Virtual Research Presentation Conference

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

Principal Investigator: Jason Rabinovitch (352B)
Co-Is: Michael J. Malaska (322), Christophe Sotin (4000), Stojan Madzunkov (389), Arnaud Borner (STC), Michael Gallis (Sandia National Laboratories)
Program: 4x Strategic Initiative

Jet Propulsion Laboratory
California Institute of Technology

Hypervelocity Sampling at Venus

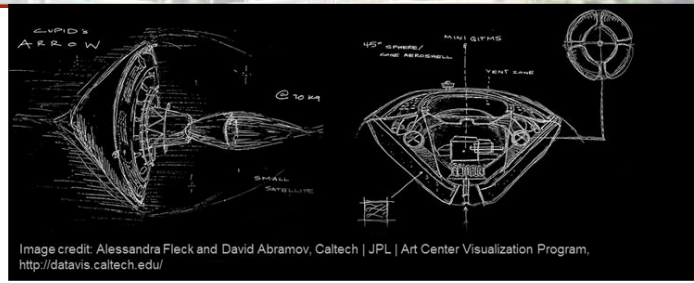


Image credit: Alessandra Fleck and David Abramov, Caltech | JPL | Art Center Visualization Program, http://datavis.caltech.edu/

Contact: jason.rabinovitch@jpl.nasa.gov

Abstract

Noble gases in planetary atmospheres are tracers of their planet's geophysical evolution, and noble gas measurements at Venus represent high-priority science as outlined in the Planetary Decadal Survey. However, noble gases cannot be sensed remotely, and instead have to be measured in situ, below an altitude referred to as the homopause, where atmospheric gases are well-mixed and samples are representative of their naturally occurring concentrations.

Historically, in-situ atmospheric noble gas measurements have been performed with probes that descend slowly through the atmosphere, which are generally complex and costly. This work is geared towards maturing a small atmospheric skimmer probe concept, representing the simplest and most cost efficient method for conducting in-situ atmospheric measurements. The small atmospheric probe architecture is ideally suited for low-cost mission opportunities such as SIMPLEx and DISCOVERY, while still returning high-priority science. This SR&TD focuses on the Cupid's Arrow mission concept, which is a small atmospheric skimmer designed to sample and measure noble gases in the Venusian atmosphere. In this mission concept, atmospheric gas samples are acquired by the spacecraft below Venus's homopause at ~110km in altitude, while the spacecraft is traveling at a velocity of ~11km/s.

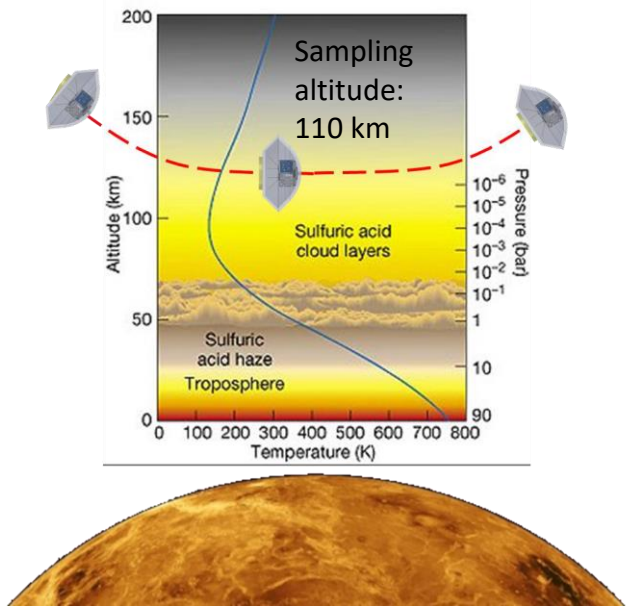
Hypervelocity Sampling at Venus: Science and Challenges

1) Two key Science questions:
   a) Is there extraterrestrial life? Are Exoplanets Earth-like or Venus-like?
   b) Why have Earth and Venus had such divergent geological evolutions? What makes a planet inhabited?

2) Mission Concept:
   a) SIMPLEx class ($55M) atmospheric skimmer, Cupid's Arrow (also proposed as part of NF VOX), would measure noble gases, which act as tracers of planetary evolution, in Venus' atmosphere.

3) Relevance to NASA and JPL (Impact on current or future programs)
   a) Hypervelocity sampling received major weaknesses on previous proposals, and this SR&TD is designed to advance the state-of-the art for hypervelocity sampling of noble gases in order to directly respond to the previously received major weaknesses

4) Driving challenge for hypervelocity sampling:
   a) Is what you measure representative of the true sample composition? Does the process of sampling a low-density high-enthalpy flow alter the noble gas elemental and isotopic ratios, and if so, can this be quantified?



Cupid's Arrow Mission Concept – sample Venus atmospheric gases at 110 km altitude (below the homopause) while traveling at ~11 km/s

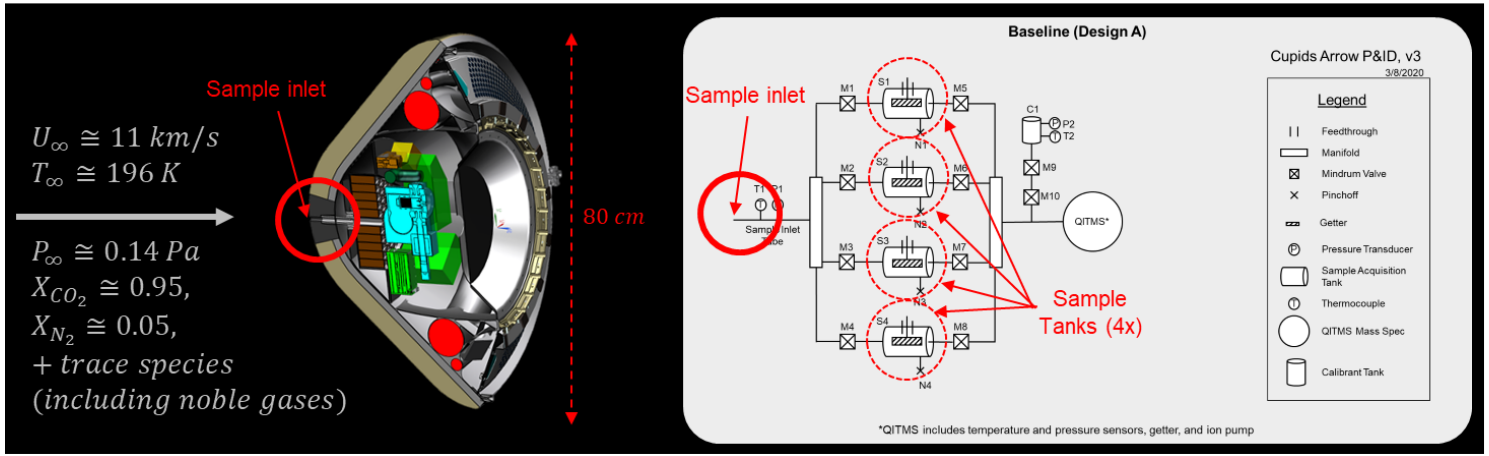
Cupid's Arrow Mission Concept

a) Cupid's Arrow is a Venus atmospheric skimmer that samples the Venus atmosphere at ~ 110 km altitude, while traveling at ~ 11 km/s. It will measure noble gas concentrations with a JPL developed miniaturized quadrupole ion trap mass spectrometer (mQITMS) or return the sample to the Earth.

b) Objective: Measure noble gas concentrations and isotopic ratios to answer key scientific questions

c) Challenges: Venus atmospheric pressure is extremely low at 110 km (~ 0.1 Pa; ~1 mtorr) → very challenging to perform relevant experiments on the earth

d) Strategic partnership with NASA Ames (Arnaud Borner) and Sandia National Labs (Michael Gallis) to perform numerical simulations



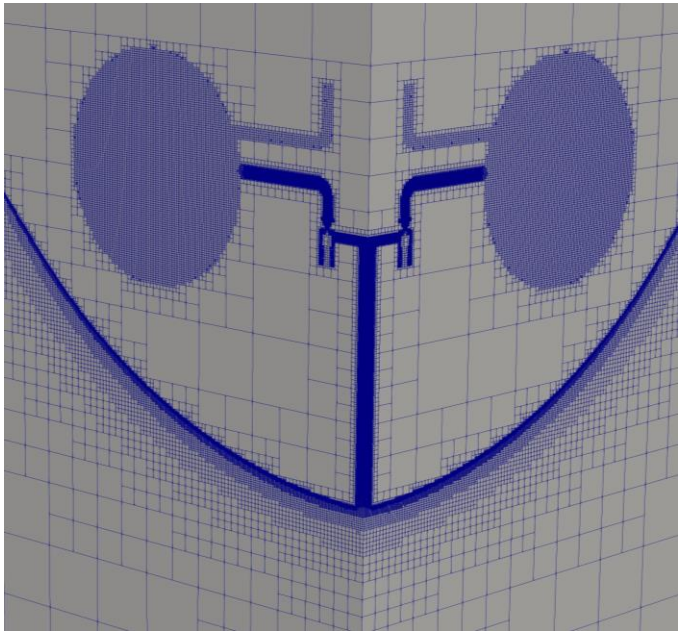
Direct Simulation Monte Carlo (DSMC)

DSMC is a numerical method that solves the Boltzmann equations in a statistical sense (collision-based algorithm)

a) We are leveraging Sandia's unique computational capabilities to run these simulations – very few institutions (internationally) have the computational resources to run these simulations in a reasonable amount of time

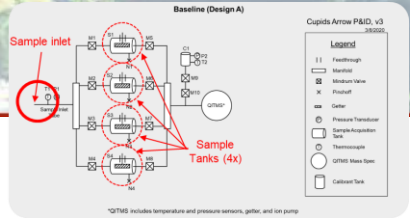
b) The DSMC method is used when the mean free path is similar in magnitude to length-scales of interest, so a continuum assumption is not valid, and traditional CFD methods based on the Navier-Stokes Equations break down

c) Used to model high-speed, low-density flows in thermal and chemical non-equilibrium
   a) https://sparta.sandia.gov/
   b) See Bird, 1994



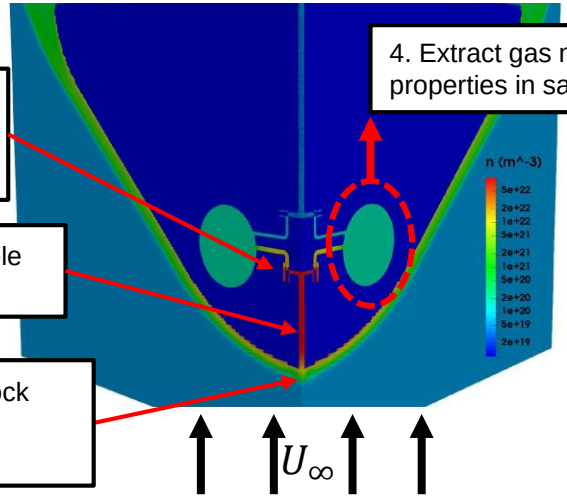
Sample mesh visualization from DSMC calculations.

Computational Cost: 512 nodes x 36 cores x 25 days ~ 11E6 core-hours
To compare: Gattaca (new JPL HPC cluster) has **4,608** cores in total, while our simulations are currently running on **18,432** cores for **25 days**.



Preliminary Simulation Results

- Using SPARTA (DSMC software developed at Sandia) to run simulations to predict the gas mixture conditions in the sampling tanks as a function of time → focusing on noble gas results
- After valves are opened to start sampling, what is the composition is the Sample Tanks?

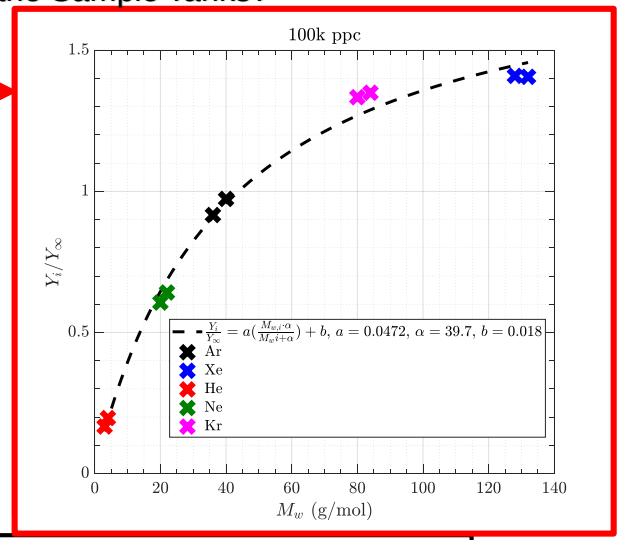


3. Valve to control sample acquisition timing

2. Flow through sample inlet tube

1. Combined bow shock and boundary layer (compression layer)

4. Extract gas mixture properties in sample tank.



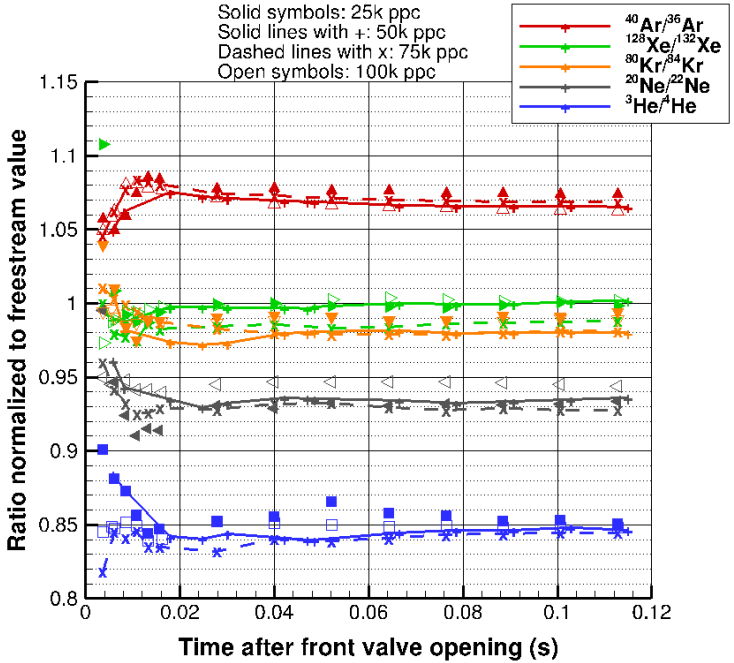
Takeaway – fractionation can be quantified!

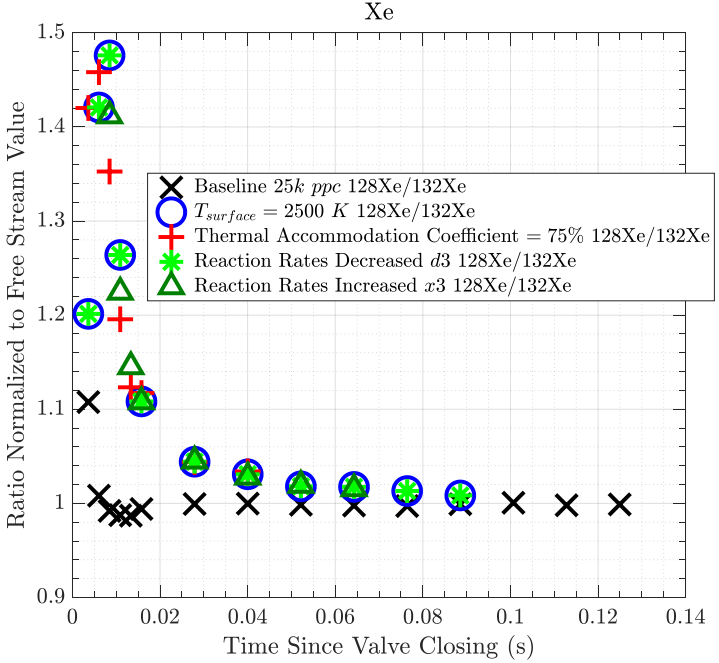
All plots are normalized by free-stream values, so a ratio of 1 would indicate no fractionation

- Fractionation does occur, and is driven by molecular weight differences
- Heavier species are preferentially sampled compared to lighter species

Future Work

a) FY'21 will focus on numerical sensitivity studies for uncertainty quantification





- New *master* version of the code used to run new simulations – currently re-running 25k ppc simulation case as it is an outlier
- Caveat: 2% uncertainty in viscosity (where all our molecular models are based), 4% discretization error of the simulations, 4% error in gas viscosity due to the increased fraction of noble gases → discrepancies due to physical models are not the largest source of error

Conference Presentations and Proceedings

- Rabinovitch, J., Sotin, C., Borner, A., Gallis, M. A., et al. (2018) Feasibility of Hypervelocity Sampling of Noble Gases in the Upper Atmosphere of Venus. 16th VEXAG Meeting, 6-8 Nov 2018, Laurel, MD. LPI Contribution No. 2137, ID 8022.
- Sotin C., Borner A. P., Gallis M. A., Rabinovitch J., Avice G., Darrach M., Madzunkov S., et al. (2018) Sampling Venus' atmosphere to measure noble gases and their isotope ratios, AGU Fall Meeting, 10-14 Dec 2018, Washington, D. C.
- Baker J., Sotin C., Rabinovitch J. (2019) Cupid's Arrow: Mission Concept and Overview, 13th IAA Low-Cost Planetary Missions Conference, 3-5 Jun 2019, Toulouse, France.
- Rabinovitch J., Borner A., Gallis M. A., Sotin, C. (2019) Hypervelocity Noble Gas Sampling in the Upper Atmosphere of Venus. AIAA Aviation 2019 Forum, 17-21 Jun 2019, Dallas, TX.
- Rabinovitch J., Borner A., Gallis M. A., Sotin C., Baker J. (2019) Cupid's Arrow: Hypervelocity Noble Gas Sampling in the Upper Atmosphere of Venus, International Planetary Probe Workshop 2019, 8-12 Jul 2019, Oxford, UK.
- Sotin C., Borner A., Gallis M., Rabinovitch J., et al. (2019) Modelling the performance of Cupid's Arrow, a small satellite that would measure noble gases in Venus atmosphere, EPSC-DPS Joint Meeting, 15-20 Sept 2019, Geneva, Switzerland.
- Borner A., Gallis M. A., Rabinovitch J., Sotin C. (2019) DSMC Simulations of Hypervelocity Sampling in Venus' Upper Atmosphere, DSMC 2019 Conference, 22-25 Sept 2019, Santa Fe, NM.
- Rabinovitch, J., Borner, A., Gallis, M. A., Sotin, C., Baker, J., "Cupid's Arrow: Hypervelocity Sampling in the Upper Atmosphere of Venus," abstract and poster at the 17th Meeting of the Venus Exploration and Analysis Group (VEXAG), 6-8 November 2019, Boulder, Colorado.