Atmospheric Entry Studies for Uranus

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Outline

• Background
  - Constraints
  - Science Objectives
  - Orbital Mechanics
  - Atmosphere
• Direct Ballistic Entry
• Aerocapture Entry
• Conclusions & Recommendations
Background

- Funded by Entry Vehicle Technology (EVT) project under In-Space Propulsion Technology (ISPT)
- Concept studies to understand the trade space for atmospheric entry, focusing on Venus, Saturn and Uranus
  - Provide in-depth analysis of mission concepts outlined in the decadal survey for these planets
  - These studies could be enabling for future Flagship and New Frontier missions designs
- The results of this study will be published and presented at IEEE aerospace conference in Big Sky Montana, March 2014
Study Objectives

- Establish a range of probe atmospheric entry environments based on the Uranus Flagship mission in the 2013-23 Planetary Science Decadal Survey
  - Two Launch windows 2021 and 2034 are being considered for this study
- Define Uranus entry trade space by performing parametric studies, by varying ballistic coefficient (vehicle mass, size) and Entry Flight Path Angle (EFPA)
- Investigate entry trajectory options, including direct ballistic and aero-capture
  - This study is not intended to design a specific mission concept
- Identify entry technologies that could be leveraged to enable viable missions to Uranus to achieve specific science objectives
- Recommend direction for future studies
Uranus Mission Science Objectives

• Probing below the methane cloud deck
• Better constrain N and S abundances
• Measuring the T profile

Min. probe depth 5 bars – stated objective.
Analysis is performed as part of this study to show the required communication time with probe for depth up to 100 bars.

• Outer planets decadal sub-panel envisioned a small, simple probe that would ride along with an orbiter to the planet
• The key instruments
  - Mass spectrometer
  - Atmospheric Structure (T, P)
  - Doppler winds (ultra-stable oscillator)

Present studies are performed to look at heavier and bigger probes as well as very light probes to cover a large trade space.
Assumptions for Entry Analysis

Trajectory Assumptions:
- Entry Velocity – 22.53 km/s (2029 arrival), 21.96 km/s (2043 arrival)
- Earth - Jupiter (flyby) - Uranus chemical propulsion trajectory (~8-9 years)
- Hyperbolic velocity $V_\infty \sim$8-10 km/s, selection of trajectories based on ring avoidance

Uranus Entry Assumptions:
- “New” engineering atmospheric Model
- Generic atmospheric gas mole fractions: $H_2$ 0.848, $He$ 0.152
- Ellipsoidal planet, equatorial radius 25,559 km, polar radius 24,973 km
- Rotation rate: $-1.012e^{-4}$ radians/sec [retrograde rotation]
- Entry altitude: 3000 km based on heat-load and initial heatflux calculations

Vehicle Assumptions:
- Galileo Probe was scaled for parametric studies
- Half angle: $45^0$
- Nose radius /Base radius: 0.351
- Tauber aerodynamic model for the Galileo Probe
- Tauber convective and radiative heat flux model for Saturn
- Outer wall temperature assuming radiative equilibrium with emissivity at 0.85
- TPS initial temperature: 197.5 K
- Bond line failure temperature: 523.2 K
Entry Trajectory Space: Ballistic Coefficient Matrix

**Trades were performed by varying EFPA \((\nu_e)\) for various ballistic coefficients \((\beta_E)\).**

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

\(m_E = \) Entry mass,  
\(D_b = \) Base diameter  
\(C_D = \) Hypersonic drag coefficient

<table>
<thead>
<tr>
<th>Mass (kg)</th>
<th>(0.7)</th>
<th>(0.8)</th>
<th>(1)</th>
<th>(1.3)</th>
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<tbody>
<tr>
<td>50</td>
<td>124</td>
<td>95</td>
<td>61</td>
<td>36</td>
</tr>
<tr>
<td>130</td>
<td>322</td>
<td>246</td>
<td>158</td>
<td>93</td>
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<tr>
<td>200</td>
<td>495</td>
<td>379</td>
<td>243</td>
<td>144</td>
</tr>
<tr>
<td>300</td>
<td>743</td>
<td>569</td>
<td>364</td>
<td>215</td>
</tr>
</tbody>
</table>

Not possible with existing technology.  
Values used for Current analysis.  
Values exceeding recommended limits.

**Value used for current decadal survey.**

- \(\beta_E\) matrix was derived based on values from Galileo and Pioneer Venus small probe.  
- For current studies, bigger and heavier probes were also investigated that could accommodate larger suite of instruments.  
- Some of the values (shown in red cells) are not possible with existing technologies.
Process and Assumptions

- For both 2029 and 2043 arrivals, a range of entry trajectories were generated by varying entry flight path angle, $\gamma_E$

- For each entry trajectory, following parameters were extracted:
  - Peak deceleration (G) load
  - Peak pressure load (stag. point, correlation)
  - Peak heat flux (stag. point, correlations for conv. & rad. heating)
  - Total heat load (time-integrated stag. point total heat flux)

- Suitable range for $\gamma_E$, for various ballistic coefficients $\beta_E$ were identified, based on following design assumptions
  - Peak deceleration not to exceed 200Gs
  - Avoid skip out
  - Fully dense carbon phenolic as TPS material for sizing analysis. The trade space for low density ablator like PICA was also investigated.
  - TPS mass determined by total heat load

- Detailed CFD analysis and TPS sizing were performed for a few selected trajectories
Deceleration Loads vs. EFPA

- The peak deceleration load increases with $\gamma_E$ and $\beta_E$.
- This constrains the upper end of suitable $\gamma_E$ for direct ballistic entry.

EPFA Limit for $\beta = 379$

EFPA Limit for $\beta = 93$

200 G load constraint based on instrument qualification.

Alternatives:
- Aerocapture
- HIAD
For $\beta_E > 150$ Kg/m² the pressure increases very rapidly for steeper entry.
This further constrains the $\gamma_E$ for vehicles with higher $\beta_E$.
Spallation is observed in carbon phenolic when exposed to stagnation pressure > 10 bar.
Low density TPS like PICA have a very small operating space.

Decadal Survey
Bounding Hot-Wall Heat Fluxes (CFD Predictions)

- The peak heating distribution along the vehicle is shown in the above plot.
- Stagnation point values were 1 - 2.0 kW/cm² (conical flank heat fluxes are ≈20% lower).

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

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.
In Space Propulsion Technology (ISPT)

Entry Trade Space

- Mid density TPS materials like woven seem a suitable choice for direct ballistic entry trajectories
  - Woven TPS with its tailorable characteristics could provide the robustness and mass efficiency
- There is a small window for which PICA could be potentially used as TPS material.

Contours of peak stagnation pressure (blue lines), total heat load (red lines), and peak deceleration load (green lines) for 130 kg probe.
Ballistic Entry Summary

- Uranus entry is similar to Saturn entry where convective heating dominates and heating due to radiation is insignificant.
  
  The environments are benign compared to Jupiter or Venus.

- Deceleration load constraint of 200G determines the upper end of the EFPA.
  
  For $\beta_E = 100$, EPFA $\sim -41^0$ and for $\beta_E = 370$, EPFA $\sim -34^0$.

- Skip out (not considering communication challenges) determines the shallowest possible entry and for Uranus the values are in the range of $-21^0$ to $-19.5^0$.

- For the above range of EPFA the stagnation peak pressures could vary from 5.0 bar to 20.0 bar based on the $\beta_E$.

- Rapid increase in heat load is observed for entries that are shallower than $-24^0$. This could give rise to very high TPS mass to maintain bond-line temperature.

- The EPFA and $\beta_E$ range where PICA can be used as forebody TPS is very small due to significantly high pressure.

- Carbon Phenolic TPS is efficient only for steeper entry and higher $\beta_E$.

Agrawal
Uranus Aerocapture Study
Aerocapture Objectives

• Explore whether aerocapture a viable alternative for Uranus entry in order to provide following benefits:
  – dissipate the incoming energy
  – reduce the deceleration load
  – provide more opportunity for communication
  – enable use of alternate TPS options to Carbon Phenolic (CP)

Current Aerocapture Study
• Aerocapture of Orbiter/probe system
• Followed by probe separation and de-orbit burn
• Probe: Direct ballistic entry

Decadal Survey Baseline
• Orbiter: Propulsive capture
• Probe: Direct ballistic entry
Vehicle Concepts

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

Fit within Atlas 551 launch shroud

Note: The value of 0.5 for L/D was chosen to demonstrate aerocapture technology based on prior experience on Venus and Saturn studies. More in-depth analysis is needed to establish sensitivity to L/D.

Probe: 45° Sphere-Cone (Ballistic)
In this case Aerocapture dissipates ~30% of the total energy. There is opportunity for further optimization.
Trajectory Parameters

Trajectories:

- **Orbiter Aero Capture to 1-day Uranus orbit, 5000 by 109650 km, $V_{entry}=22.35 \text{ km/s } @ \text{3000km}$**
- **Probe De-orbit maneuver, 2 cases:**
  - $\Delta V=279.3 \text{ m/s}: 18.340 \text{ km/s } @ \text{altitude=3000km, } \gamma=-16.7^\circ. \text{ (Limit to avoid skip out)}$
  - $\Delta V=291.5 \text{ m/s}: 18.338 \text{ km/s } @ \text{altitude=3000km, } \gamma=-17.3^\circ \text{ (Chosen to stay within PICA limits)}$

<table>
<thead>
<tr>
<th></th>
<th>Orbiter (3.5m)</th>
<th>Probe (0.76m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COBRA</td>
<td>45°</td>
<td></td>
</tr>
<tr>
<td>L/D</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>906.5</td>
<td>127</td>
</tr>
<tr>
<td>Bal. Coef., kg/m$^2$</td>
<td>60</td>
<td>285</td>
</tr>
<tr>
<td>$\Delta V$, m/s</td>
<td>N/A</td>
<td>279.3</td>
</tr>
<tr>
<td>Entry Velocity, km/s</td>
<td>22.3</td>
<td>18.3</td>
</tr>
<tr>
<td>Entry FPA</td>
<td>-19.4</td>
<td>-16.7</td>
</tr>
</tbody>
</table>

**Note:** COBRA and L/D values are specific to the orbiter and probe, respectively.
Aerocapture Trajectory Results

**Altitude Time History**

- **Acap**
- **FP=-16.7**
- **FP=-17.3**

**Deceleration Loads**

- **Acap**
- **FP=-16.7**
- **FP=-17.3**

**Max. Dynamic Pressure**

- **Acap**
- **FP=-16.7**
- **FP=-17.3**

**Max. Cold Wall Heatflux**

- **Acap**
- **FP=-16.7**
- **FP=-17.3**
TPS Sizing: Analysis Results

TPS System (TPS + Attachment) Thicknesses

Orbiter

Note: For probe PICA was considered as TPS material

Probe

TPS splitlines for the orbiter

Blankets
Tiles
PICA

cm
inches

6.65
2.62

5.19
2.04

3.73
1.47

2.28
0.90

0.82
0.32

6.7
2.6

5.9
2.32

5.1
2.0

4.3
1.69

3.5
1.38

16.7
FPA entry

17.3
FPA entry
### Comparison of Aerocapture to Propulsive Capture

**Aerocapture via Cobra mid L/D Shape Compared to Orbiter From Decadal Survey**

<table>
<thead>
<tr>
<th>Relevant Subsystems Mass</th>
<th>Propulsive Capture, [kg]</th>
<th>Aerocapture [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Structure</td>
<td>140</td>
<td>451</td>
</tr>
<tr>
<td>Secondary Structure</td>
<td>25</td>
<td>56</td>
</tr>
<tr>
<td>Aeroshell TPS</td>
<td>0</td>
<td>318.8</td>
</tr>
<tr>
<td>Aeroshell Separation System</td>
<td>0</td>
<td>16.8</td>
</tr>
<tr>
<td>Main Engine &amp; Install</td>
<td>5.8</td>
<td>0</td>
</tr>
<tr>
<td>N2H4 Fuel Tank</td>
<td>36</td>
<td>10</td>
</tr>
<tr>
<td>Oxidizer Tank</td>
<td>28.7</td>
<td>0</td>
</tr>
<tr>
<td>Pressurization</td>
<td>26.7</td>
<td>4.7</td>
</tr>
<tr>
<td>Feed System</td>
<td>14.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Thrust Structure</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Propellant</td>
<td>981</td>
<td>27</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1257</strong></td>
<td><strong>887</strong></td>
</tr>
</tbody>
</table>
Aerocapture Summary

- Entry from orbit would facilitate the use of PICA rather than Carbon Phenolic with marginal increase in mass due to de-orbit maneuver.
- Aerocapture has the potential to save mass as compared to Solar Electric Propulsion (SEP) orbit capture.
- 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

- Suitable entry vectors corresponding to 2029 and 2043 arrivals were established
  - We were able to select trajectories that avoided the wide Uranus ring system

- An engineering atmospheric model that combined the various published atmospheric models was constructed

- A ballistic-coefficient matrix including several mass and diameter combinations was created. Thousands of entry trajectories were generated using the in-house code, TRAJ, by varying the EPFA for various ballistic coefficients.

- The results from trajectory analysis indicated that steepest possible EFPA without exceeding the 200 g requirements is -41°. Both deceleration and pressure loads rise with steeper entry.

- The shallowest entry is determined by skip-out that is in the range of -19.5° to 20°.
  - The analysis did not look at the impact of EFPA on communications.

- The aerothermal heating was dominated by convective heating and radiative component of heating was negligible.
Summary & Conclusions

- Peak stagnation pressure varied in the range of 5 bar to 20 bar, thus precluding use of low density ablators like PICA for most trajectories.
  - A very small window was found that can be further explored for PICA.
  - A suitable mid density ablator that can withstand high pressure would be desirable TPS candidate.

- An aerocapture maneuver assessment for a 1-Uranus-day orbit using a mid L/D aeroshell for the orbiter was performed.
  - The results show that an aerocapture maneuver is a potentially viable alternative for looking at low deceleration alternatives that can utilize low density ablators like PICA.
Recommendations for Future Work - I

- Full-filling Broad Science Based Objectives
  - Understanding the location and gap between the rings, perform trajectory analysis to optimize Uranus entry
  - Trajectory analysis for optimum communication window
    (A collaborative effort with planetary science community, mission designers, communications team will be needed)
  - Examining sensitivity to various atmospheric models.
    (Literature survey and communications with science community shows different atmospheric models. Based on the date of arrival the probe may encounter different atmosphere. It is important to understand the effects of these changes in entry parameters)

- Entry System Technology Development
  - More in-depth aero-capture analysis should be performed for orbiter and probe including
    Optimization for L/D ratio and vehicle concepts
    Trajectory optimization for energy dissipation
    System scale study for potential mass savings
Recommendations for Future Work - II

• Entry System Technology Development (Continued)
  – Infusion of new enabling technologies like woven and conformal TPS can be examined to fill the TPS gap
  – PICA could be examined as a case study for discovery class missions

• Mission Design and Optimization
  – In-depth analysis for flagship class missions can be performed with various case studies.
  – Other options e.g. secondary payloads from SLS launch to places like Uranus can be examined

This study will be closed at this time. No funds are allocated by ISPT for further work on this project.

The results of this study will be published and presented at IEEE aerospace conference in Big Sky Montana, March 2014.
Acknowledgements

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  - Mary Livingston
  - Jeff Bowles

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  - Pat Beauchamp
  - Mike Hofstadter
  - Chester Borden

- **APL**
  - Zibi Turtle
Questions??
Backup
Uranus Facts → Constraints

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

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
**Earth-Jupiter-Uranus Chemical Trajectory**

- **Time of Flight**: 8 years
- **Earth Launch**: 2021 APR 30 ET
- **Jupiter Flyby**: 2022 NOV 6 ET
  - Altitude=1.51e6km
- **Uranus Arrival**: 2029 APR 28 ET
- **V\text{inf}**: 10.028 km/s

**B-plane Targeting**

*Orientation of V\text{inf} (hyperbolic excess velocity) vector dictated by orbital mechanics. Available entry latitude band can be established for a fixed EFPA and Entry radius*

<table>
<thead>
<tr>
<th>EFPA</th>
<th>maxLat</th>
<th>minLat</th>
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<tbody>
<tr>
<td>-19.5</td>
<td>9.04 deg N</td>
<td>30.76 deg S</td>
</tr>
<tr>
<td>-20.5</td>
<td>10.57 deg N</td>
<td>29.23 deg S</td>
</tr>
<tr>
<td>-21.5</td>
<td>11.74 deg N</td>
<td>27.7 deg S</td>
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</tbody>
</table>

**Note**: The target radius is selected to be \( R = 28,474 \) km
## TPS Candidates

<table>
<thead>
<tr>
<th>TPS Family</th>
<th>Density</th>
<th>Heat flux (W/cm²)</th>
<th>Pressure (atm)</th>
<th>Mission Flown</th>
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<tbody>
<tr>
<td>PICA</td>
<td>Low</td>
<td>1650*</td>
<td>1.3*</td>
<td>Stardust, MSL</td>
</tr>
<tr>
<td>Carbon Phenolic</td>
<td>High</td>
<td>30,000</td>
<td>10.0</td>
<td>Galileo, Pioneer Venus</td>
</tr>
<tr>
<td>Woven</td>
<td>Mid</td>
<td>3900*</td>
<td>5.0*</td>
<td>None</td>
</tr>
<tr>
<td>Conformal</td>
<td>Low</td>
<td>1000*</td>
<td>1.0*</td>
<td>None</td>
</tr>
<tr>
<td>Phencarb</td>
<td>Mid</td>
<td>1000*</td>
<td>1.0*</td>
<td>None</td>
</tr>
<tr>
<td>Carbon-Carbon</td>
<td>N/A</td>
<td>700</td>
<td>(?)</td>
<td>Genesis</td>
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</table>

* Highest limit to which arcjet tests were performed.
Parachute Descent of Uranus Probe