Cupid's Arrow: a small satellite to measure noble gases in the atmosphere of Venus and Titan

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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
• Isotopically fractionated
• Comparative planetology will help determine the processes involved in the distribution of noble gases

(Pepin et al., 1991; Chassefiere et al., 2012)
- $^{40}\text{Ar}$ is a good tracer of the amount of outgassing since it comes from the decay of $^{40}\text{K}$ and it does not escape on Earth and Venus.
- 25% of the interior has been outgassed based on $^{40}\text{Ar}$ (Kaula, 1999)
- The upper mantle is about 25% of the total mantle in mass

<table>
<thead>
<tr>
<th></th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}\text{Ar}$ in atm (kg)</td>
<td>1.6 (±0.5) $10^{16}$</td>
<td>6.6 $10^{16}$</td>
<td>5 $10^{14}$</td>
</tr>
<tr>
<td>$^{40}\text{Ar}$ (kg/kg planet)</td>
<td>3.3 $10^{-9}$</td>
<td>1.11 $10^{-8}$</td>
<td>7.9 $10^{-10}$</td>
</tr>
<tr>
<td>$^{40}\text{Ar}$/Si</td>
<td>1.7 $10^{-8}$</td>
<td>5.2 $10^{-8}$</td>
<td>4.1 $10^{-9}$</td>
</tr>
<tr>
<td>potential $^{40}\text{Ar}$ (kg)</td>
<td>6.8 $10^{16}$</td>
<td>1.4 – 1.56 $10^{17}$</td>
<td>1.6 $10^{16}$</td>
</tr>
<tr>
<td>$^{40}\text{Ar}$ atm / potential</td>
<td>24 (±10)%</td>
<td>42-56 %</td>
<td>3%</td>
</tr>
</tbody>
</table>

Is the recent resurfacing due to plumes raising from the Core/Mantle boundary (CMB)?
The Xenon case (1/2)

9 isotopes, some of them coming from the decay of radioactive elements:

- $^{129}$I decaying (half life of 16 Ma) in $^{129}$Xe
- $^{244}$Pu fission (half-life of 80 Ma) producing $^{131}$-$^{136}$Xe isotopes with a diagnostic yield
- extant fission of $^{235}$-$^{238}$U (4.5 & 0.7 Ga) producing Xe isotopes with different yields

The analysis of xenon in the Venusian atmosphere will permit a major leap of understanding in (i) the origin(s) of inner planet volatiles, in particular that of Venusian ones, (ii) accretion and differentiation processes, and (iii) timing of these events. Cupid’s Arrow will measure Venus Xe isotopic ratios to distinguish among these models.

Madzunkov and Nikolic, 2014
Xe (9 isotopes):
- Depleted / Kr
- Isotopically fractionated
- Comparative planetology will help determine the processes involved in the distribution of noble gases
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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</thead>
<tbody>
<tr>
<td></td>
<td>A. How did the atmosphere of Venus form and evolve?</td>
<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 nebula ingredients, and to determine if large, cold comets played a substantial role in delivering volatiles.</td>
</tr>
<tr>
<td></td>
<td></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>
</tr>
</tbody>
</table>
Objective IA: How did the atmosphere of Venus form and evolve

This objective is responsive to all three crosscutting science themes of the DS and to all three Inner Planets Research Goals described in the DS. Measuring noble gases is the most important investigation of this objective.

CA can also determine the escape rate of Xe in particular (Investigation # II-A-2)

<table>
<thead>
<tr>
<th>Decadal Survey Crosscutting Science Theme</th>
<th>Relevant Venus Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building new worlds</td>
<td>I.A, II.B, III.A</td>
</tr>
<tr>
<td>Planetary habitats</td>
<td>I.A, I.C, III.A, III.B</td>
</tr>
<tr>
<td>Workings of solar systems</td>
<td>All Objectives</td>
</tr>
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<tr>
<th>Decadal Survey Inner Planets Research Goal</th>
<th>Relevant Venus Objectives</th>
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<tbody>
<tr>
<td>Origin and diversity of terrestrial planets</td>
<td>All Objectives</td>
</tr>
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</table>
Atmospheric Entry Conditions

Velocity of 10 km/s
Altitude of 110 km

Homopause between 119 km (evening terminator) and 135 km (night side close to the morning terminator) with a weak dependence on latitude (Limaye et al., 2017)
The values of density are required for the instrument performance model and for the design of the probe.
Cupid’s Arrow miniaturized Quadrupole Ion Trap Mass Spectrometer (mQITMS) is a miniaturized version of the compact 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
- Very stable measurements

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>Isotopic Ratios</th>
<th>Assumed Fractional Abundance</th>
<th>Expected Intensity (cnts)</th>
<th>Requirement**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Major</td>
<td>Minor</td>
</tr>
<tr>
<td>3He / 4He</td>
<td>0.0003</td>
<td>1.08E+08</td>
<td>1.08E+04</td>
</tr>
<tr>
<td>20Ne / 22Ne</td>
<td>12</td>
<td>7.56E+08</td>
<td>6.41E+07</td>
</tr>
<tr>
<td>36Ar / 40Ar</td>
<td>0.16</td>
<td>5.78E+08</td>
<td>3.56E+09</td>
</tr>
<tr>
<td>36Ar / 38Ar</td>
<td>0.18</td>
<td>5.78E+08</td>
<td>3.21E+09</td>
</tr>
<tr>
<td>82,83,86Kr / 84Kr</td>
<td>0.16-0.48</td>
<td>2.70E+06</td>
<td>0.4-1.3E+06</td>
</tr>
<tr>
<td>129, 136 Xe / 132Xe</td>
<td>1,0.3</td>
<td>2.05E+05</td>
<td>2,0.6E+05</td>
</tr>
<tr>
<td>124-128Xe / 132Xe</td>
<td>0.003-0.07</td>
<td>2.33E+04</td>
<td>0.7-14E+03</td>
</tr>
</tbody>
</table>

Measurements integrated during one hour

Ongoing work to calibrate the mQITMS and determine accuracy and compare it with the statistical precision

*1/sqrt(counts)  
**Chassefiere et al., 2012
Purple: mQITMS; Blue: chamber; Green: PCBs; Brown: separation ring; Dark gray: XTJ solar cells; Black: batteries; Yellow: LNA
Design Configuration

Probe

Cruise Stage

STAR27H SRM

Entire Stack in Pegasus XL Launch Fairing
L/V + Trajectory

- OSC Pegasus XL L/V with a STAR27H motor*
- Nominal Launch Date: 05/18/23 12:00 UTCG
- $C_3 = 6.1 \text{km}^2/\text{s}^2$ for a 55 kg payload
- Type II direct transfer

Conclusions

• Understanding how Earth and Venus have diverged in their geological history is key to understanding the habitability of earth-like planets

• Measuring the concentrations of noble gases and isotope ratios in Venus atmosphere would provide key information on the formation and evolution of Venus

• A free-flying SmallSat probe with mass < 55 kg could deliver high-priority science at Venus for a fraction of the cost of a conventional Discovery mission

• Same approach could be adapted to other environments: Titan’s atmosphere, Enceladus’ plume, possible plume at Europa, …