Sampling Venus’ atmosphere with a low-cost probe mission concept

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Goal I: Atmospheric formation, evolution and climate history

Goals, Objectives, and Investigations for Venus Exploration

Table 2. VEXAG Goals, Objectives and Investigations

<table>
<thead>
<tr>
<th>Goal</th>
<th>Objective</th>
<th>Investigation</th>
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<tr>
<td>1. Measure the relative abundances of Ne, O isotopes, bulk Xe, Kr, and other noble gases to determine if Venus and Earth formed from the same mix of solar nebular ingredients, and to determine if large, cold comets played a substantial role in delivering volatiles.</td>
<td></td>
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<tr>
<td>A. How did the atmosphere of Venus form and evolve?</td>
<td>2. Measure the isotopes of noble gases (especially Xe and Kr), D/H, $^{15}$N/$^{14}$N, and current O and H escape rates to determine the amount and timeline of the loss of the original atmosphere during the last stage of formation and the current loss to space.</td>
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</tbody>
</table>

Noble gases are tracers of the evolution of planets

They trace:
- The supply of volatiles from the solar nebula
- The supply of volatiles by asteroids and comets
- The escape rate of planetary atmospheres
- The degassing of the interior (volcanism)
- The timing of these events

For example Xe (9 isotopes):
- Depleted / Kr
- Fractionated in mass
- Comparative planetology will help determine the processes involved in the distribution of noble gases

Pepin et al., 1991; Chassefiere et al., 2012)
Venus Probe

4 Architectures Compared

I. Atmospheric Entry and Descent
II. Drop-off from Orbit
III. Free-flying Probe + Flyby
IV. Gravity Assist Drop-off
I. Atmospheric Entry and Descent

**Mission Profile**
- Launch from Earth on a Type I or II trajectory
- Probe dropped off on Venus approach
- Probe follows descent path all the way down to the surface
- Carrier spacecraft flies by Venus
- Probe has to complete gas analysis before encountering surface ~60 mins after atmospheric entry
- Probe data are relayed back to Earth thru’ flyby spacecraft

**Strengths**
- Can measure noble gases below homopause
- Additional Science:
  - Faster response instruments (e.g. Tunable Laser Spectrometer) can sample gases at different altitudes
  - Opportunity to sense emission from surface features in Near-IR atmospheric windows

**Complexity**
- Entry, Descent and Landing System needed
- Pressure vessel needed to house instruments
- Probe has to complete gas analysis before encountering surface ~60 mins after atmospheric entry
- Increasing range separation as probe descends and carrier spacecraft executes flyby

Atmospheric Entry Conditions

Probe dips down to 120km

The values of density are required for the instrument performance model and for the design of the probe.
II. Drop-off from Orbit

**Mission Profile**

- Launch from Earth on any viable trajectory
- Carrier S/C and Probe inserted into a highly elliptical capture orbit
- Probe released at apoapsis with a few m/s Delta-V (A)
- Probe skims through atmosphere at altitude < 120 km (B)
- Skim-through maneuver ~ 5 mins
- Probe has ~60 mins + margin to relay data to orbiting Carrier S/C
- Data are then relayed back to Earth thru’ orbiting spacecraft (C)

**Strengths**

- Can measure noble gases below homopause
- Incremental additional cost compared with primary mission
- Multiple orbits provide opportunities for release of probe
- No EDL System needed
- No Pressure Vessel needed

**Complexity**

- Probe has ~60 mins + margin to complete gas analysis after atmospheric entry
- Carrier S/C has to execute on-orbit maneuvers to release probe and receive data

III. Free-flying Probe + Flyby

**Mission Profile**
- Launch from Earth on any viable trajectory
- Probe is released on approach to Venus
- Carrier S/C executes a lateral maneuver
- Probe skims through atmosphere at altitude < 120 km
- Skim-through maneuver ~ 5 mins
- Probe has ~60 mins + margin to relay data to flyby S/C
- Data are then relayed back to Earth thru’ flyby spacecraft

**Strengths**
- Can measure noble gases below homopause
- No EDL System needed
- No Pressure Vessel needed

**Complexity**
- Probe has ~60 mins + margin to complete gas analysis after atmospheric entry
- Flyby S/C has to execute approach maneuvers to release probe and then deflect its own trajectory

IV. Gravity Assist Drop-off

**Mission Profile**
- Launch from Earth on any viable trajectory
- Probe is released on approach to Venus
- Carrier S/C executes a lateral maneuver
- Probe skims through atmosphere at altitude < 120 km
- Skim-through maneuver ~ 5 mins
- Probe has ~60 mins + margin to relay data to flyby S/C
- Data are then relayed back to Earth thru’ flyby spacecraft

**Strengths**
- Can measure noble gases below homopause
- Incremental additional cost compared with primary mission
- Opportunistic science
- No EDL System needed
- No Pressure Vessel needed

**Complexity**
- Probe has TBD mins + margin to complete gas analysis after atmospheric entry
- Variable range separation between Probe and Carrier S/C after skim-thru
- Available data return window duration depends on comms link budget
- Flyby S/C has to execute approach maneuvers to release probe and then deflect its own trajectory

Venus Probe

Cassini Venus Gravity Assist Example

[Approach speed ~6 km/s]

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Free-flying Probe Design Configuration

Probe

Cruise Stage

Entire Stack in Pegasus XL Launch Fairing

Quadrupole Ion Trap Mass Spectrometer (QITMS)

Compact QITMS

• No discrete wires to make electrical connections to mass spectrometer parts.
• 7.3 kg mass; 4U volume
• Extremely robust against shock/vibe loads

QITMS Isotopic Precision is 3-5 times better than required

## Instrument Requirements vs. Performance

Performance versus requirements for noble gases ratio

<table>
<thead>
<tr>
<th>Approximate Isotopic Ratios</th>
<th>Assumed Fractional Abundance</th>
<th>Expected Intensity (cnts)</th>
<th>Precision [%]</th>
<th>Requirement*</th>
</tr>
</thead>
<tbody>
<tr>
<td>3He / 4He</td>
<td>0.0003</td>
<td>2.80E+08</td>
<td>8.39E+04</td>
<td>0.345</td>
</tr>
<tr>
<td>20Ne / 22Ne</td>
<td>12</td>
<td>1.63E+08</td>
<td>1.36E+07</td>
<td>0.028</td>
</tr>
<tr>
<td>36Ar / 40Ar</td>
<td>0.9</td>
<td>9.32E+08</td>
<td>8.39E+08</td>
<td>0.005</td>
</tr>
<tr>
<td>36Ar / 38Ar</td>
<td>5.4</td>
<td>1.08E+08</td>
<td>2.00E+07</td>
<td>0.024</td>
</tr>
<tr>
<td>82,83,86Kr / 84Kr</td>
<td>1</td>
<td>1.63E+05</td>
<td>1.63E+05</td>
<td>0.350</td>
</tr>
<tr>
<td>129, 136 Xe / 130Xe</td>
<td>1</td>
<td>2.33E+04</td>
<td>2.33E+04</td>
<td>0.926</td>
</tr>
<tr>
<td>124-128Xe / 130Xe</td>
<td>0.2</td>
<td>2.33E+04</td>
<td>4.66E+03</td>
<td>1.605</td>
</tr>
</tbody>
</table>

Measurements integrated over 5 mins

*Chassefiere et al., 2012
Design Summary - Probe

- **Instrument**
  - 8 kg Quadrupole Ion Trap Mass Spectrometer (QITMS)
  - Pressure transducer

- **Telecom**
  - Vulcan UHF transceiver
  - NanoCom ANT430 UHF dipole antenna

- **Mechanical**
  - 4kg aeroshell structure
    - UHF transparent material allows crosslink through the backshell
  - 3kg TPS
  - 2.5kg internal structure
  - 1kg harness
  - 0.5kg balance mass
  - 0.5kg for upper half of Lightband

- **Total Mass**: 21.6 kg
- **Total Volume**: 17 liters

- **C&DH**
  - JPL Sphinx Avionics

- **Thermal**
  - MLI and Heaters

- **Power**
  - 10 Saft LO30SHX primary battery cells
  - 0.1kg Custom EPS

Probe Design

• Entry probe shape
  – 45 deg sphere-cone
    • Scaled-up version of Hayabusa probe; Pioneer-Venus also 45 deg s-c
    – D = 60 cm (diameter), Rn = 30 cm (nose radius)
    – Assumed constant drag coefficient of 1.12 based on Hayabusa data
    – Design for worst-case altitude of 110 km
Probe Thermal Design

- Simplified heatshield TPS stackup:
  - PICA, RTV-560 adhesive, Aluminum
- 3-sigma low altitude (~110 km) drives TPS design
  - (Margined) Peak heat flux is ~150 W/cm²
  - (Margined) Max heat load is >9200 J/cm²
<table>
<thead>
<tr>
<th></th>
<th>Atmospheric Entry and Descent</th>
<th>Drop-off from Orbit</th>
<th>Free-flying Probe + Flyby</th>
<th>Gravity Assist Opportunity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Science Rating</strong></td>
<td>Primary</td>
<td>Secondary</td>
<td>Primary</td>
<td>Secondary</td>
</tr>
<tr>
<td><strong>Probe Mass</strong></td>
<td>150-250 kg</td>
<td>20-30 kg</td>
<td>20-30 kg</td>
<td>20-30 kg</td>
</tr>
<tr>
<td><strong>Launch Approach</strong></td>
<td>Dedicated Atlas V-class</td>
<td>Secondary payload</td>
<td>Dedicated Pegasus XL-class</td>
<td>Secondary payload</td>
</tr>
<tr>
<td><strong>Carrier Spacecraft</strong></td>
<td>400-500 kg</td>
<td>&gt;400-500 kg</td>
<td>25-35 kg</td>
<td>Any</td>
</tr>
<tr>
<td><strong>Lowest altitude</strong></td>
<td>0 km</td>
<td>120 km</td>
<td>120 km</td>
<td>120 km</td>
</tr>
<tr>
<td><strong>Probe Complexity</strong></td>
<td>High (EDL + Pressure vessel)</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Data Return Strategy</strong></td>
<td>Relay thru’ Flyby S/C</td>
<td>Relay thru’ Carrier S/C</td>
<td>Relay thru’ Flyby S/C</td>
<td>Relay thru’ Primary S/C</td>
</tr>
<tr>
<td><strong>Data return window</strong></td>
<td>&lt; 60 mins</td>
<td>60 mins + margin</td>
<td>60 mins + margin</td>
<td>TBD mins + margin</td>
</tr>
</tbody>
</table>

Conclusions

• 4 architectures were compared to sample the noble gases in Venus’ atmosphere at an altitude below the homopause

• *Atmospheric Entry and Descent* approach has more complexity than the other 3 architectures, and stronger cost drivers (L/V, Carrier S/C mass, Probe mass)

• Lowest cost approaches drop the probe off at Venus as a secondary payload on a Venus Orbiter or a Gravity Assist Flyby [But, Secondary Payload = Secondary Science]

• Low cost, low complexity, with noble gas measurement as Primary Science possible with a *Free-flying Probe + Flyby* architecture