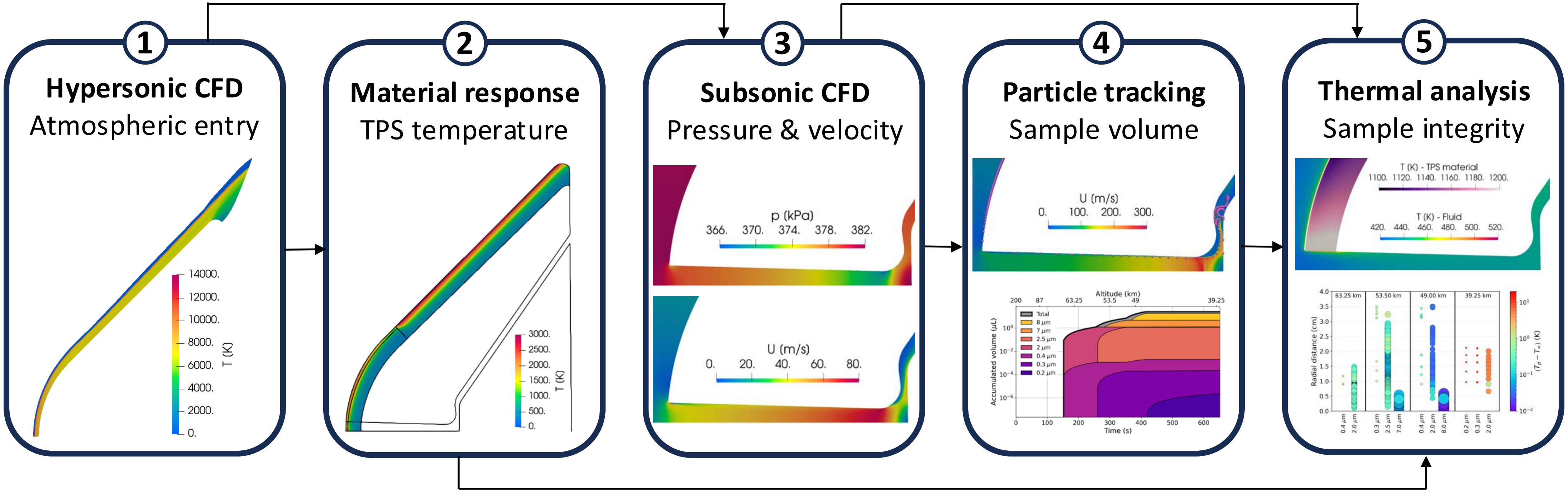


Maximum temperature augmentation of 13 K.

Fig. 2 Maximum temperature augmentation of the collected particles as a function of the radial distance from the impactor plate.

Conclusion & Future work

A comprehensive suite of computational tools designed to analyze aerosol chemistry within the framework of fast descent and rapid analysis using single-body planetary probes.



1 **Hypersonic CFD**
Atmospheric entry

2 **Material response**
TPS temperature

3 **Subsonic CFD**
Pressure & velocity

4 **Particle tracking**
Sample volume

5 **Thermal analysis**
Sample integrity

These tools predict sample degradation and quantify particle collection. They enable optimizations for future interplanetary missions aimed at collecting aerosol samples, ultimately enriching our understanding of their influence on planetary environments.

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Questions?

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[9] Weller, Henry G., et al. "A tensorial approach to computational continuum mechanics using object-oriented techniques." Computers in physics 12.6 (1998): 620-631.