CUPID'S ARROW: ANALYSIS OF HYPERVELOCITY SAMPLING IN THE UPPER ATMOSPHERE OF VENUS.

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Introduction: Cupid's Arrow is a small satellite mission concept that would determine the amount of noble gases and associated isotope ratios in the upper atmosphere of Venus by acquiring and analyzing atmospheric gas samples below the predicted homopause altitude. This mission concept, and the importance of possible scientific return of the mission has been discussed in previous works [1-3] and in a companion publication [4]. Performing high-fidelity noble gas measurements in the Venus atmosphere would help provide the required information to understand why Earth and Venus have diverged in their geological evolution; a critical piece of information required to assess whether a terrestrial exoplanet is Earth-like or Venus-like.

Mission Concept: In brief, the Cupid's Arrow mission concept is a stand-alone small spacecraft (~80 cm diameter, sphere/cone geometry – Fig. 1) that is designed to skim through the Venus upper atmosphere and acquire gas samples below the homopause altitude, where the different atmospheric compounds are expected to be well mixed [1-3]. The velocity of the spacecraft where sampling would occur is expected to be between ~10.5 km/s and ~13.1 km/s, depending on the trajectory chosen. The altitude during sampling operations is expected to be ~110 km. QITMS, a miniaturized quadrupole ion trap mass spectrometer developed at JPL, will be used to measure the noble gas concentrations in the acquired gas samples [5]. In order to ensure that it is possible to relate the composition of the sampled gases to the free stream atmospheric composition, numerical simulations are used to model the flow through the Cupid's Arrow sampling system. In particular, an emphasis is placed on quantifying fractionation that occurs during the sample acquisition process in order to determine how measured isotopic ratios of noble gases in the sample compare to actual isotopic ratios in the Venus atmosphere.

Numerical Simulations: The Direct Simulation Monte Carlo (DSMC) code SPARTA, an open source software package developed by Sandia National Laboratories [6], is used in this work. SPARTA, based on Bird's DSMC method [7], is a molecular-level gas-kinetic technique. As SPARTA is able to model hypervelocity reacting flows in strong chemical and thermal non-equilibrium, this software package is well suited to determine relevant flow properties for the Cupid's Arrow mission concept, and to numerically quantify the expected level of elemental and/or isotopic fractionation in the sample acquired by Cupid's Arrow.

Preliminary 3D Simulation Results: Recent work has focused on 3D simulations that include realistic valve and tank geometries for the internal flow in the Cupid's Arrow sampling system. Due to the strong bow shock in front of the spacecraft (Fig. 1), the gas number density increases by several orders of magnitude before it enters the sample acquisition system, which causes the mean free path to decrease accordingly. This results in near-continuum flow conditions inside of the sampling system which causes the computational cost of these 3D simulations (one-quarter of the full domain is simulated through the use of symmetry boundary conditions) to be quite high, even when the adaptive grid strategy in SPARTA is employed [8].

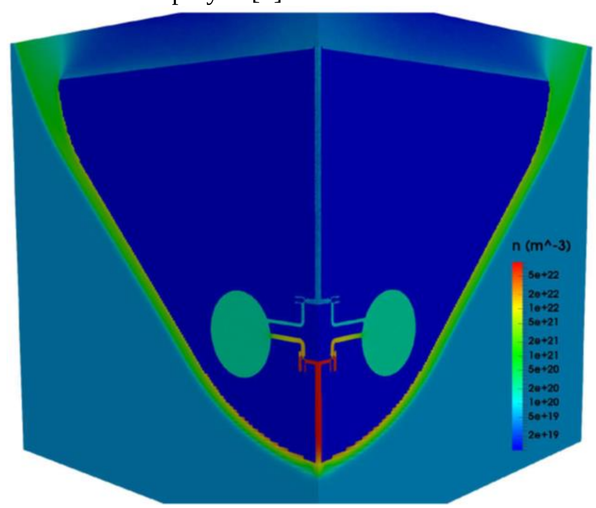

Figure 1 - Sample 3D DSMC simulation results showing a strong bow shock in front of the spacecraft.

Furthermore, valves (Fig. 2), are used to isolate the sample acquisition tanks and to control the amount of gas sample acquired, which are complicated geometrical features that must be included in the DSMC simulations. The gas velocity through the valve and into the sampling tanks (Fig. 3) has been determined to be a quantity of interest that is quite sensitive to the numerical parameters chosen in the simulations (primarily with respect to levels of grid adaptation chosen along with numerical simulators/cell in the freestream). The velocity of the sampled gases into the sampling tank determines the mass flow rate of sample into the tanks, so knowing this parameter is essential in order to determine how long gas needs to be acquired to collect enough noble gases in order to generate an accurate measurement using QITMS.

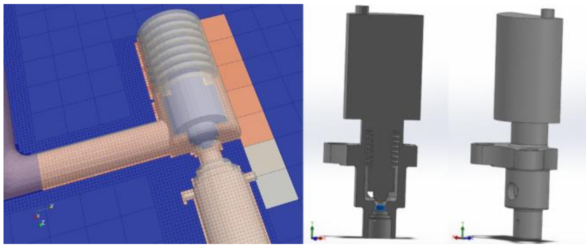

Figure 2 – Valve used to isolate the sample acquisition tanks for the Cupid's Arrow mission concept. Sample numerical discretization in SPARTA (left) and CAD model (right). Approximate height of the geometry shown is 4 cm.

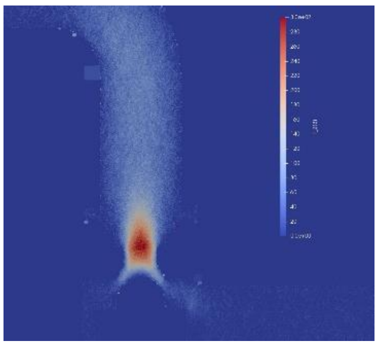

Figure 3 – Sample contour plot of gas flow velocity (red represents the highest speed) though the valve shown in Fig. 2. The flow starts at the right of the image, travels through the valve, and then exits in the vertical direction.

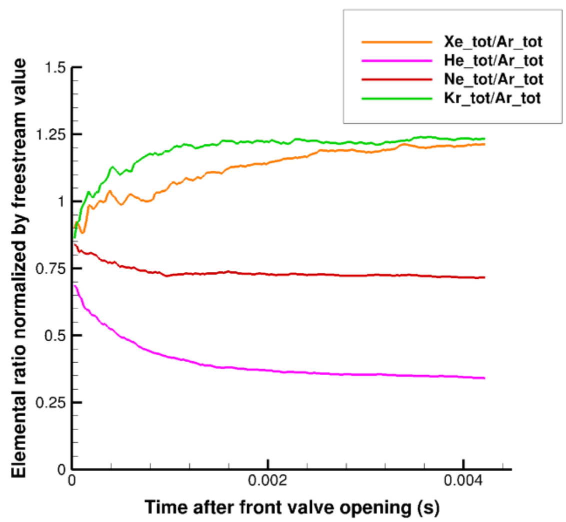

Figure 4 – Sample simulation results showing elemental fractionation in the sample acquisition tank.

Preliminary simulations suggest that while there is some elemental and isotopic fraction as the flow travels through the sampling system (i.e., whether or not relative concentration ratios are the same in the sampling tanks as they are in the freestream), it can be quantified with DSMC simulations (Figs. 4 and 5).

Ongoing simulation work is focused on understanding the sensitivity of the numerical results, in order to be able to predict as best as possible the performance of the proposed sampling system. A quasi-sensitivity analysis is ongoing in order to quantify the uncertainty expected with the numerical predictions. Numerical results and uncertainties will be compared to the original Science Traceability Matrix, in order to ensure that all science objectives can be accomplished.

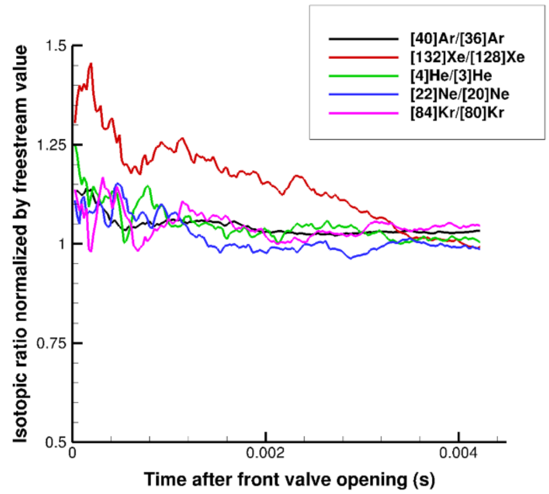

Figure 5 – Sample simulation results showing isotopic fractionation in the sample acquisition tank.

Conclusion: Through the ongoing numerical simulations, it is believed that a better understanding of the physical processes occurring during hypervelocity sampling in the upper atmosphere of Venus will be acquired. This knowledge will demonstrate whether or not elemental and/or isotopic fractionation is expected to occur in the Cupid's Arrow sampling system, and allow measured gas compositions to be related to the freestream composition and isotopic ratios. Ongoing numerical sensitivity study efforts will give additional confidence in the numerical results and will help quantify uncertainty associated with the numerical predictions. Future work will also include experiments to validate specific aspects of the numerical simulations.

References: [1] Sotin et al., *LPSC*, 2018, 1763, [2] Rabinovitch et al., *VEXAG*, 2018, 2137, [3] Rabinovitch et al., AIAA 2019-3223, [4] Sotin et al., *LPSC*, 2020 [5] G. Avice, et al., *J. Anal. At. Spectrom.*, 2019, [6] Plimpton and Gallis, http://sparta.sandia.gov, [7] Bird, 1994, [8] Plimpton et al., *Phys. Fluids*, 2019.

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