National Aeronautics and Space Administration

Hypervelocity Sampling Across the Solar System: Retiring Risks for Enceladus, Europa, Titan and Venus - Task 2 Venus

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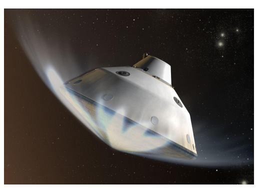
Program: FY21 R&TD Strategic Initiative **Strategic Focus Area: Hypervelocity Sampling Across Solar System**

Objective

The principal objective of this work was to determine whether current hypervelocity gas acquisition strategies are suitable for analyzing samples from planetary atmospheres and plumes during fast flyby / flythrough encounters. The main challenge was to demonstrate that sample collection is possible either without introducing significant fractionation or fragmentation effects that would compromise subsequent sample measurements, or to demonstrate the capability to quantitatively predict system-induced fractionation / fragmentation effects with respect to the undisturbed environment. To this end, international state-of-the-art numerical simulations were designed and performed to retire the risk associated with the two main weaknesses from the Venus Origins Explorer (VOX) mission proposal:

1. Failure to discuss fractionation effects and the relationship between the ingested sample and the Venus atmosphere, and
2. Viability of the gas inlet sample collection system at hypervelocity.



Conditions after the bow shock facilitate molecular dissociation, thus rendering hypervelocity atmospheric sampling very challenging.

Significance

The Direct Simulation Monte Carlo (DSMC) approach successfully addressed the complexities of modeling gas sampling at hypervelocity and rarefied flows through the sampling system for Cupid's Arrow, including sophisticated hardware geometries (valves). A thermal and chemical non-equilibrium flow with trace species, has been modeled where length-scales range from rarefied to continuum conditions. The DSMC results established the quantitative relationship between the constituents of the unperturbed Venus atmosphere at the sampling altitude and the sample collected in the tanks. The estimated pressure and temperature values attest to the viability of the sample collection system, at hypervelocity conditions.

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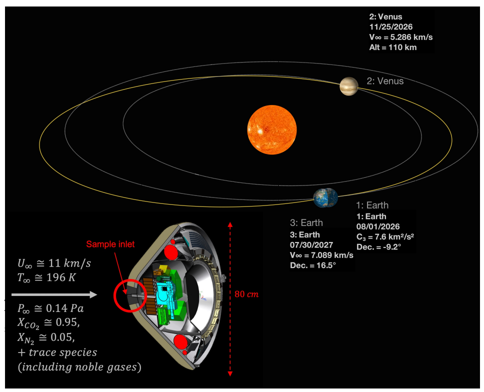
Approach and Results

Viability of sampling system inlet

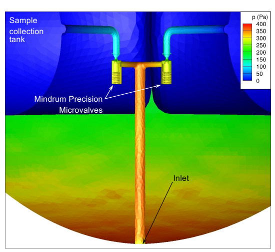
Analysis of the noble gas isotopes present in the Venus atmosphere below the homopause open a window to the planet formation and evolution. Collecting an atmospheric sample in a flythrough at hypervelocity aids measurement precision by evading the limited hardware lifetime in the hostile surface conditions; however, system viability must be demonstrated.



Above: Example spacecraft trajectories from Earth to Venus for a sample-return mission. Inset: Free stream atmospheric conditions at 110 km altitude and a cross-section of Cupid's Arrow spacecraft, showing the gas sample inlet (arrow) and the four collection tanks (red).

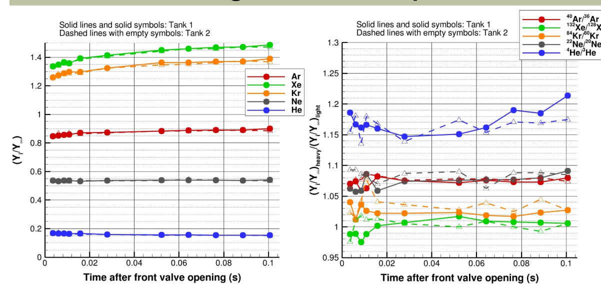
DSMC simulations, carried out to evaluate the viability of the sampling system, showed that the high temperatures recorded on the thermal shield do not penetrate significantly into the gas track, except for the shallow depth at the inlet. All internal components remain at nominal temperatures.

The stagnation pressure (figure below) exceeding 300 Pa allows for the collection of a significant amount of Venus atmospheric sample (0.1-0.2 mol).

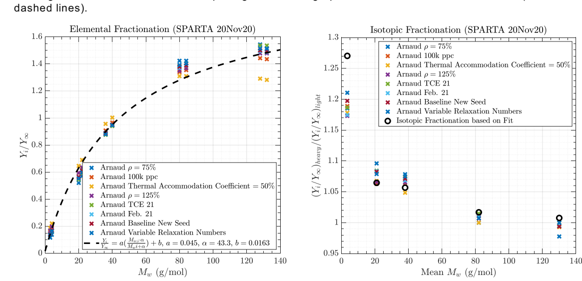


Left: DSMC model of the pressure inside the sample collection system after opening the valves, showing stagnation pressure exceeding 300 Pa. The high temperatures at the inlet do not propagate inward more than 1-2 diameters, and the rest of the gas sample collection system experiences nominal temperatures with the tanks remaining at room temperature.

DSMC: Establishing the relationship between the atmosphere and the collected sample



Above left: Molar ratios for noble gases, carried out by ionized CO_2 media, collected in the tanks with respect to the free-stream as a function of valve opening time. **Right:** Isotopic ratios for selected pairs of noble gases as a function of valve opening time. Both graphs show the results for two tanks (solid and dashed lines).



Above: Elemental (**left**) and isotopic fractionation (**right**) as derived from the SPARTA DSMC model. The results demonstrate that fractionation is predictable within acceptable uncertainty bounds.

DSMC simulations yielded time evolution of two isotopes of each noble gas species in a rarefied atmospheric carrier gas flow into the storage tanks. The figures show the elemental fractionation of the noble gases with respect to the free stream for two tanks (top left) and the isotopic fractionation for each pair of noble gas species (top right). The fractionation is expectedly mass-dependent, being strongest for He (15-20%) and diminishing for Xe.

The sensitivity of the DSMC simulations to various parameters governing the diffusion was tested in conservative bounds. Examples are shown in the two lower figures. The bottom left figure shows the mass-dependence of the elemental fractionation, which is fitted with a mass diffusion dependence. The isotopic fractionation (bottom right) show moderate variability even in extreme conditions.

These state-of-the-art DSMC simulations illustrated conclusively that fractionation can be predicted. The attained accuracy appears sufficient to satisfy the science requirements for a mission designed to investigate the Venus evolution through noble gas isotopic ratios. Notably, $^3He/^4He$ ratio carries the least stringent requirement (<50%), whereas the most valuable science is derived from the Xe isotope ratios, for which the fractionation during sample collection diminishes.

Plans are in put in place to conduct experimental verification of the DSMC simulations using benchtop setup and a high-fidelity facility (NASA Arc Jet).

Other accomplishments

The project responded to the Red Team recommendations by expanding the scope of the DSMC calculations and constructing a benchtop experimental setup for validation of the diffusion part of the model.

Cupid's Arrow has been redefined as a sample return mission that will bring 100 times larger atmospheric sample for studies with highest precision mass spectrometry equipment.

The work on this project has been described in eight conference presentations. Peer-reviewed publications in preparation include: a description of the science for a revised sample-return mission, the results of the DSMC simulations predicting the elemental and isotopic fractionation, and experimental results from the fast pulse valve tests.

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Venus sample return mission

The selection of DAVINCI+, VERITAS and EnVision missions attests to the renewed strong interest in investigating Venus. The reenvisioning of Cupid's Arrow as a sample-return mission offers a unique opportunity to return >100 times larger Venus atmospheric sample that originally intended for *in situ* analysis, distribute the sample in multiple variable portions as needed for interrogation by the most advanced state-of-the-art laboratories in the world, benefitting the science field beyond that devoted to noble gas research. The accuracy of such measurements far exceeds the maximum attainable accuracy of any space-borne instrument; hence, significantly enhancing the science return. Future correlation with complementary *in situ* DAVINCI+ results can further benefit the science return from both missions.

Clearance Number:
RPC/JPL Task Number: R19053