“A Lifting ADEPT is considered for aerocapture at Venus. Analysis concerning the heating environment leads to an initial sizing estimate. In tandem, a direct entry profile at Earth is considered to act as a facsimile for the Venus aerocapture heating environment. The bounds of this direct entry profile are determined and it is found that a trajectory from a Geostationary Transfer Orbit with a Lifting ADEPT capable of fitting on a rideshare opportunity is capable of matching certain aspects of this heating environment.”

# Candidate Earth Entry Trajectories to Mimic Venus Aerocapture Using a Lifting ADEPT

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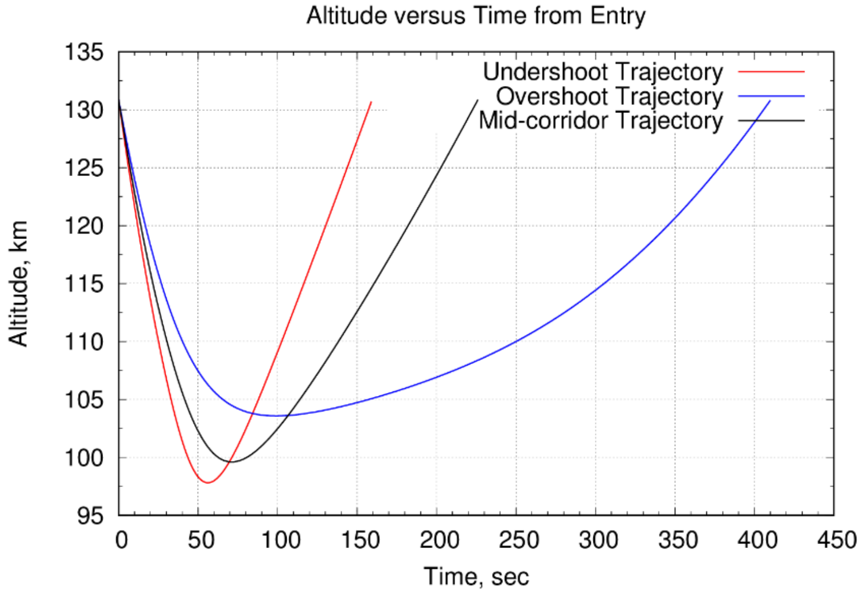
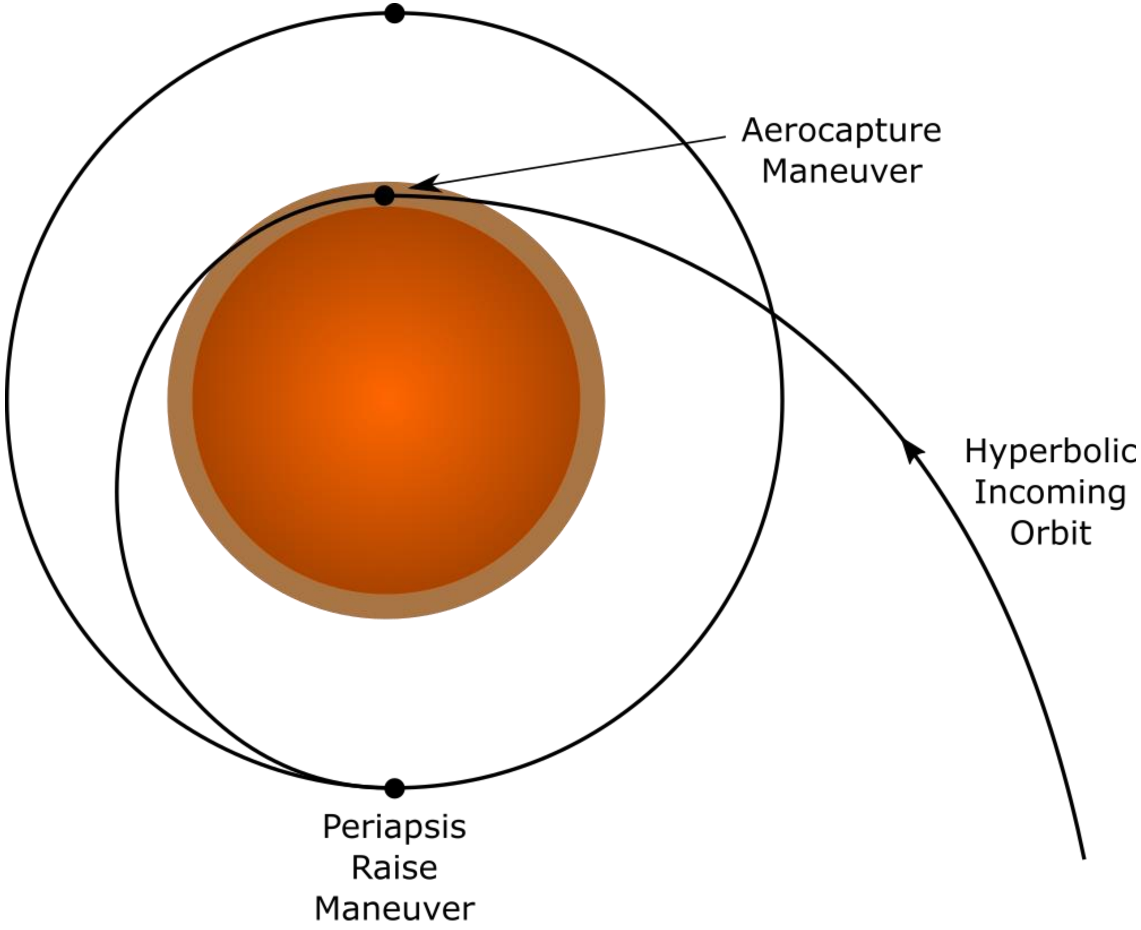
# Problem Statement

- Can we perform aerocapture at Venus with Lifting ADEPT?
- What size of Lifting ADEPT is required to do this?
- How do we validate Lifting ADEPT aerothermodynamics for Venus at Earth?

# Aerocapture

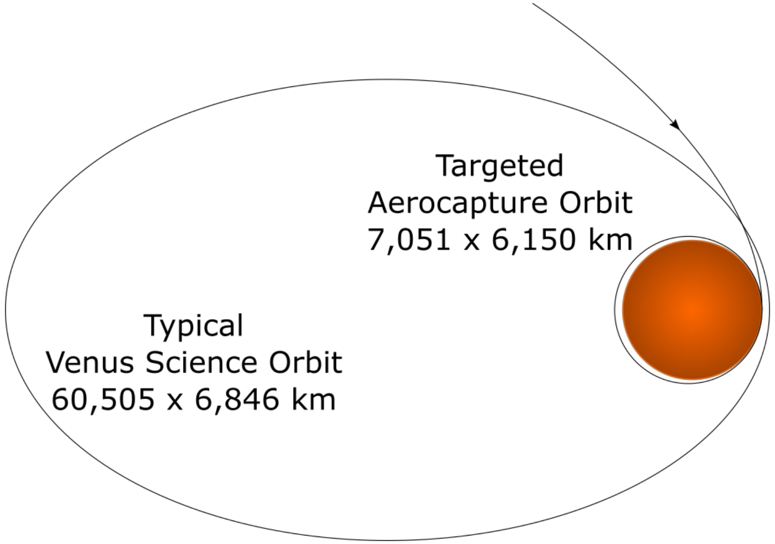
- Aerocapture: Using a body's atmosphere to slow a craft from a hyperbolic to an elliptical trajectory
- Entry Corridor:
  - Undershoot: Lift up, high heat rate
  - Overshoot: Lift down, high heat load
  - Mid-corridor: Lifting out-of-plane, mix of heating

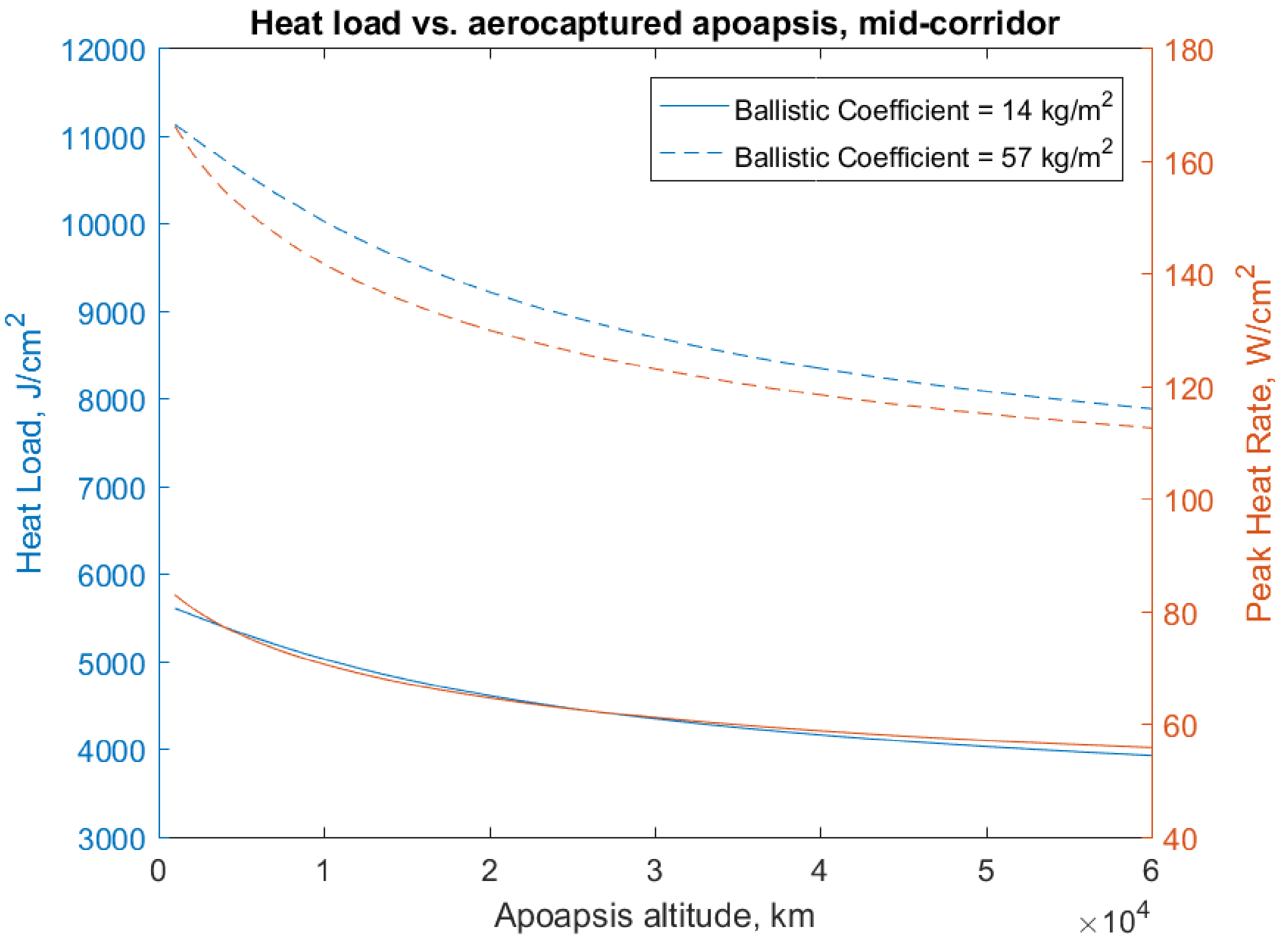




# Why Venus Aerocapture?

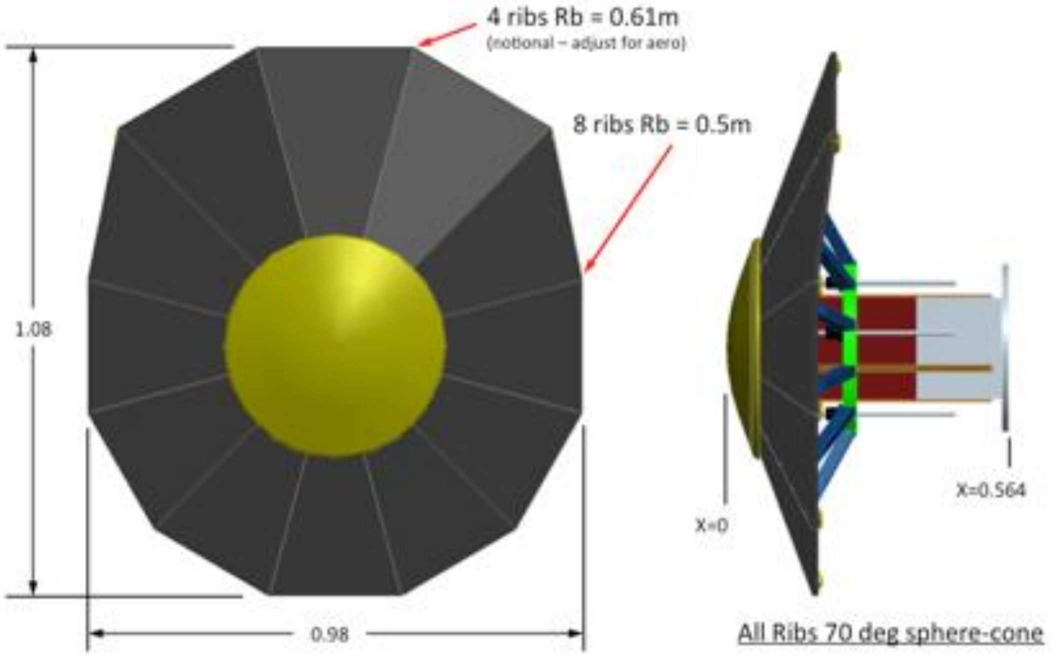
- Aerocapture allows for much higher science payload mass for a similar apoapsis when compared with propulsive insertion
  - Required ΔV ~4 km/s
- Aerocapture is an enabling method for CubeSat-class orbital missions to Venus
- Venus heating environment heavily influenced by ballistic coefficient and target apoapsis





# Lifting ADEPT

- ADEPT – Adaptable, Deployable Entry and Placement Technology
- Lifting ADEPT is asymmetric variant
- Aerodynamics:
  - Hypersonic invariance
  - Trim Angle of Attack: 10°
  - $L/D_{trim}$: 0.19
  - $CD_{trim}$: 1.43
- Configurations are based on previous Lifting Nano-ADEPT study (LNA 2016 CIF)
- Base payload volume is ~4U



| Subsystem | Estimated mass (kg) |
|---|---|
| Decelerator | 12.2 |
| Ancillary | 34.3 |
| **Entry Mass** | **47** |

# Lifting ADEPT Configurations

- Three sizes of Lifting ADEPT considered
  - 1, 2, 3 $m$ deployed diameter
- Upper and lower bounding mass for each considered:
  - Lower – Only decelerator and ancillary mass
  - Upper – Payload is based on CubeSat Standard
  - Component masses scale differently with size
  - Ancillary ~ Constant
  - Decelerator ~ $R^2$
  - Payload ~ $R^3$

| Deployed Diameter ($m$) | Payload Volume ($m^3$) | Payload Mass | Mass ($kg$) | Ballistic Coefficient ($kg/m^2$) |
|---|---|---|---|---|
| 1 | 0.012 | 0 | 47 | 42 |
| | | 24 | 71 | 63 |
| 2 | 0.096 | 0 | 65 | 14 |
| | | 192 | 256 | 57 |
| 3 | 0.324 | 0 | 88 | 9 |
| | | 648 | 736 | 72 |

# Venus Aerocapture – Conditions

| Entry Velocity $(km/s)$ | Interface Altitude $(km)$ | Target Apo. Alt. $(km)$ | Angle of Attack | L/D |
|---|---|---|---|---|
| 11.0 | 130 | 1,000 | 10° | 0.19 |

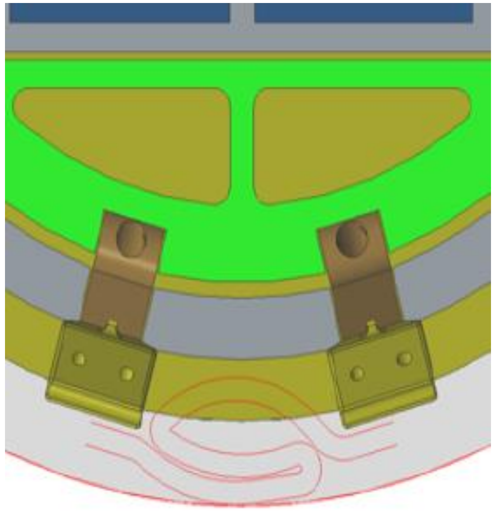
| Deployed Diameter $(m)$ | Nose Radius $(m)$ | Mass $(kg)$ | Ballistic Coefficient $(kg/m^2)$ | Max Acceleration $(Earth\ g's)$ | Peak Stag. Point Flux $(W/cm^2)$ | Total Stag. Point Load $(J/cm^2)$ |
|---|---|---|---|---|---|---|
| 1 | 0.5 | 47 | 42 | 7.3 | 190.00 | 13.0e3 |
| | | 71 | 63 | 7.3 | 230.00 | 15.8e3 |
| 2 | 1.0 | 65 | 14 | 7.2 | 83.00 | 5.6e3 |
| | | 256 | 57 | 7.3 | 166.00 | 11.1e3 |
| 3 | 1.5 | 88 | 9 | 7.2 | 53.00 | 3.6e3 |
| | | 736 | 72 | 7.3 | 162.00 | 10.7e3 |

All configurations flown at mid-corridor

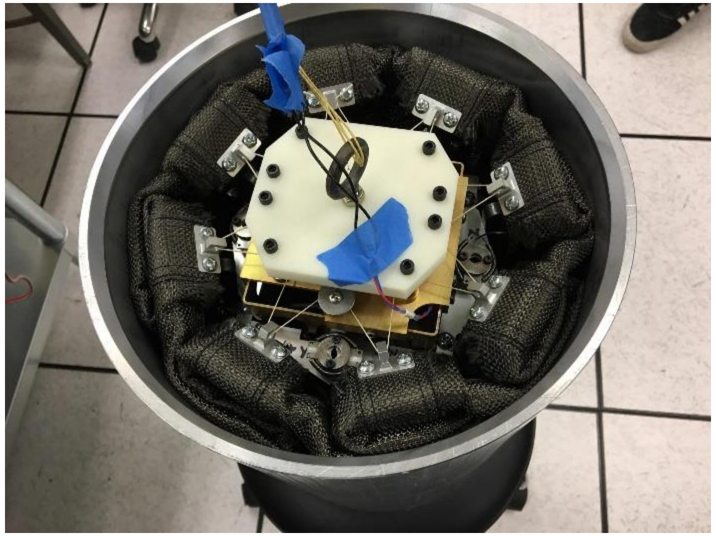
# Venus Aerocapture – TPS Sizing

- Lifting ADEPT makes use of layers of flexible, woven, carbon fiber TPS
  - Each thermal layer ablates after ~0.5 kJ/cm$^2$ (Smith, 2015)
  - Design practice adds a layer for thermal margin
  - Design assumes 2 additional layers for structure
- Folding is a key design constraint, especially for smaller sizes
  - 3:1 deployed-to-stowed ratio
- 0.7 m ADEPT used in SR-1 with 4 layers and 8 ribs is near the limit of stowability
- It appears that the 1 m Venus aerocapture variant is unfeasible due to large amount of layers required
  - 2 m full-mass variant is design point

| Size ($m$) | Mass ($kg$) | Number of Layers |
|---|---|---|
| 1 | 47 | 10 |
| | 71 | 11 |
| 2 | 65 | 6 |
| | 256 | 9 |
| 3 | 88 | 5 |
| | 736 | 9 |



Notional view of fabric folding



SR-1 in its stowed configuration

# Earth Direct Entry Facsimile

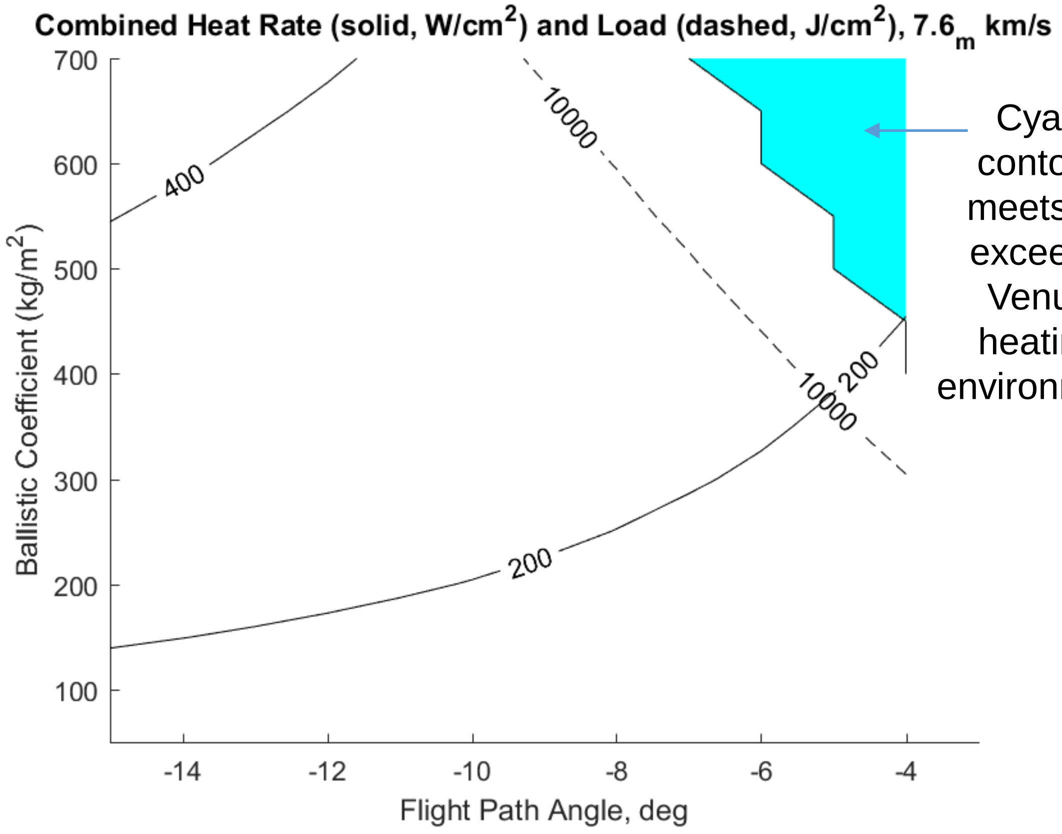
- A direct entry demonstration at Earth is desired to mimic the aerocapture environment at Venus for 2-m size of ADEPT
- Important parameters:
  - Peak heat flux
  - Total heat load
  - Peak Acceleration
- Variables:
  - Ballistic coefficient
  - Entry Flight Path Angle
  - Entry velocity (LEO or GTO)
- Constraints:
  - ADEPT must fit in adapter for rideshare (mass and volume limits)

Targeted Venus Aerocapture Conditions

| **Max Acceleration ($Earth\ g's$)** | **Peak Stag. Point Flux ($W/cm^2$)** | **Total Stag. Point Load ($J/cm^2$)** |
|---|---|---|
| 7.3 | 166.00 | 11.1e3 |

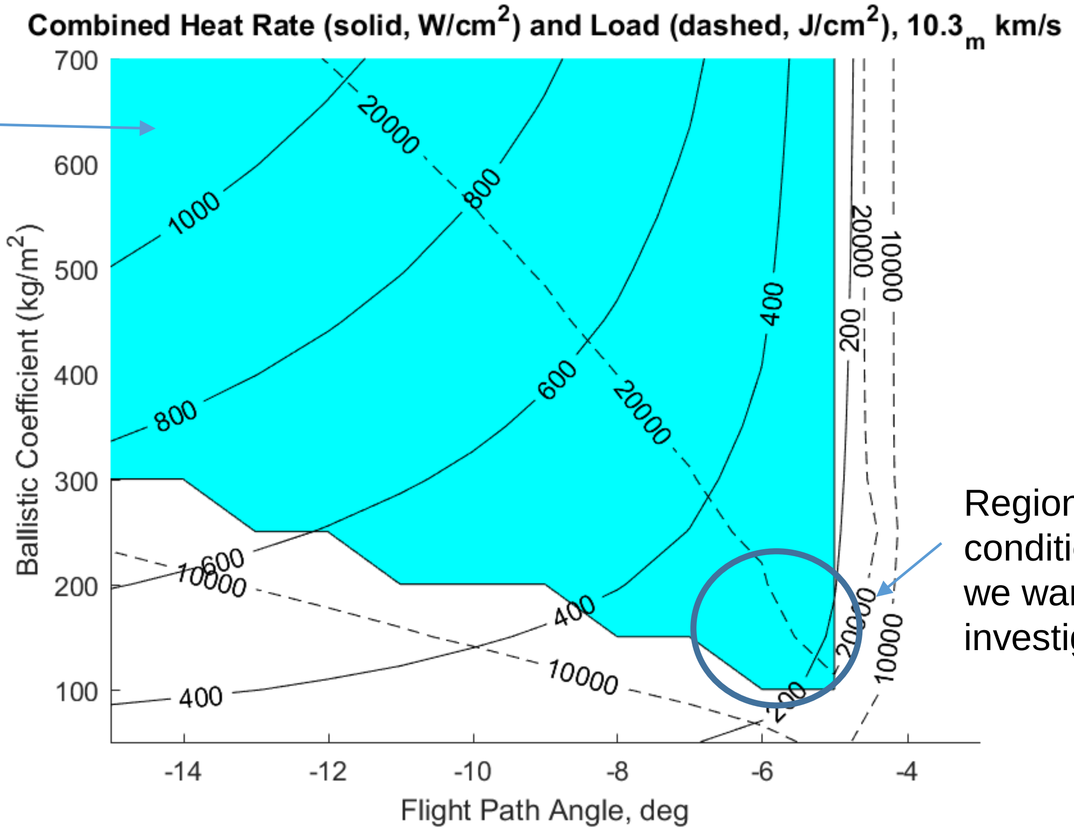
# Earth Direct Entry Facsimile – LEO and GTO

Increasing entry speeds to those near GTO drastically reduces the required BC



LEO Case

Cyan contour meets or exceeds Venus heating environment



GTO Case

Region of conditions we want to investigate

All cases flown at lift-right bank angle

# Earth Direct Entry Facsimile – Rideshare Possibilities

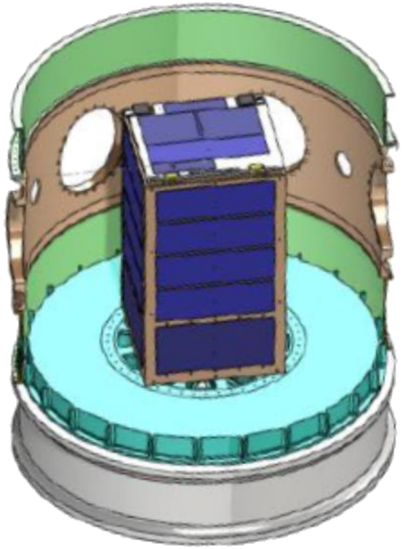
| Deployer | Status | Orbits | Payload Mass (kg) | Payload Volume |
|---|---|---|---|---|
| P-POD | Operational | LEO - GTO | 1.33 | 10 x 10 x 10 cm |
| C-Adapter Platform | Unlaunched | LEO - GTO | 45 | 23 x 31 x 33 cm |
| Aft Bulkhead Carrier | Operational | LEO - GTO | 80 | 51 x 51 x 76 cm |
| ESPA | Operational | LEO - Escape | 181 | 61 x 71 x 96 cm |
| ESPA Grande | Operational | LEO - Escape | 190 | 125 x 115 x 100 cm |
| AQUILA | CDR 2012 | LEO - MEO | 1,000 | 142-cm dia. x 152 cm |

Two separate rideshare opportunities seem feasible

# Earth Direct Entry Facsimile – AQUILA and ESPA Grande

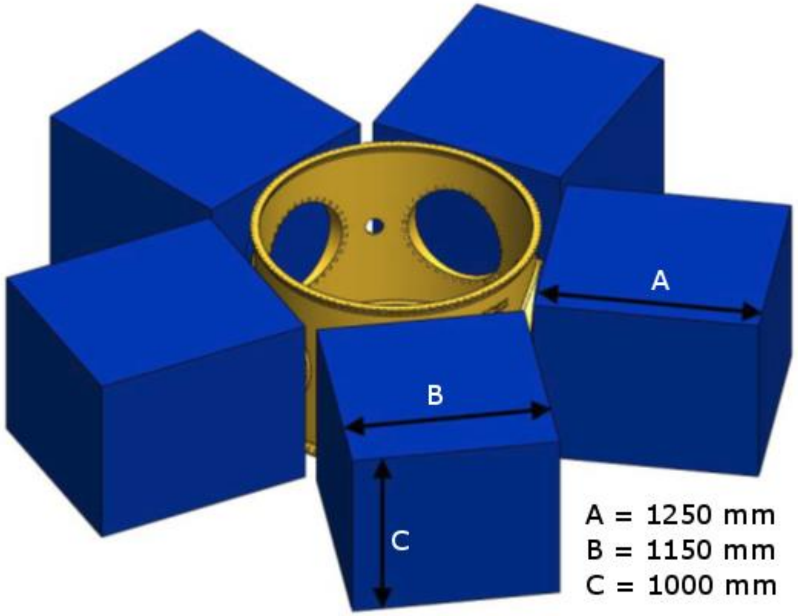
- AQUILA
  - ~ 2.4 m$^3$ capacity
  - 1000 kg capacity
  - Available on ULA Atlas V and Delta IV
  - In development
- ESPA Grande
  - ~ 1 m$^3$ capacity
  - 190 kg capacity (w/provided separator)
  - Available on multiple launch vehicles (Falcon 9, Atlas V, Delta IV)
  - Notable Heritage
    - ORBCOMM OG2 (LEO)
    - LCROSS (ESPA-basic, Lunar impact)

AQUILA

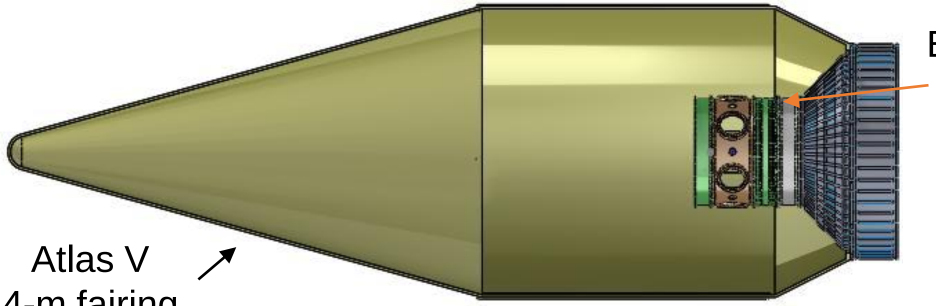


Max Diameter: 1420 mm
Max Height: 1520 mm

ESPA Grande



A = 1250 mm
B = 1150 mm
C = 1000 mm



ESPA and AQUILA

Atlas V
4-m fairing

# Earth Direct Entry Facsimile – Can we match either conditions with ESPA Grande?

| **Entry Mass $(kg)$** | **Ballistic Coefficient $(kg/m^2)$** | **Entry Velocity $(km/s)$** | **Bank Angle** | **EFPA** | **Peak Acceleration $(Earth\ G's)$** | **Peak Stagnation Flux $(W/cm^2)$** | **Total Stagnation Heat Load $(J/cm^2)$** |
|---|---|---|---|---|---|---|---|
| 190 | 55 | 10.3 | 90° | -5 | 23 | 91 | 7,312 |
| 190 | 55 | 10.3 | 0° (Lift Down) | -4.15° | 13 | 53 | 12,264 |
| 190 | 55 | 10.3 | 180° (Lift Up) | -10° | 29 | 165 | 4,331 |

It is possible to design a direct entry profile with the 190 kg case which can mimic the peak flux or total load

# Conclusions

- Venus aerocapture presents a harsh heating environment, which challenges the Lifting ADEPT architecture.
- To test the Lifting ADEPT architecture at Earth with a reasonable ballistic coefficient, a GTO orbit is required
- Rideshare to GTO presents limitations on packaged mass and volume which must be considered for Earth facsimile tests

# Questions

# References

- Smith, B., et. al., “Nano-ADEPT: An Entry System for Secondary Payloads,” *IEEE Aerospace Conference,* 2015
- Karuntzos, K., “ULA Rideshare Overview,” 2015
- Allen, G., Trajectory Analysis Program, 2017
- Wercinski, P., et. al., “Lifting Nano ADEPT Mid-Year Study Status,” 2016
- Heritage Venus science orbits sourced from NASA Space Science Data Coordinated Archive

# Backup

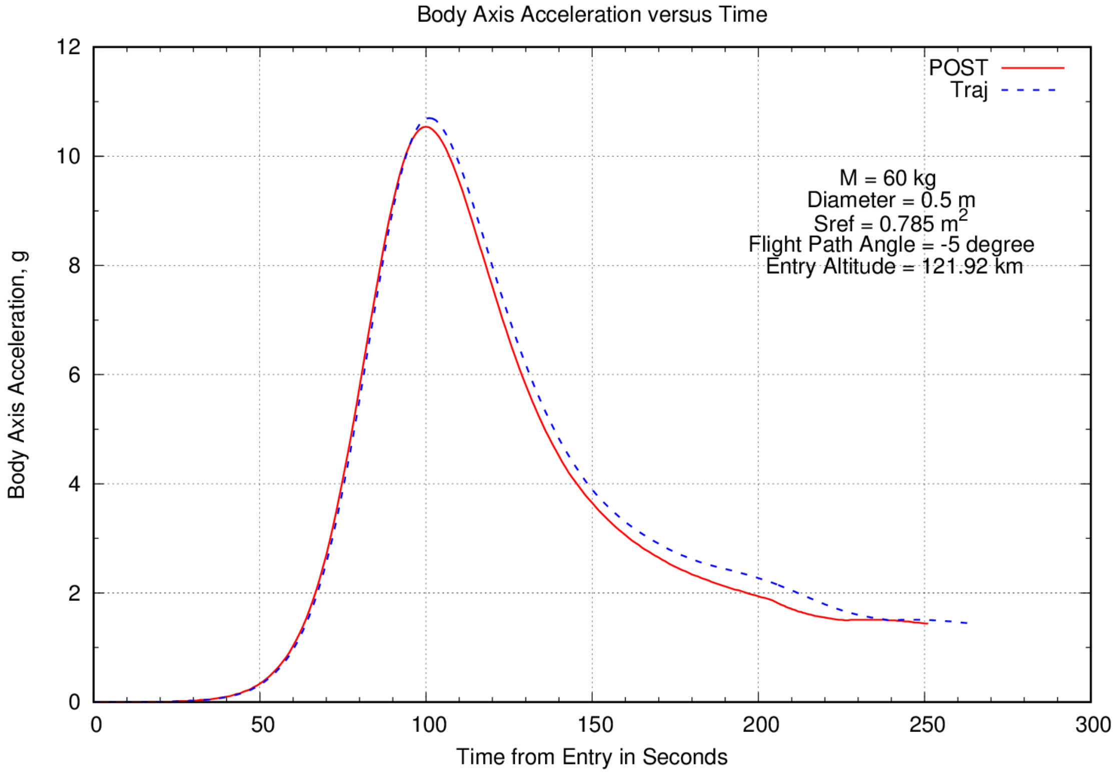
# LNA Sizing

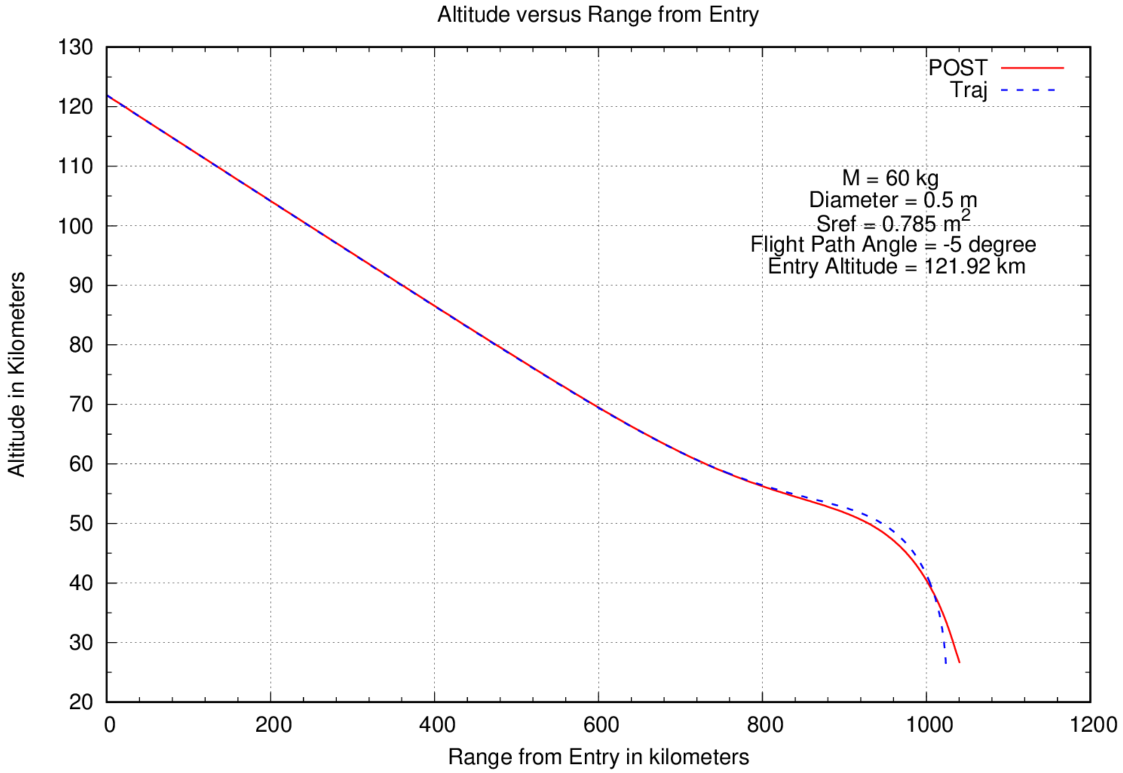
| Decelerator Mass Breakdown $(kg)$ | 30% MGA Mass $(kg)$ |
|---|---|
| Ribs | 5.5 |
| Struts | 3.9 |
| Carbon Fabric Skirt | 2.9 |
| **Decelerator Mass** | **12.2** |

| Base Ancillary Mass Breakdown | 30% MGA Mass $(kg)$ |
|---|---|
| Deployment System | 2.60 |
| Aft Bulkhead/Release | 1.43 |
| C-Band Transponder | 1.30 |
| Video Cameras | 0.78 |
| CORESAT Avionics | 1.82 |
| Battery | 0.13 |
| Propulsion Module | 2.21 |
| Propellant | 1.82 |
| Parachute System | 5.20 |
| Fasteners | 0.65 |
| Cable Harness | 0.65 |
| **Nominal Mass Totals** | **34.3** |

# Aerodynamics Verification

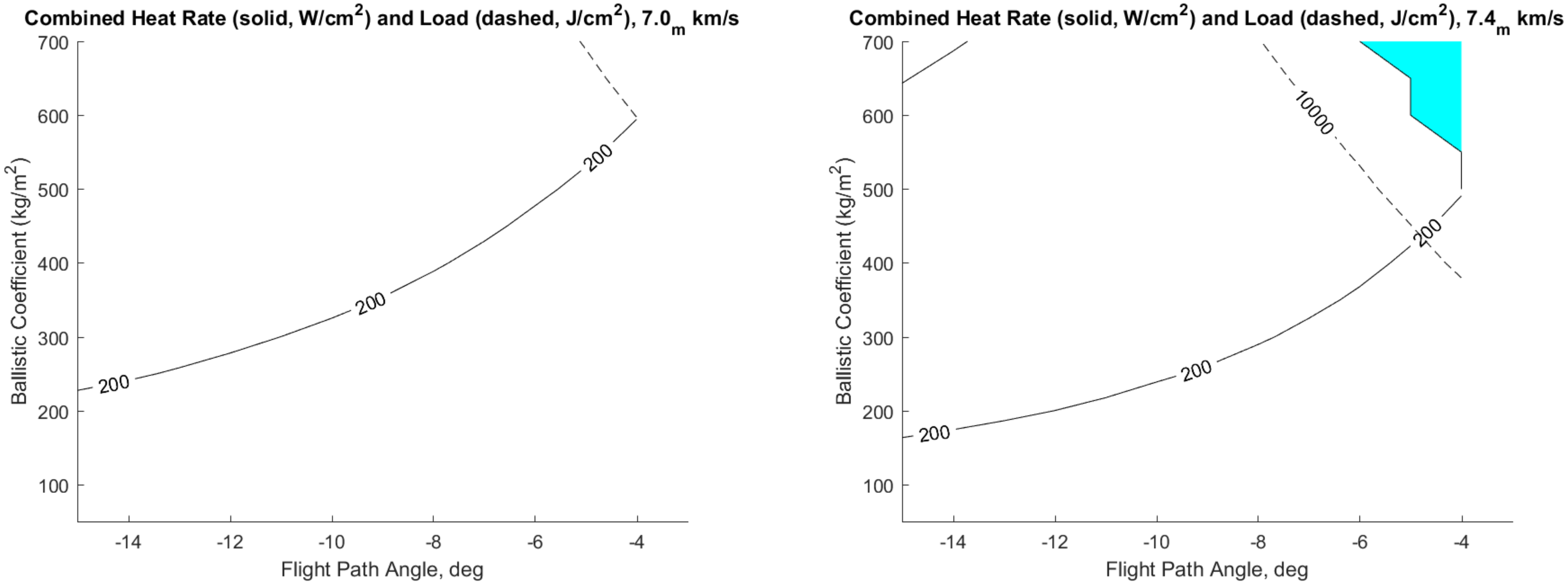
Traj software was compared with POST2 to verify correct implementation of aero data, with good results





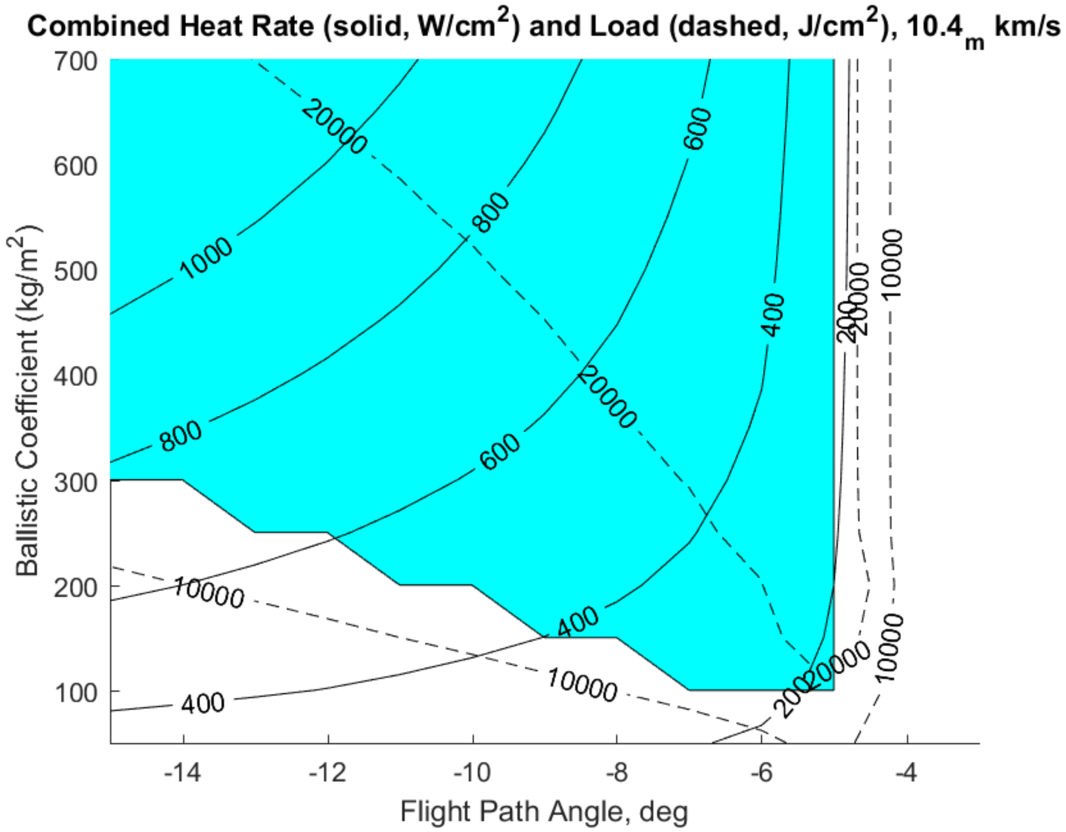
# Earth Entry Facsimile – Low Speed

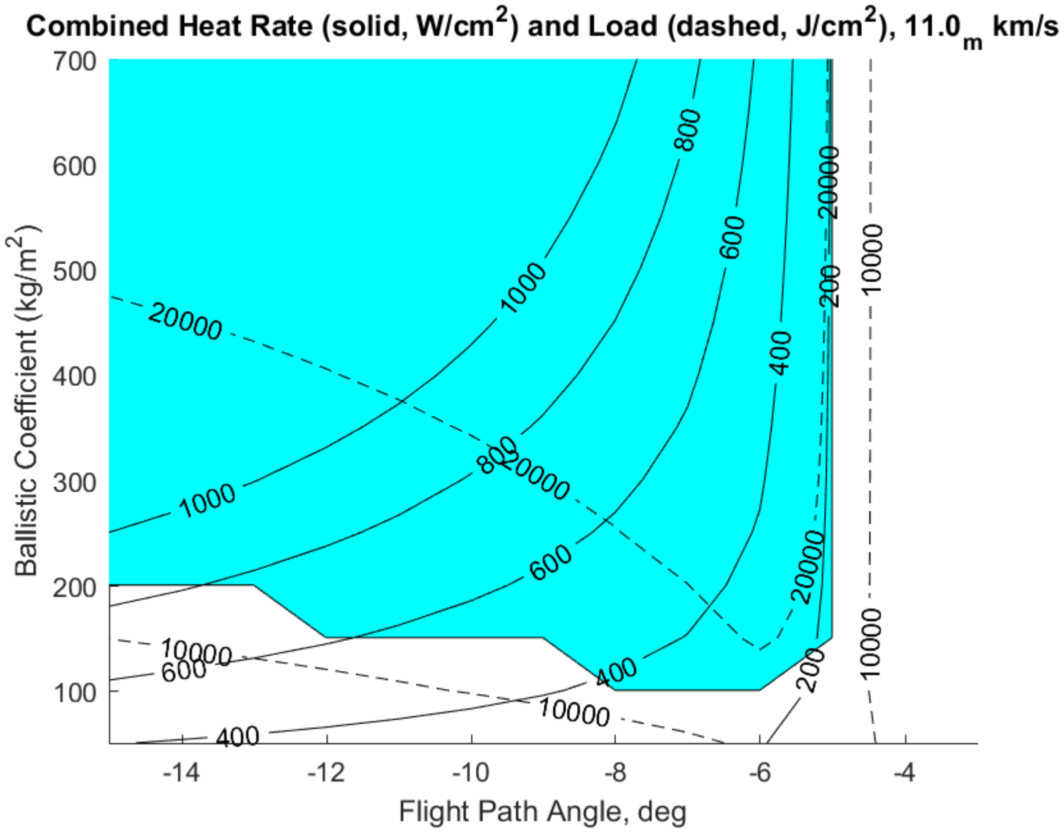
Extremely high ballistic coefficients required to meet Venus aerocapture requirements



# Earth Entry Facsimile – High Speed

Little improvement over GTO case


Combined Heat Rate (solid, W/cm$^2$) and Load (dashed, J/cm$^2$), 10.4$_m$ km/s


Combined Heat Rate (solid, W/cm$^2$) and Load (dashed, J/cm$^2$), 11.0$_m$ km/s

# Example Earth Entry Trajectory

| Ballistic Coefficient | EFPA | Entry Velocity |
|---|---|---|
| 100 $kg/m^2$ | -5° | 10.3 $km/s$ |
| **Size** | **Entry Mass** | **Peak G's** |
| 2 $m$ | 450 $kg$ | 460 |