Introduction: Getting reliable measurements of noble gases in Venus’ atmosphere with a Small Satellite mission concept is very challenging. However, if feasible it could change how we make this fundamental geochemical measurement in planetary atmospheres and other gaseous environments (e.g., plumes emanating from icy moons or dwarf planets) across the solar system. Venus poses the most urgent and nearby target for such measurements in order to fill in a key piece of the puzzle of Venus’ origin, evolution, and divergence from Earth’s geological history. Understanding Venus’ geological evolution is also key to interpreting observations of “Earth-like” exoplanets in order to assess whether they are Earth-like or Venus-like, which has obvious implications for their habitability potential. Noble gases are tracers of the evolution of planets. They trace physical processes such as the original supply of volatiles from the solar nebula, delivery of volatiles by asteroids and comets, escape rate of planetary atmospheres, degassing of the interior, and its timing in the planet’s history. However, a major observational missing link in our understanding of Venus’ evolution is the elementary and isotopic pattern of noble gases and stable isotopes in its atmosphere, which remain poorly known [1]. The concentrations of heavy noble gases (Kr, Xe) and their isotopes are mostly unknown, and our knowledge of light noble gases (He, Ne, Ar) is incomplete and imprecise. The Cupid’s Arrow mission concept would measure those quantities below the homopause where gas species are well mixed.

The Cupid’s Arrow mission concept was first developed under the NASA PSDS3 (Planetary Science Deep Space SmallSat Studies) program [2]. At the end of this study, a few science issues needed to be resolved: (1) the fractionation of noble gases during sampling, (2) the best strategy for sample acquisition, and (3) the precision and accuracy of the measurements. The first question is addressed in a companion abstract [3]. The present study focuses on issues (2) and (3).

Strategy for sample acquisition: The objectives of the Cupid’s Arrow mission are to determine (1) the origin of the volatiles, (2) the atmospheric loss mechanisms, and (3) the history of volcanic outgassing [2]. These objectives would be achieved by measuring noble gases concentrations and their isotope ratios below the homopause. Cupid’s Arrow is an atmospheric skimmer that would collect four atmospheric samples at high velocity and would have plenty of time (several hours to several days) to measure the abundances of noble gases and their isotopes once outside Venus atmosphere. It would then transmit the results to Earth. The measurements would be made by a miniaturized quadrupole ion trap mass spectrometer (mQITMS) that has been developed at JPL.

During hypervelocity sampling, the main molecules in Venus atmosphere (CO₂ and N₂) dissociate through the bow shock in front of the vehicle, and can recombine further downstream. The reactions are modeled in the numerical simulations [3]. The main components to be removed by a getter in the sample acquisition tanks are CO, CO₂, O, O₂, N₂, N, NO. We are currently testing getter efficiency in order to remove as much as non noble gases as possible. The pressure inside the tank for optimizing the mQITMS performances is 1.10⁻⁶ Torr (~0.13 mPa). With the known abundance of ⁴₀Ar in the Venus atmosphere [1], the numerical simulations using the geometry of the valves [3] suggest that a one liter tank would be filled in approximately 1 second. This time is much smaller that the time spent below the homopause at periapsis ~100 s [2]. The altitude of the

![Figure 1: Representative geometry of the Cupid’s Arrow sampling system including four tanks that will be used for sample acquisition while skimming through Venus atmosphere below the homopause. Collecting four samples provides flexibility and robustness for the mission concept](Image)
homopause varies as a function of latitude and local solar time [4,5]. To be conservative, the lowest altitude of 120 km is assumed and a sampling altitude of 110 km is chosen, which is more than two scale heights below the lowest altitude of the homopause.

We have studied two mission scenarios. The first and simplest one is to perform one flyby. In the second scenario, the probe would get in orbit around Venus and could have a second pass through the atmosphere for additional sampling acquisition.

**Precision and accuracy of the measurements:**
We have conducted measurements in the lab in order to validate the performance model that is given by the instrument team. We demonstrated that the performances exceed the requirements on precision with ample margins with a 40-mm integration time [2]. After the analysis of the first tank, the integration time can be adjusted in order to optimize the counting precision for the three other tanks.

The accuracy of the measurements can only be tested by comparing the measurements by the mQITMS with those obtained by a laboratory mass spectrometer. Such measurements were made on the Allende meteorite [6] and the comparison is excellent as can be seen in Figure 2 for the Xenon isotopes. Isotope ratios are expressed relative to the isotopic composition of the atmosphere and using the delta notation:

\[
\delta^{129}_{\text{Xe}} = 1000 \left( {^{132}\text{Xe}}_{\text{Allende}} / {^{132}\text{Xe}}_{\text{air}} - 1 \right)
\]

The comparison with published data [7] is excellent (Fig. 2). It demonstrates the high degree of accuracy of the measurements made by the mQITMS.

![Figure 2: Isotopic composition of Xe extracted from Allende carbonaceous residue. The isotope compositions of Xe of a previous study on the Allende meteorite [7] are shown for comparison. Error bars for literature data are not visible at this scale. Errors at 1σ.](image)

**Conclusions and perspectives:** The mission concept that has been developed during the study funded by the PSDS3 NASA program. It has matured during the last two years to provide answers to some issues identified during internal and external reviews. The cost would be less than the $100M PSDS3 cost cap. However, the SIMPLEX cost cap is currently at $55M which has led the team to look for cheaper ways to build the probe.

One important step will be the validation of the numerical simulations. This will be achieved by doing laboratory simulations at an arc jet facility located at NASA Ames Research Center. The conditions of the laboratory experiments will be used as inputs to the numerical simulations. Comparisons between the modeled values and the observed values will inform us on the validity of the numerical simulations. Such lab measurements are foreseen at the end of 2020.

The Cupid’s Arrow proposal could not be submitted to the first SIMPLEX call because there was no opportunity to launch in the direction of Venus. The second call, supposedly during the second semester of 2020, may contain options to go to Venus. We are also investigating the possibility of demonstrating aerocapture at the same time we do the noble gases measurements.

Although Venus is the most urgent application, this mission concept could also be applied to other places such as Titan where the probe could be piggy-packed by a mission such as the Dragonfly mission that was recently selected as NASA’s New Frontiers 4 mission. It could also be used to analyze plumes emanating from icy moons such as Enceladus and Europa.

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