Atmospheric Entry Studies for Uranus

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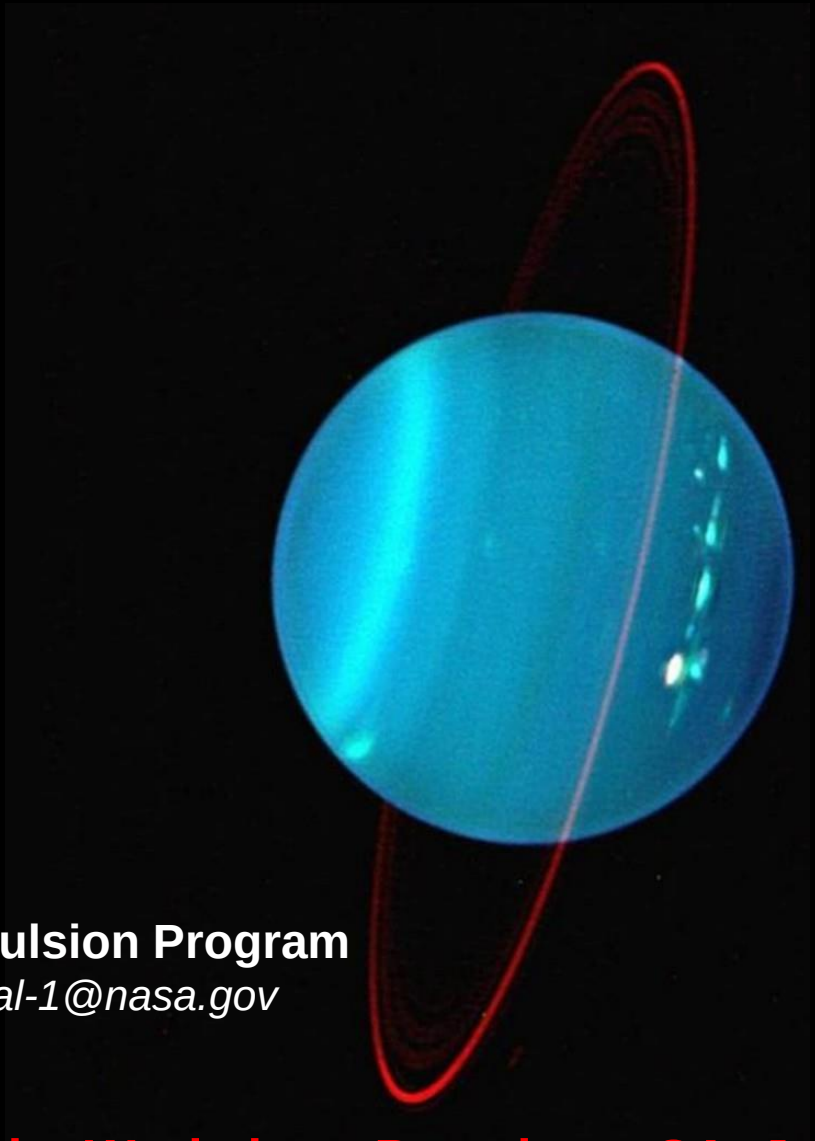

Funded by NASA In-Space Propulsion Program

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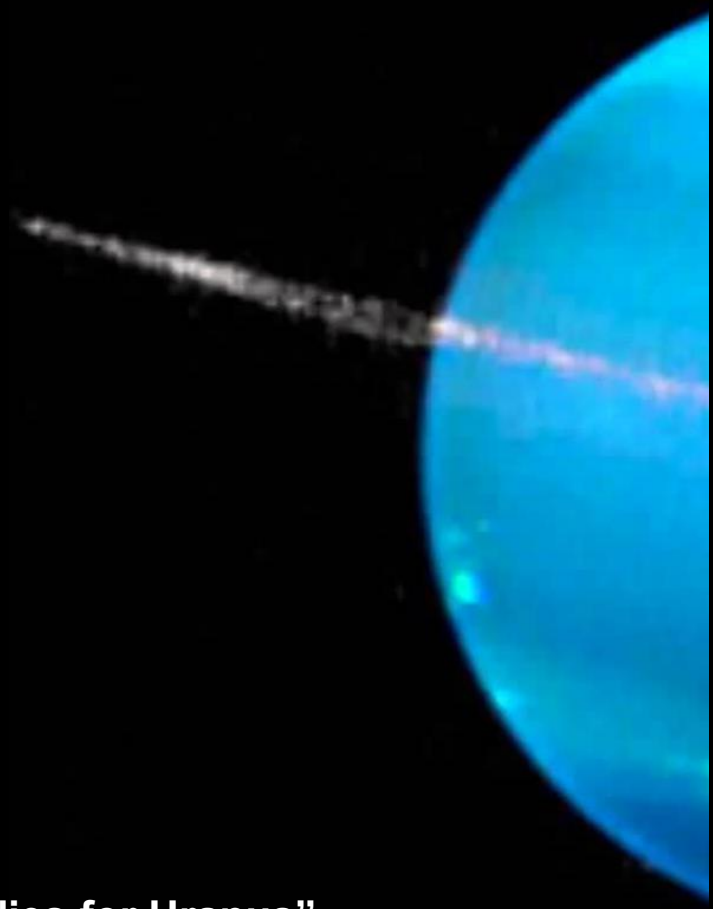
Outline

- **Background**
  - Orbital Mechanics
  - Atmosphere
- **Direct Ballistic Entry**
- **Aerocapture Entry**
- **Conclusions & Recommendations**

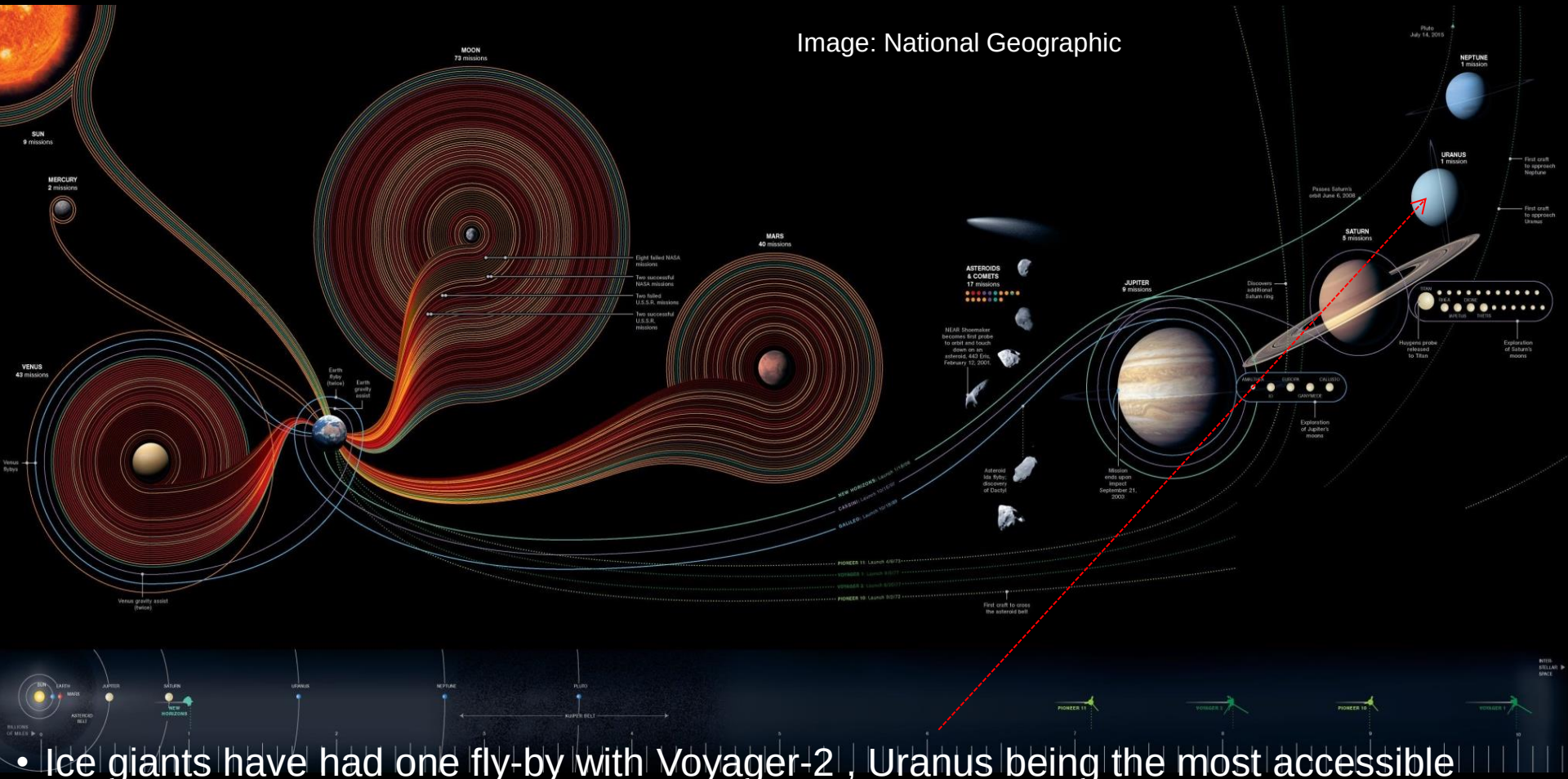


Reference: Agrawal et. al., "Atmospheric Entry Studies for Uranus" 2014 IEEE Aerospace conference, Big Sky Montana.

Background

- **Funded by NASA's Science Mission Directorate** (SMD)
  - **In-Space Propulsion Technology** (ISPT) program
    - **Entry Vehicle Technology** (EVT) project
- **Analyzed mission concepts outlined in the 2013-23 Planetary Science Decadal Survey with a focus on Venus, Saturn and Uranus**
- **Concept studies to understand trade space for atmospheric entry**
- **Goal: support future Flagship and New Frontier mission designs**

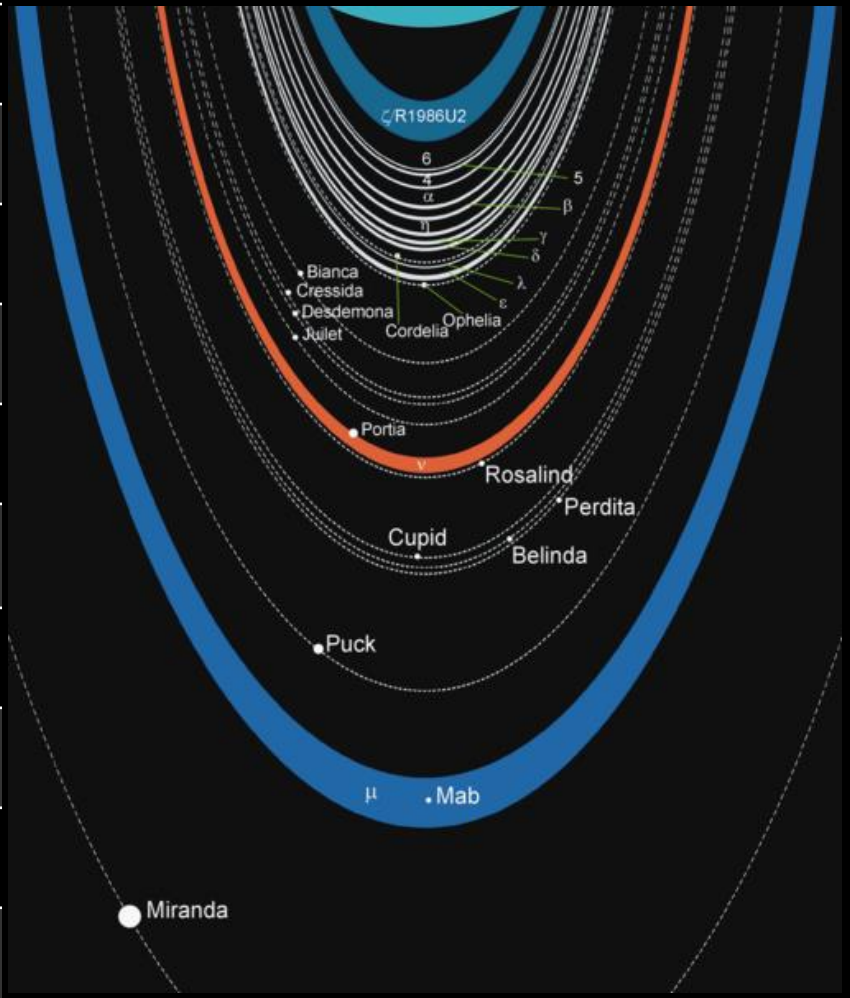
Motivation



- Ice giants have had one fly-by with Voyager-2 , Uranus being the most accessible
- Kepler and microlensing suggest ice giants may be Galaxy's most common class of planet
- Entry probe provides context for direct imaging detections by ground and space based coronagraphs and transit observations

Uranus Facts → Constraints

Semi-major axis	**2,876,679,082 km (19.2 AU)**
Orbital Period	84.323 earth year
Equatorial Radius	25,559 km (4x earth)
Polar Radius	24,973 km (3.9x earth)
Mass	8.68 10^{25} kg (14.536 earth)
Equatorial Surface Gravity	8.69 m/s (0.886g)
Escape Velocity	21.3 km/s
Axial tilt	97.77 deg
Moons	27
Composition (below 1.3 bar)	Hydrogen, Helium, Methane



The trajectories were selected such that rings could be avoided.

Ring Location

38,000 (or cloudtop) to 52,000 km

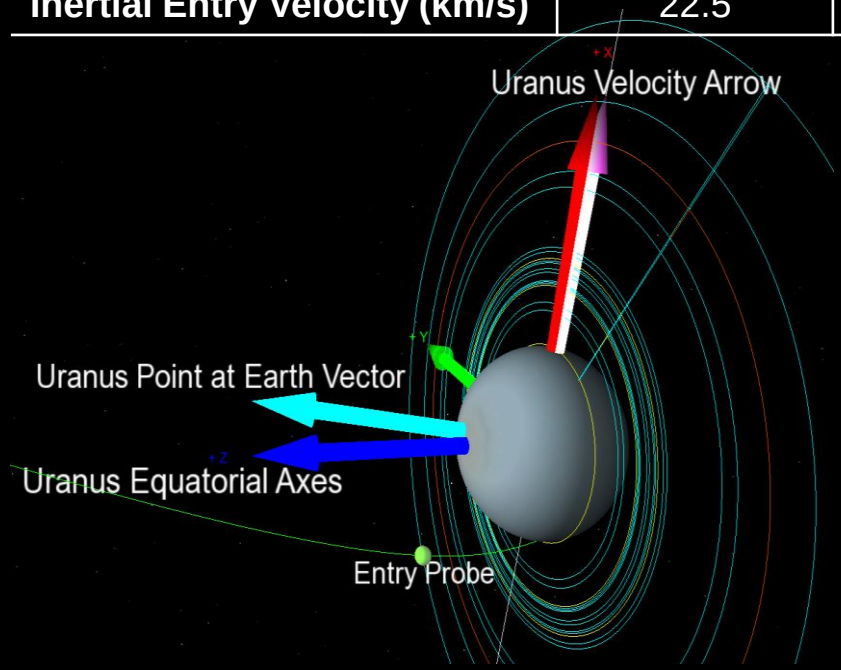
67,000 +/- 2,000 km

90,000 +/- 9,000 km

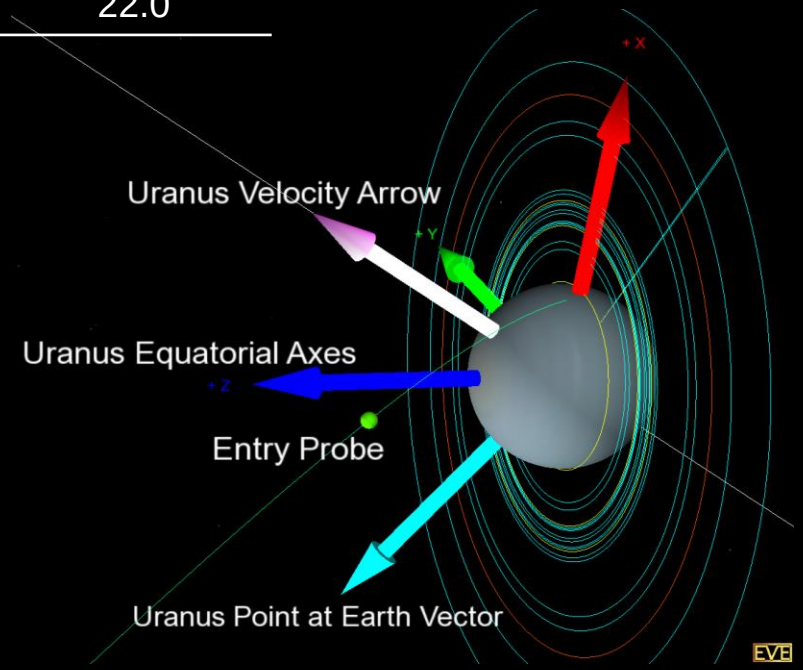
Trajectory Design

	Trajectory 1	Trajectory 2
Launch Date	2021 Apr 30	2034 Jun 12
Time of Flight (years)	8.0	8.8
Arrival Date	2029 Apr 28	2043 Mar 17
V_∞ (km/s)	10.0	8.7
Target Radius (km)	28,467	28,475
Longitude E (deg)	6.3	164.5
Centric Latitude N (deg)	8.7	27.7
Inertial Entry Velocity (km/s)	22.5	22.0

- **Earth-Jupiter-Uranus Chemical Trajectory**
- **Trajectories selected to avoid rings**



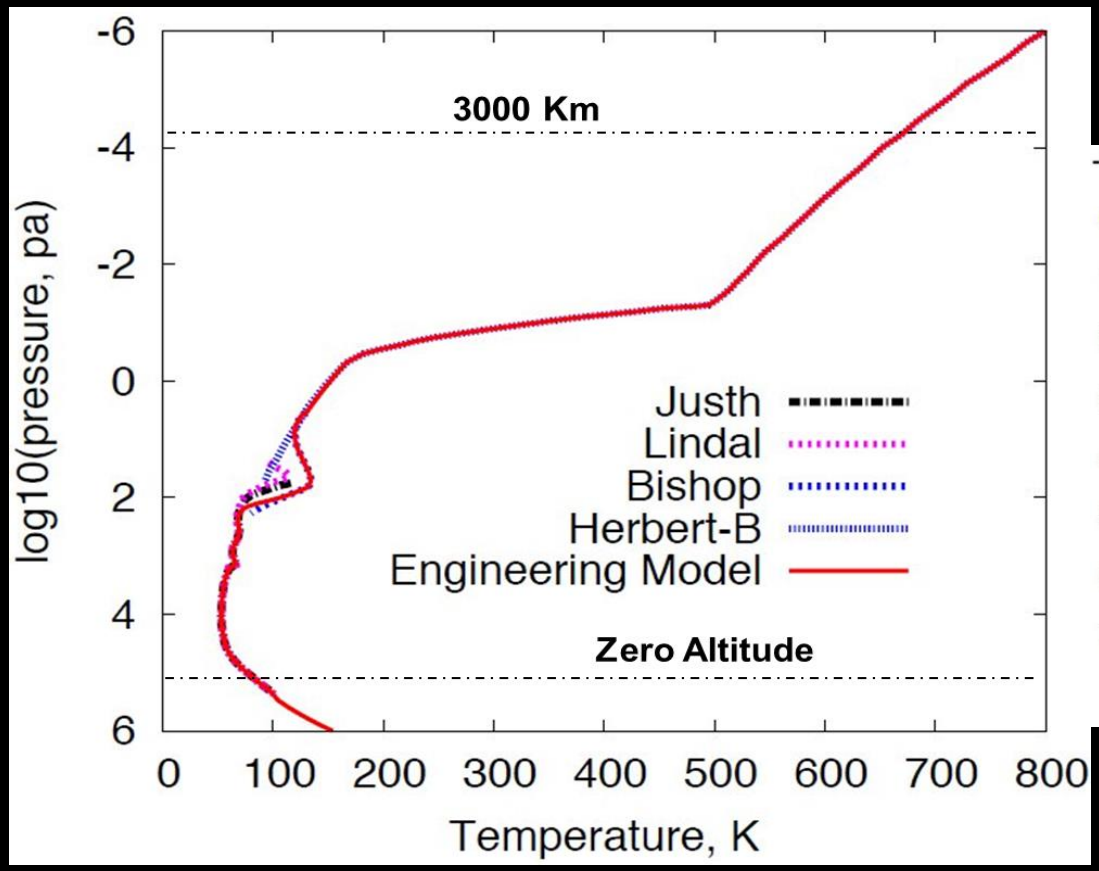
Trajectory 1: 2029 Arrival

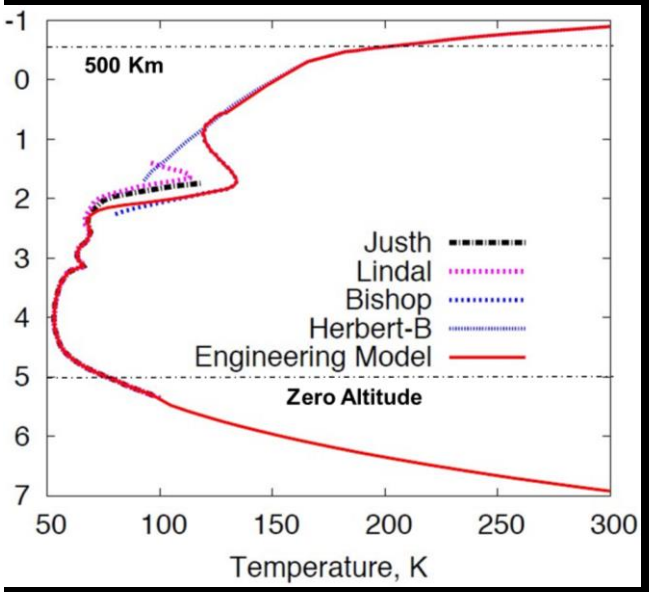


Trajectory 2: 2043 Arrival

Uranus Atmosphere

- Team conducted extensive literature survey but unable to find a unified model that span pressures between 10^{-11} bar to 100 bar
- Composite *Engineering Model* ranged from below zero to 5000 km was created by stitching existing Uranus atmospheric models
- Significant seasonal change in atmosphere not considered

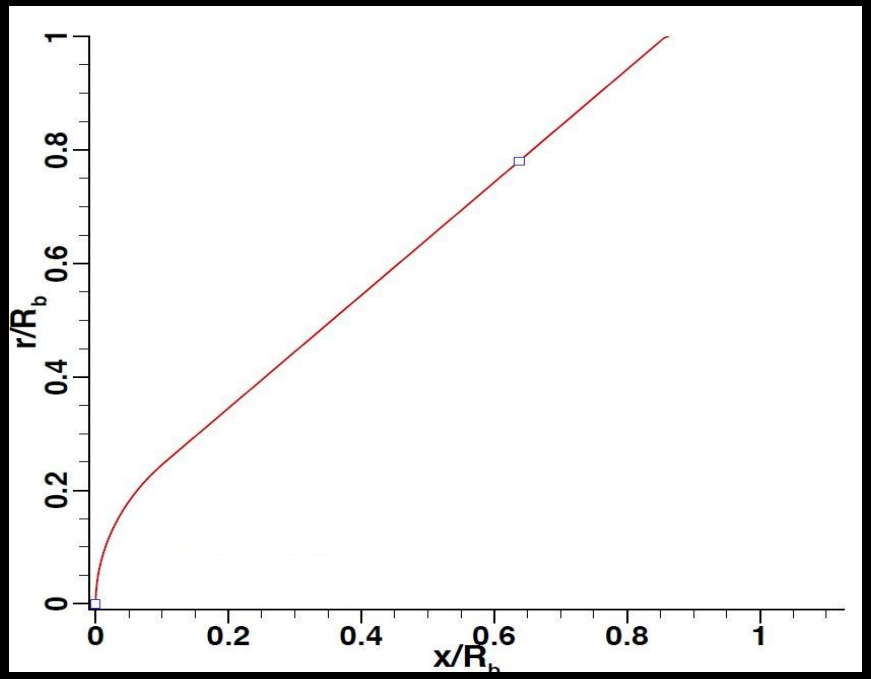


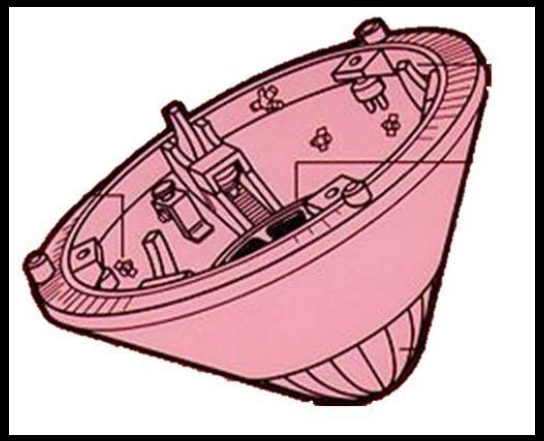


Direct Entry: Vehicle Analysis

Vehicle assumptions

- Galileo Probe scaled for parametric studies
- Half angle: 45^0
- Nose radius / Base radius: 0.351
- Tauber aerodynamic model
- Tauber convective and radiative heat flux model
- TPS initial temperature: 197.5 K
- Bond line failure temperature: 523.2 K





Entry Trajectory Space

Trades performed varying Entry Flight Path Angle EFPA (γ_E) for various ballistic coefficients (β_E).

$$\beta_E = \frac{4m_E}{C_D \pi D_b^2}$$

m_E = Entry mass

D_b = Base diameter

C_D = Hypersonic drag coefficient

β_E MATRIX

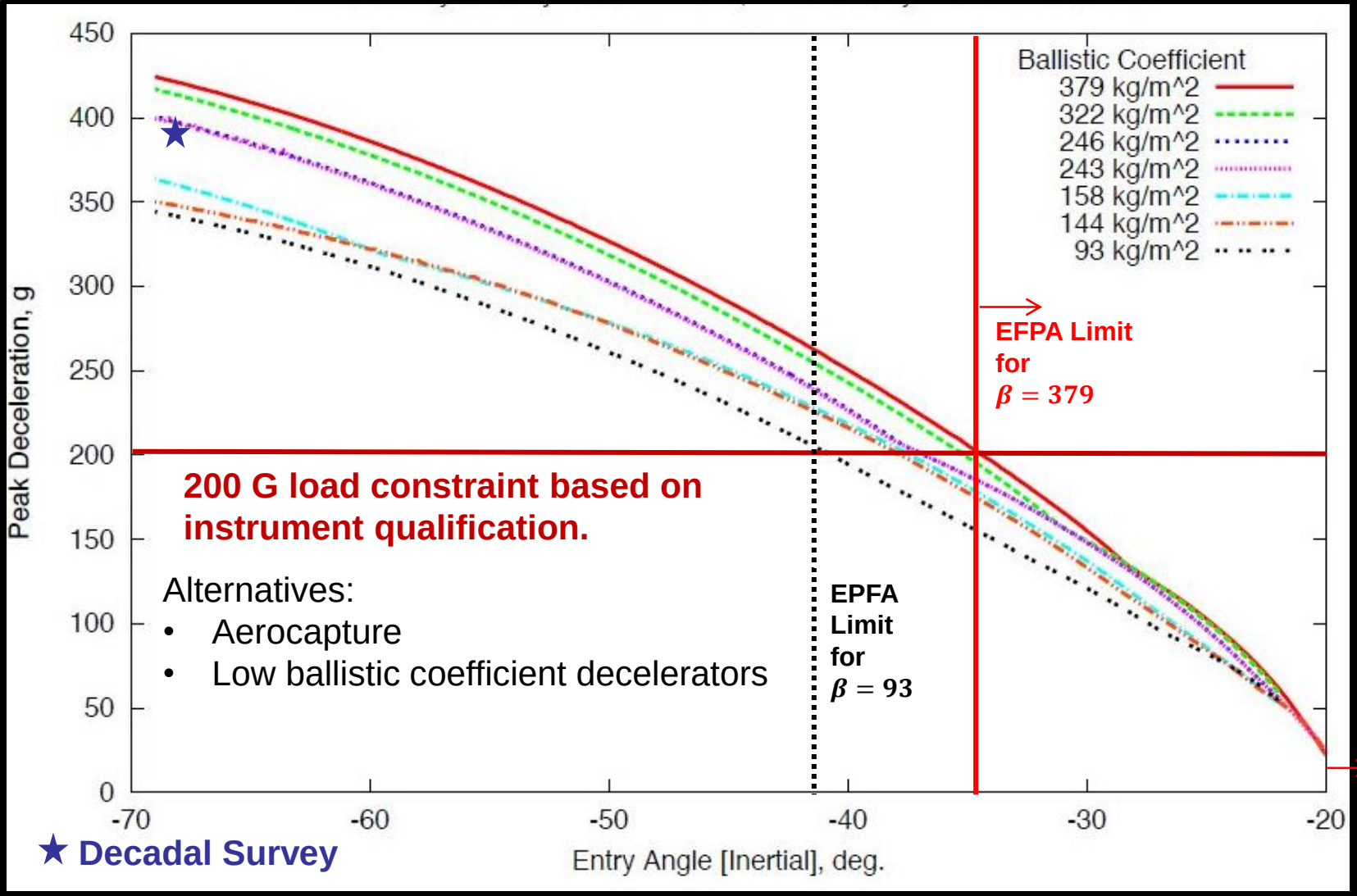
Mass (kg)	Base Diameter (m)			
	0.7	0.8	1	1.3
50	124	95	61	36
130	322	246*	158	93
200	495	379	243	144
300	743	569	364	215

Values exceed existing technology | Values used in current analysis | Values exceed recommended limits

* used in current Decadal Survey

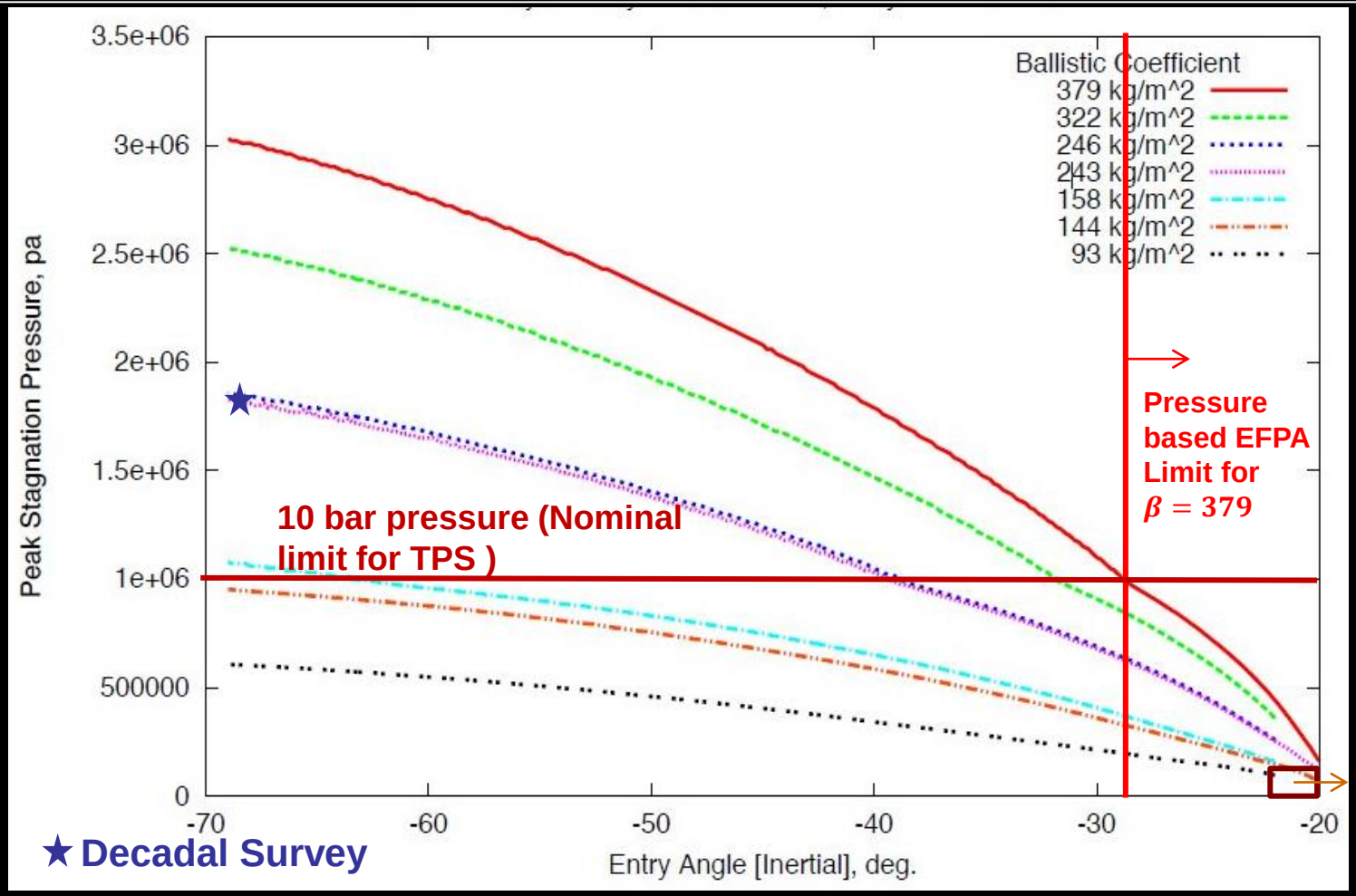
- **β_E matrix derived from Galileo and Pioneer Venus small probe**
- **Bigger / heavier probes with larger suite of instruments**
- **1000s of trajectories were generated by varying the EFPA**

Deceleration Loads vs. EFPA



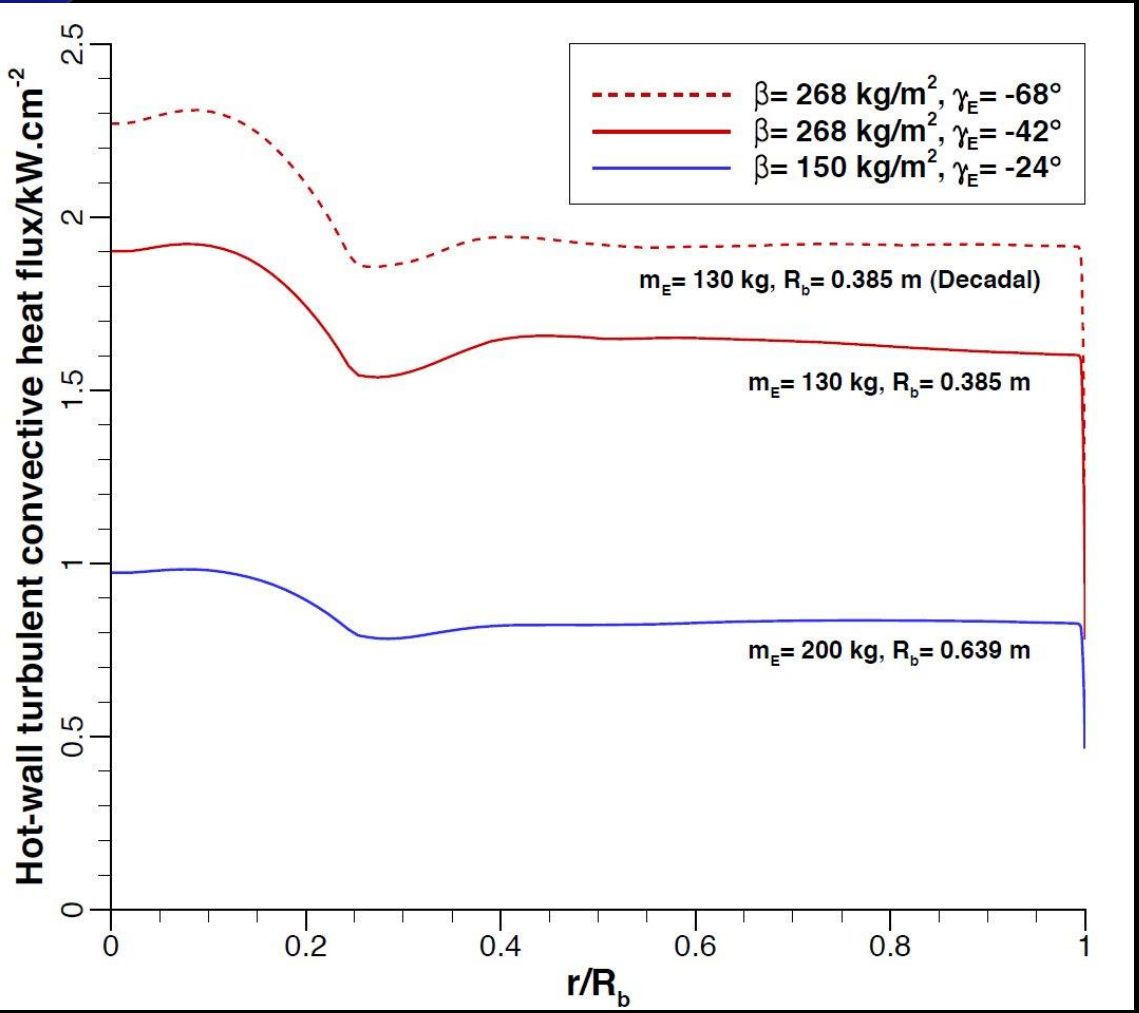
- **The deceleration loads constrains the upper end of suitable γ_E for direct ballistic entry.**
- **The highest $\gamma_E = -41° \; for \; \beta_E$= 93 and $\gamma_E = -34° \; for \; \beta_E$= 379**

Stagnation Pressure vs. EFPA



- Spallation is observed in carbon phenolic when exposed to pressure > 10 bar .
- For β_E > 150 Kg/m^2 the pressure increases very rapidly for steeper entry.
- This further constrains the γ_E for vehicles with higher β_E.
- Low density TPS like PICA have a very small operating space.

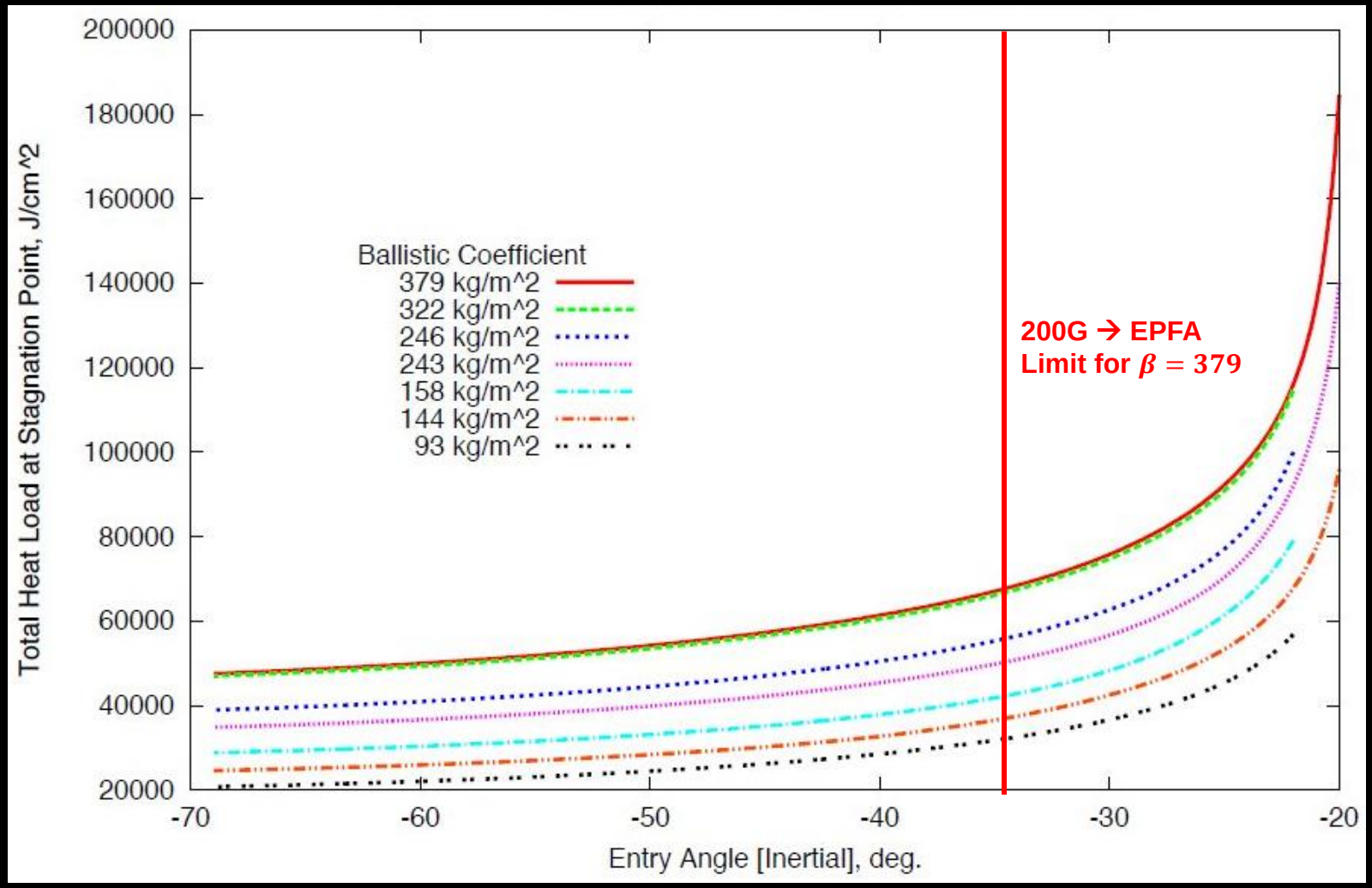
Bounding Hot-Wall Heat Fluxes (CFD Predictions)



- High-fidelity flow simulations using the CFD software *DPLR*
- The shock layer is assumed to be in thermal equilibrium, due to high pressure
  $T_{rot} = T_{vib} = T_{trans} = T_{elec.}$
- The gas mixture at the wall is assumed to be in thermodynamic equilibrium due to high pressure

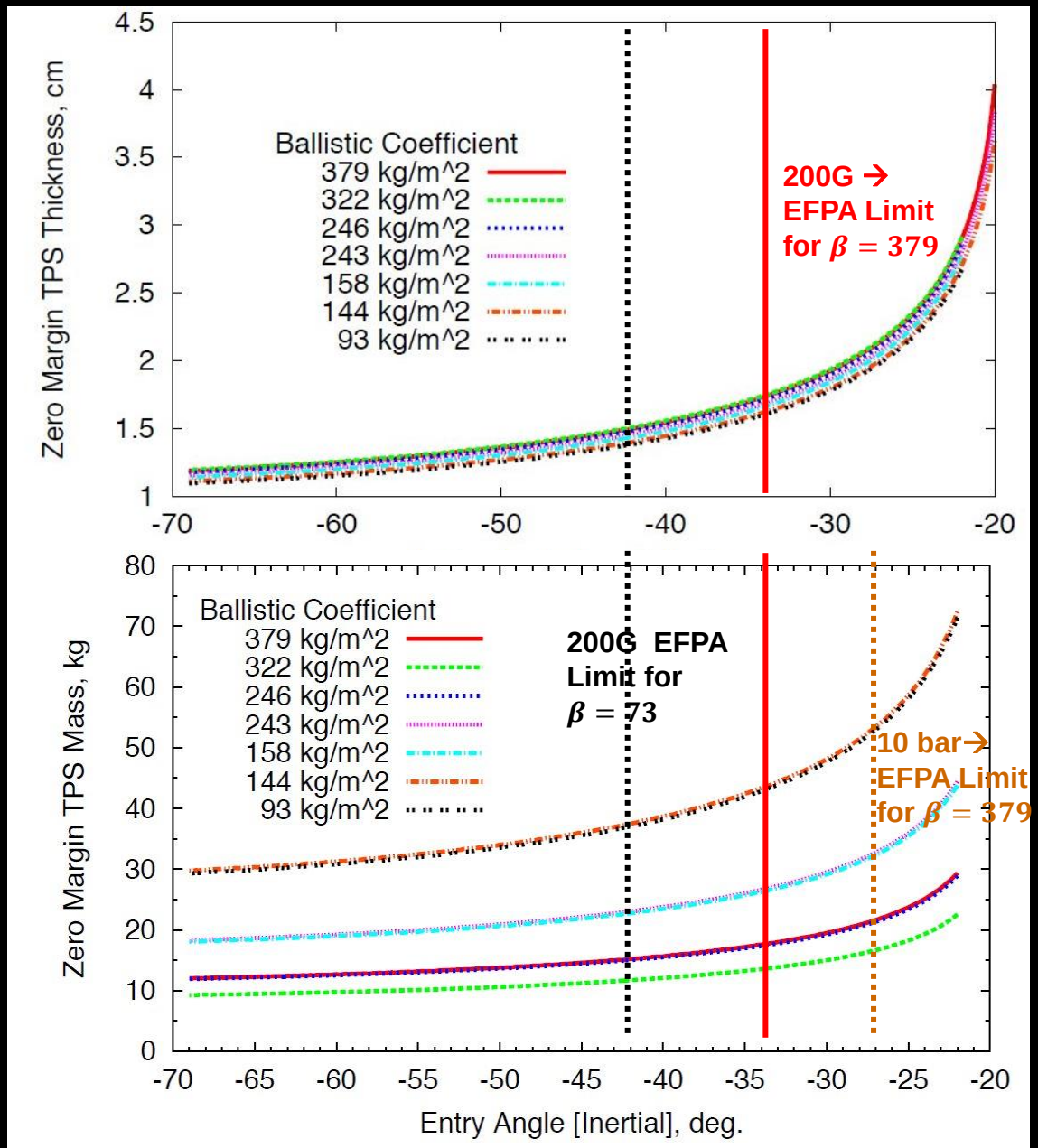
- **For Uranus the convective heating dominates and heating due to radiation is insignificant.**
- **The heating environments are benign compared to Jupiter or Venus**

Total Heat-load vs. EFPA



The total heat-load increases very rapidly for entries that are shallower than -24 deg. For higher ballistic coefficients the increase is significantly higher.

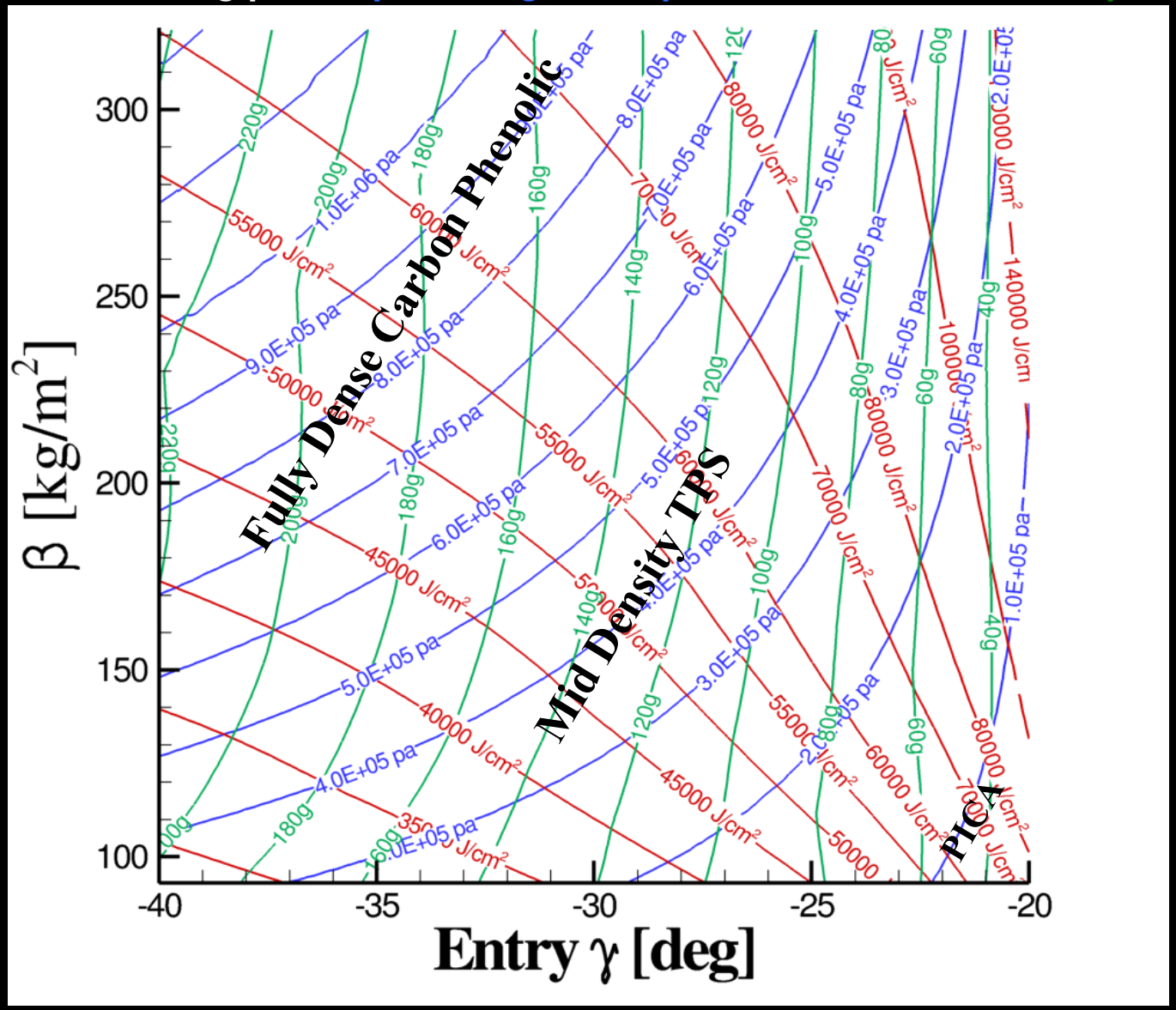
Carbon Phenolic TPS Sizing (No Margin)



- **Calculations show thickness of 1.5 - 3.0 cm** (un-margined)
  - With a 30% margin the thickness will be in the range of 2.0 - 4.0cm
- **Higher ballistic coefficients show more effective use of CP**
- **However the pressure rises rapidly with high ballistic coefficient so the EFPA window becomes very narrow.**

Entry Trade Space

For 130 kg probe: peak stagnation pressure, total heat load, peak deceleration load



Carbon phenolic suitable for many extreme entry conditions

Woven TPS, with its tailorable characteristics, suggests robustness and mass efficiency for many high heat flux conditions

Standard PICA could be useful for limited entry windows

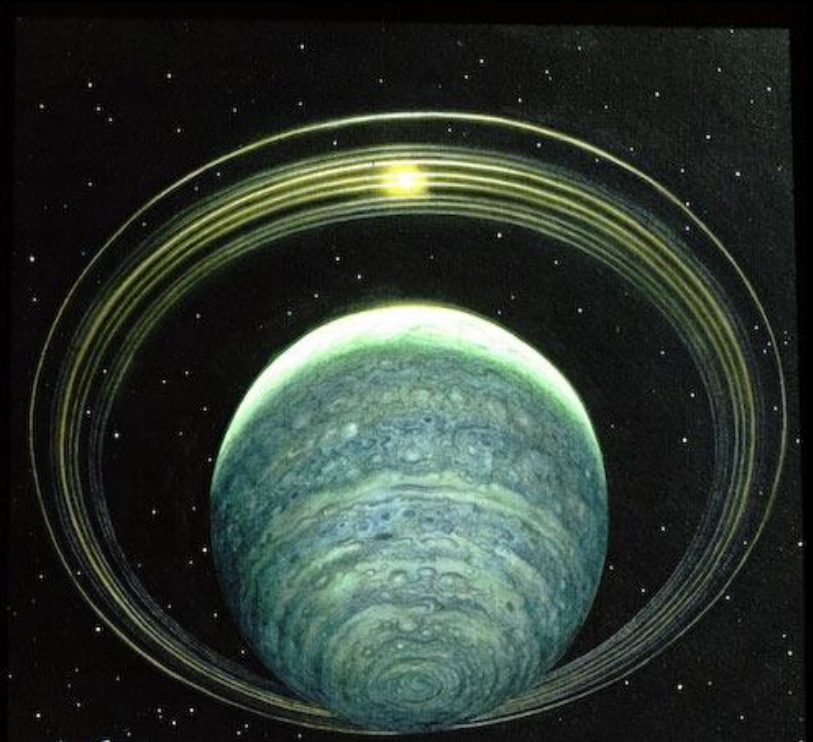
Advanced PICA is TBD

Ballistic Entry Summary

- **Deceleration and pressure load constraint → upper end of the EFPA**
  - Not ideal for data communication
- **Convective heating dominates, heating due to radiation is insignificant**
  - The environments are benign compared to Jupiter or Venus
- **Carbon Phenolic TPS is efficient only for steeper entry and higher β_E**
  - Rapid increase in heat load for $\gamma_E < -24^0$ → very high TPS mass
- **The EPFA and β_E range where standard PICA can be used as forebody TPS, is very small due to significantly high pressure**

Uranus Aerocapture Study

- **Benefits**
  - Reduced probe's kinetic energy prior to entry via orbital mechanics
  - More opportunity for Probe-Earth communication
  - Reduced deceleration load during entry and descent
  - TPS trade space no longer limited to only Carbon Phenolic (CP)



Uranus Aerocapture

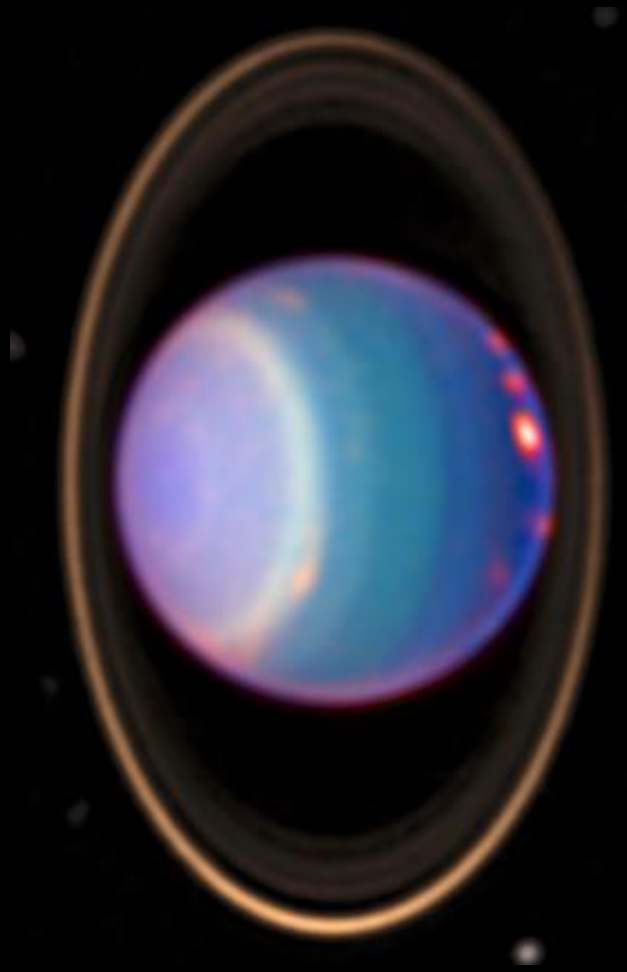
- **Objective: assess viability of aerocapture for Uranus entry**

Decadal Survey Baseline

- Orbiter: Propulsive capture
- Probe: Direct ballistic entry

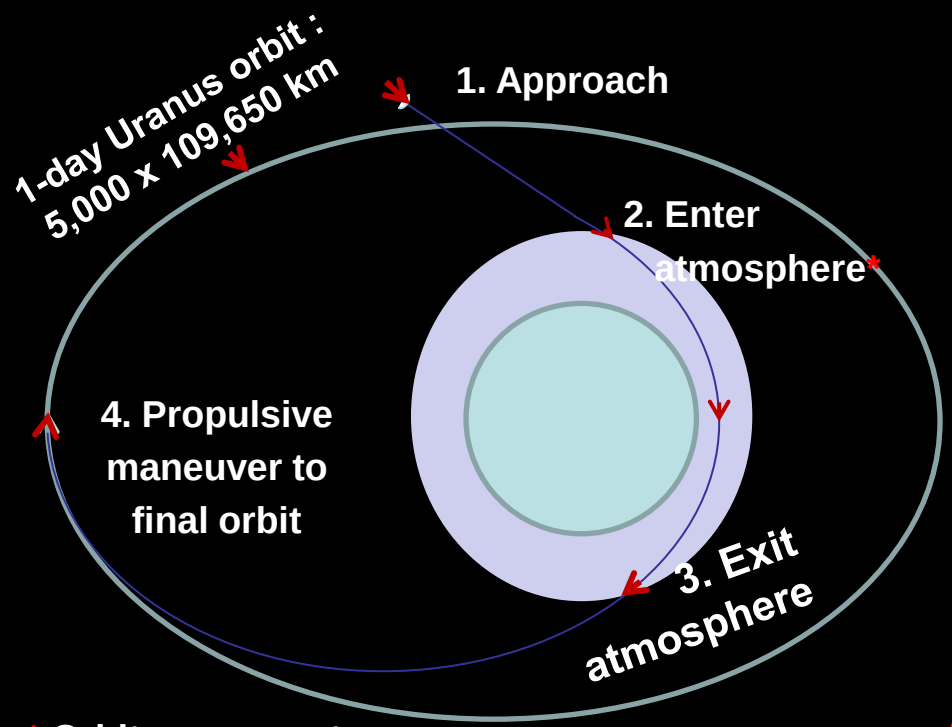
Current Aerocapture Study

- Aerocapture of Orbiter/probe system
- Probe separation and de-orbit burn
- Probe: Direct ballistic entry

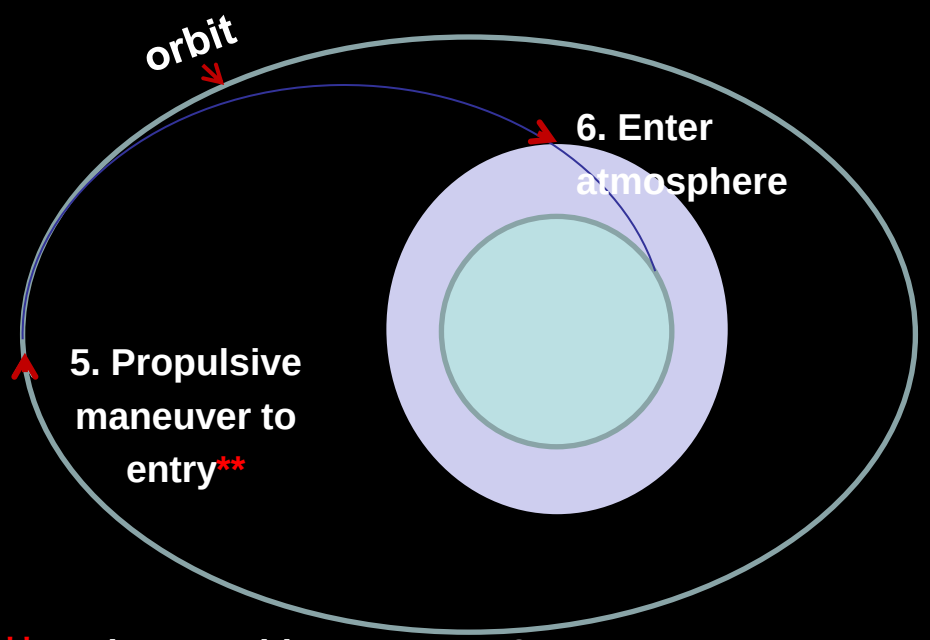


Trajectory Schematic and Parameter

Orbiter Aerocapture



Probe Entry



* Orbiter aerocapture maneuver:

V_{entry} = 22.35 km/s at 3,000 km

	Orbiter (3.5m) Cobra	Probe (0.76m) 45°
Mass (kg)	906.5	127.0
Ballistic Coefficient ($\frac{kg}{m^2}$)	60	285

** Probe De-orbit maneuver, 2 cases:

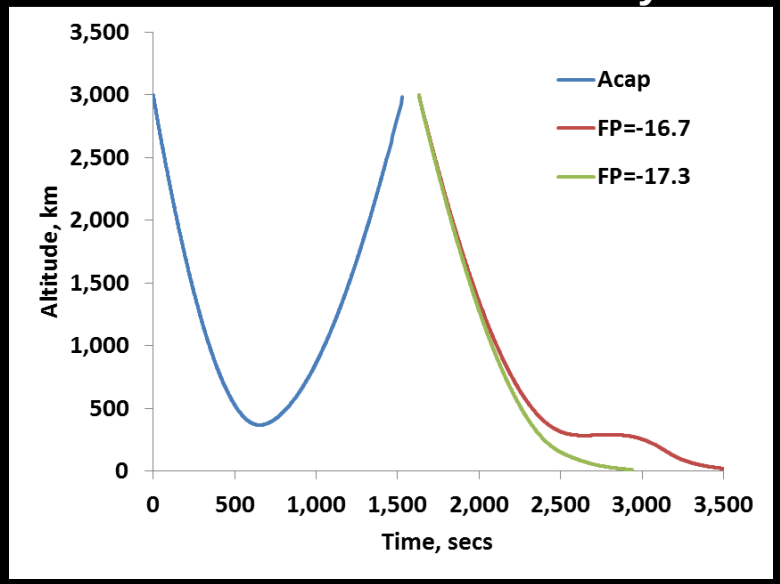
ΔV = 279 m/s, 18.34 km/s, altitude = 3,000 km, γ = -16.7 °

ΔV = 292 m/s, 18.34 km/s, altitude = 3,000 km, γ = -17.3°

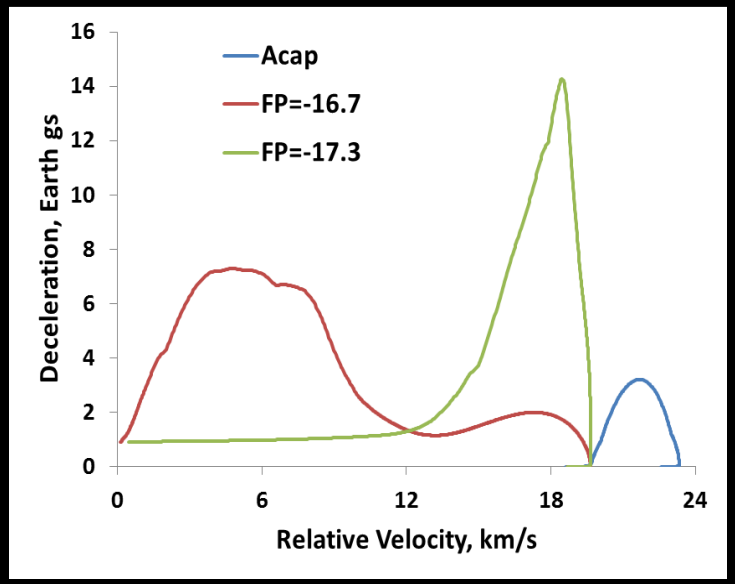
In this case, Aerocapture dissipates ~30% of the total energy (opportunity for further optimization)

Aerocapture Trajectory Results

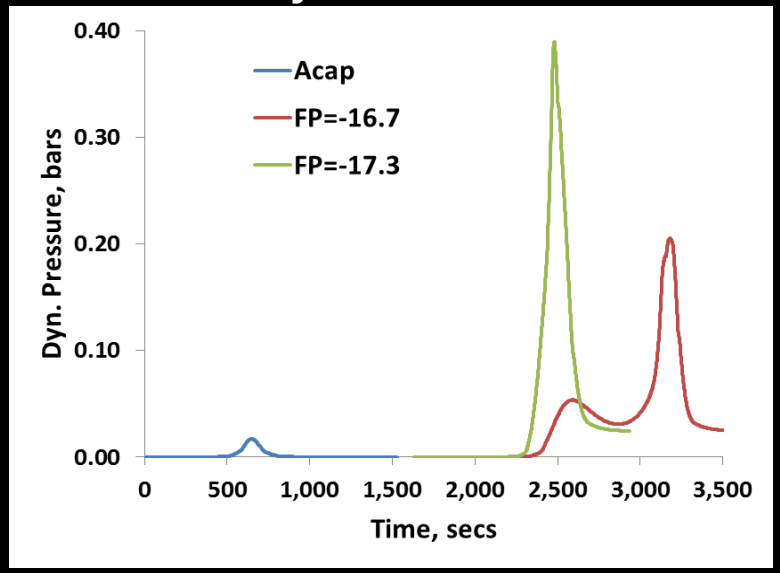
Altitude Time History



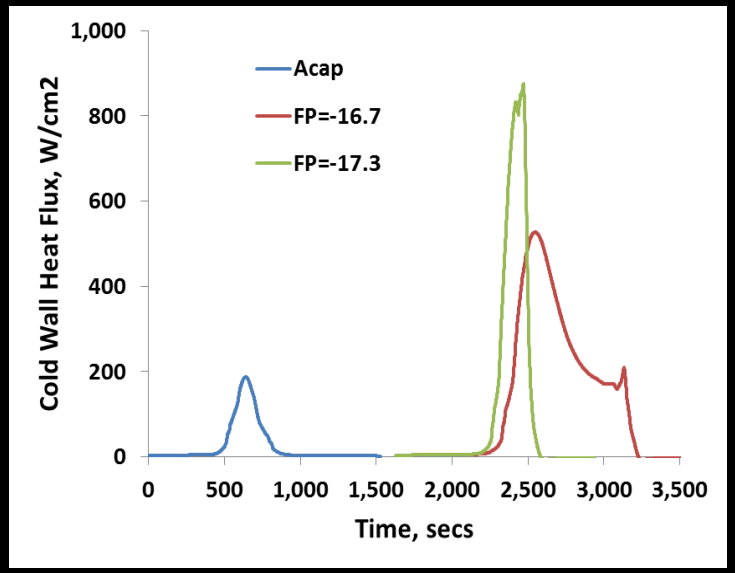
Deceleration Loads



Max. Dynamic Pressure



Max. Cold Wall Heatflux



Comparison of Aerocapture to Propulsive Capture

Aerocapture via Cobra mid L/D Shape vs. Orbiter From Decadal Survey

Relevant Subsystem Mass	Propulsive Capture (kg)	Aerocapture (kg)
Primary Structure	140	451
Secondary Structure	25	56
Aeroshell TPS	0	319
Aeroshell Separation System	0	17
Main Engine & Install	6	0
N_2H_4 Fuel Tank	36	10
Oxidizer tank	29	0
Pressurization	27	5
Feed System	14	3
Trust Structure	0	0
Propellant	981	27
TOTAL (kg)	1,257	887

Aerocapture Summary

- **Entry from orbit would facilitate the use of PICA rather than Carbon Phenolic with marginal increase in mass due to de-orbit manuever**
- **Aerocapture has the potential to save mass as compared to orbiter described in the Decadal Survey**
- An integrated system study with more accurate structural mass estimates and system closure should be performed for the proposed Aerocapture architecture to make a better comparison with the Decadal survey SEP results.

Summary & Conclusions

- The steep entry point design described in the 2013-23 decadal survey is not feasible due to high deceleration and pressure loads.
- A shallow entry (EFPA < -40^0) will be needed from TPS and instrumentation perspective. A joint study with EDL community, mission designers, communications and planetary scientists is required as a next step.
- A mid density ablator like woven TPS is needed to fill the TPS gap and provide more entry options.
- Aerocapture assessment demonstrates potential benefits. Further analysis is required.
- Study complete. Additional studies / follow on work contingent on funding.

Recommendations for Future Work

Decadal Survey study expanded to investigate entry options

The following studies are recommended to address open issues

1. Define ring locations and gaps, then perform optimized entry trajectories
2. Optimize trajectories to expand Earth-Probe communication window
3. Examine vehicle / mission design sensitivity to various atmospheric models
4. Conduct more thorough aero-capture analysis
5. Examine vehicle / mission design impacts from advanced TPS
6. Conduct more in-depth analysis for flagship class missions

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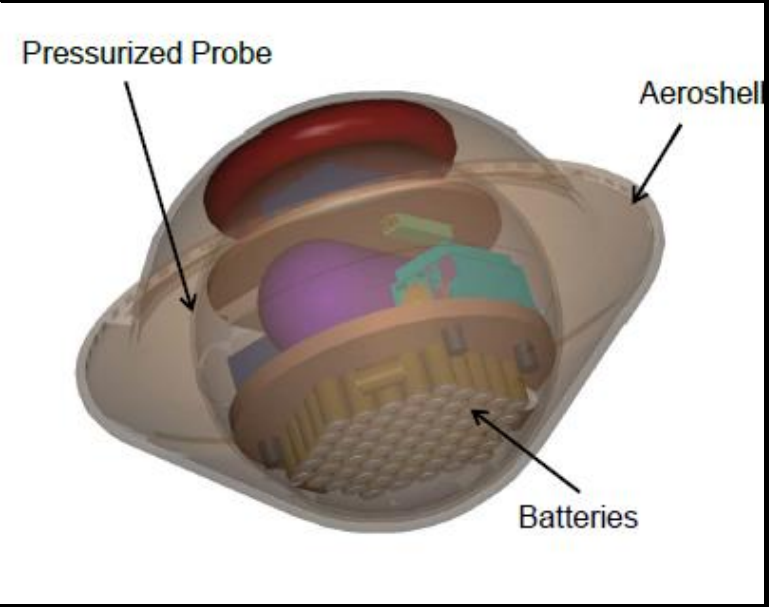
APL

Zibi Turtle

Backup

2013 Decadal Survey – Uranus Probe Design

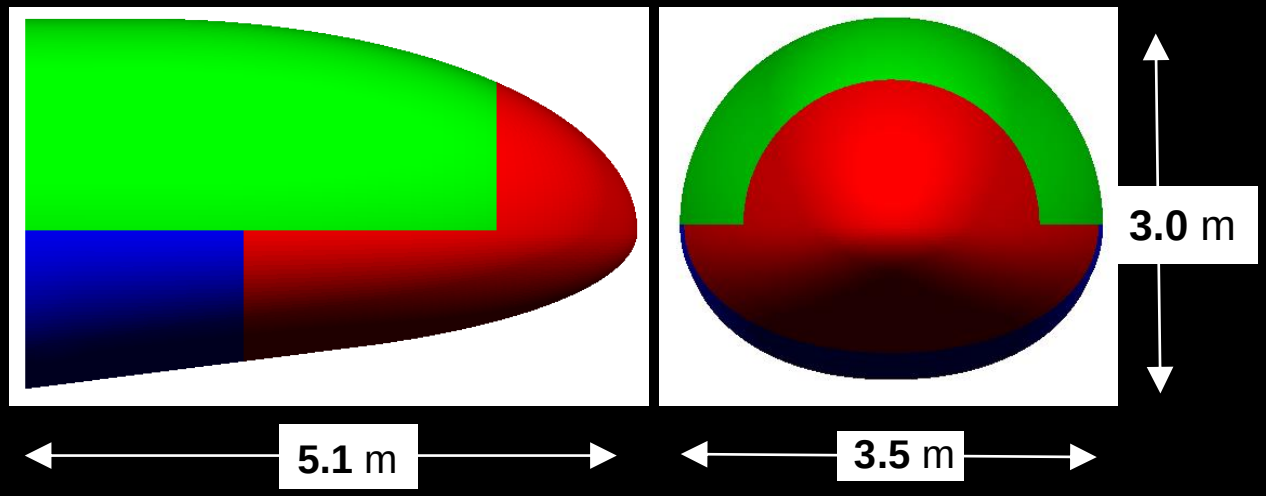
Probe Type	Pioneer Venus Small Probe
Entry Vehicle Diameter (m)	0.76
Cone Angle (deg)	45
Mass with margin (Kg)	127
Instruments	Mass spectrometer, temp-pressure sensors, USO and nephlometer
Entry Flight Path Angle (deg)	68
Entry Velocity (km/s)	22.35
Launch date	July-August 2020
Arrival Time	28-Jun-33
Peak Deceleration (g Load)	390



Altitude for descent : 550 Km
Shallow descent up to 5 bar pressure.

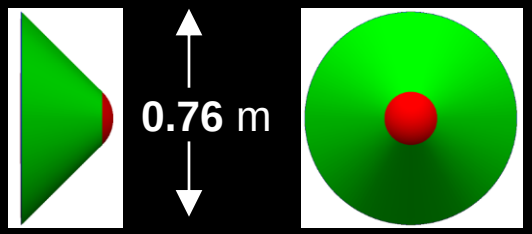
Vehicle Concepts

Orbiter: Mid L/D Cobra Shape (L/D=0.5)



Fit within Atlas 551 launch shroud

Probe: 45° Sphere-Cone (Ballistic)



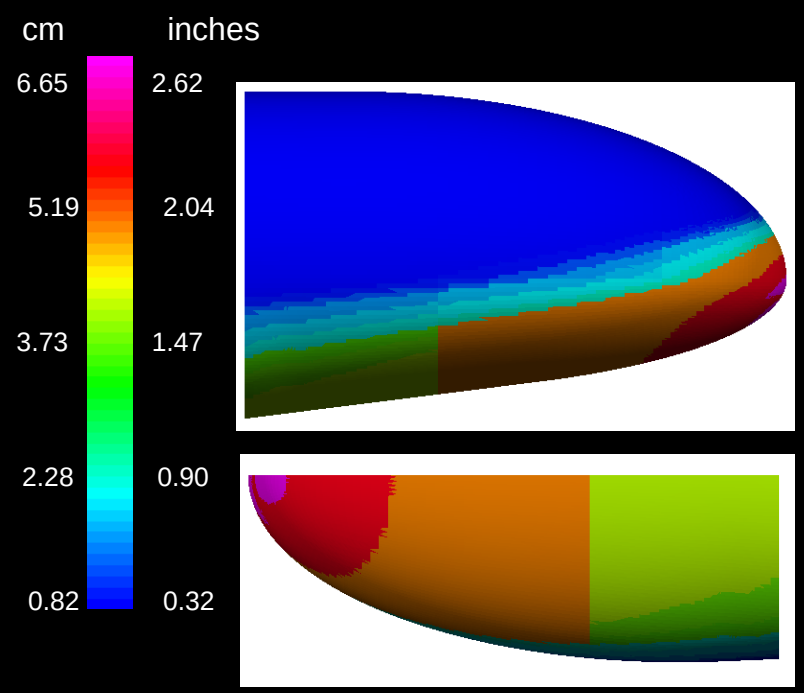
Value of 0.5 for L/D chosen to demonstrate aerocapture technology based on prior experience on Venus and Saturn studies.

More in-depth analysis needed to establish sensitivity to L/D.

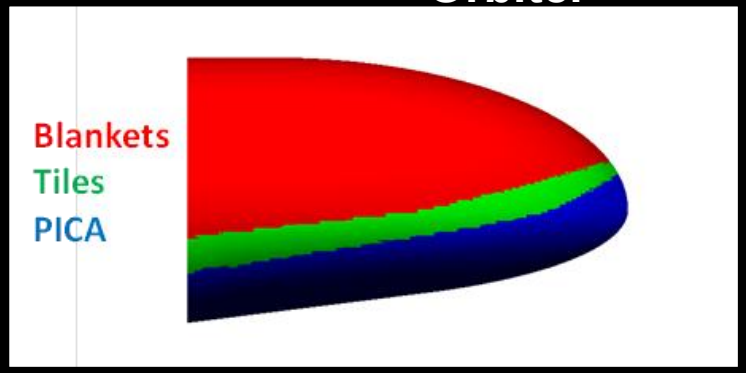
TPS Sizing: Analysis Results

TPS System (TPS + Attachment) **Thicknesses**

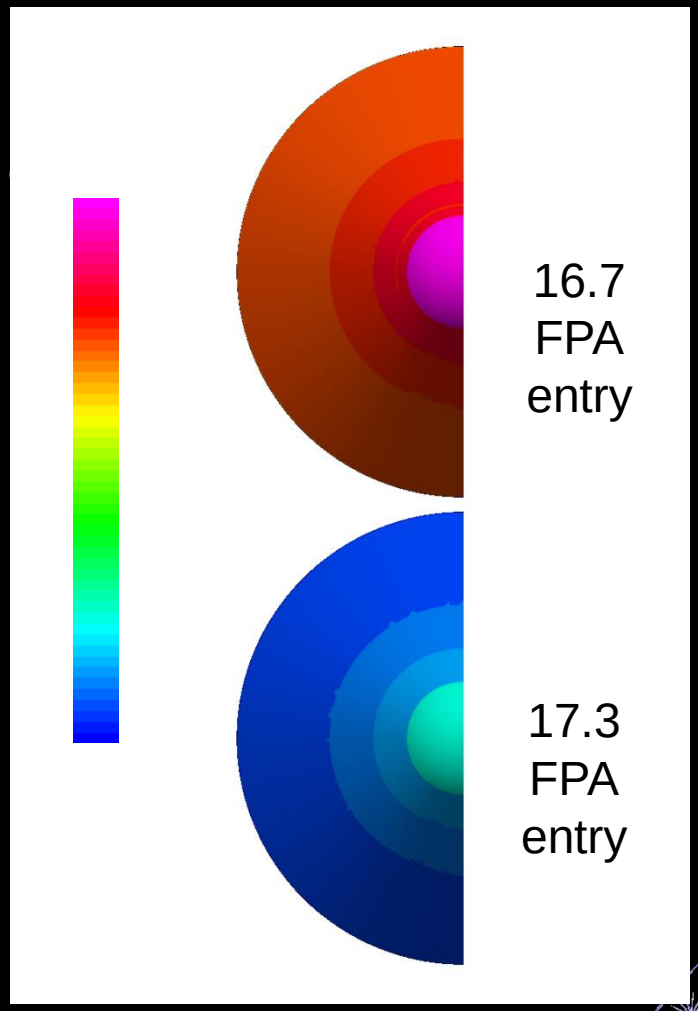
Note: For probe PICA was considered as TPS material



Orbiter



TPS splitlines for the orbiter



Probe