Cupid's Arrow: An Innovative Nanosat to Sample Venus' Upper Atmosphere

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Abstract— **In NASA's Discovery 2014 AO, the opportunity to propose a Technology Demonstration Opportunity (TDO) to enhance the primary mission was specified. For the Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) mission, we elected to include the Cupid's Arrow nanosat TDO to sample and measure the abundances of noble gases and their isotopic ratios in Venus's upper atmosphere below the homopause.**

This paper will provide a basic overview of the VERITAS mission, with a focus on the Cupid's Arrow concept including a description of the mission, spacecraft design, and JPL's quadrupole ion trap mass spectrometer (QITMS) instrument specifications and design. In previous planetary entry probe mission designs, particularly at Venus, engineers were focused on entry and descent. A landed probe was also proposed for the New Frontiers SAGE mission. For Cupid's Arrow, the nanosat is designed to skim through the upper atmosphere, just below the homopause, in order to sample the atmosphere, perform the analysis, and then exit the atmosphere to transmit its data to the orbiting VERITAS spacecraft.

Cupid's Arrow is a compelling addition to the VERITAS geology mission. A key missing link in our understanding of Venus' evolution is the noble gas abundances and their isotopic ratios. Not since Pioneer Venus have these measurements been made in the Venus atmosphere and never in the upper atmosphere, just below the homopause, to the degree of accuracy that will be accomplished by VERITAS' Cupid's Arrow nanosat.Such measurements were ranked as the number 1 investigation of the number 1 objective of the goal "Atmospheric Formation, Evolution, and Climate History".

TABLE OF CONTENTS

1. INTRODUCTION

In November 2014, NASA released the Discovery 2014 Announcement of Opportunity (AO). NASA's Discovery Program gives scientists the opportunity to dig deep into their imaginations and find innovative ways to unlock the mysteries of the solar system. Beginning in 1992, this program represented a breakthrough in the way NASA explores space. For the first time, scientists and engineers were called on to assemble teams and design exciting, focused planetary science investigations that would deepen the knowledge about our solar system.

As a complement to NASA's larger "flagship" planetary science explorations, Discovery's main objective is to enhance our understanding of the solar system by exploring the planets, their moons, and small bodies such as comets and asteroids. The program also seeks to improve performance through the use of new technology and broaden university and industry participation in NASA missions. As stated in the AO, the goals and objectives were to:

- Advance scientific knowledge and exploration of the elements of our Solar System
- Add scientific data, maps, and other products to the Planetary Data System archive for all scientists to access
- Announce scientific progress and results in the peer-reviewed literature, popular media, scholastic curricula, and materials that can be used to inspire and motivate students to pursue careers in science, technology, engineering, and mathematics
- Expand the pool of well-qualified Principal Investigators and Program Managers for implementation of future missions in Discovery and other programs, through current involvement as Co-Investigators and other team members
- Implement technology advancements proven in related programs

It was the last point that was particularly emphasized in the Discovery AO with the description of a Technology Description Option (TDO): The basic description of the TDO was as follows:

- It would be desirable for Discovery missions to introduce new technologies in order to enable new scientific investigations or enhance the investigation's science return
- Investigation could be a non-NASA developed instrument, investigation, new technology, hardware or software that could be demonstrated on either the flight

system or ground system

- The TDO must use innovative technological approaches that may have continuing applicability to future SMD missions
- Radioisotope power systems not allowed
- The TDO must be clearly separable from the proposed baseline and threshold science investigations to the extent that it will not impact either the Baseline or Threshold Mission if the TDO development has technical, schedule or cost problems and is deleted from the mission, or if the TDO fails in flight

2. VERITAS AND CUPID'S ARROW MISSION

One of the 5 Discovery 2014 proposals selected by NASA for Phase A funding was the Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) mission. Proposed to launch in November 2021., VERITAS follows an Earth-Earth-Venus Type IV trajectory on a 27-month cruise, with Venus Orbit Insertion (VOI) in February 2024. Once in orbit at Venus, VERITAS circularizes its orbit via aerobraking for 8.6 months to achieve a 216 km orbit at 88.5° inclination. Over the course of three Venus cycles (2.3 years), VERITAS will produce global, high-resolution topography and imaging of Venus' surface and produce the first maps of deformation and global surface composition.

The VERITAS' TDO, named Cupid's Arrow, is a low cost, high value investigation to sample the Venus atmosphere using CubeSat-components in a unique configuration. Cupid's Arrow is planned to demonstrate a new ultracompact quadrupole ion-trap mass spectrometer (QITMS) to measure fundamental geochemical properties of planetary atmospheres.

The VERITAS spacecraft serves as Cupid's Arrow's mother ship by supporting the small spacecraft to Venus, housed in a small container on the –Z deck, through launch, cruise, VOI and the beginning of aerobraking. Throughout cruise, the container supplies keep-alive power, thermal control, and a telemetry link for commanding and health checks. Cupid's Arrow mission is summarized in Figure 1. At aerobraking pass 200, Cupid's Arrow is deployed with at a spin rate of 5 rpm and a relative velocity of 1.25 m/sec in the along-track direction of the VERITAS spacecraft. At 7.5 hours after deployment, with a 125 km periapsis altitude (below the homopause) at a velocity of 9.7 km/sec, the Cupid's Arrow science mission begins. Under these conditions, the released spacecraft will encounter an atmospheric density of 149 kg/km3, a heating rate of 7w/cm2 and a dynamic pressure of 7Pa. Under these conditions, the heating rate is higher than that of the VERITAS spacecraft yet still quite modest compared to aerocapture or direct entry probes.

The QITMS opens a cap, to ingest a 100 ml atmosphere sample and scrub major constituents in a noble gas enrichment cell for 5 minutes. Cupid's Arrow provides 30 WHrs of power and 16.4 Mb of data storage for its 20 minute science mission. Upon exit from the atmosphere, Cupid's Arrow transmits its data to the VERITAS spacecraft at a range of about 1000km.

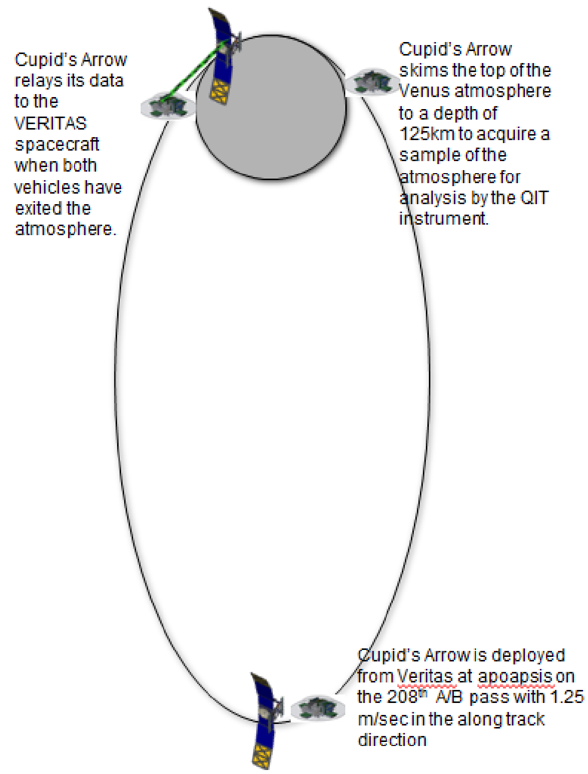

Figure 1. Cupid's Arrow Concept of Operations

Cupid's Arrow has design inheritance from JPL's planetary CubeSats under development, including MarCO and INSPIRE. The avionic designs for JPL's CubeSat are taken directly from those developments and are all space-qualified. Communication with the VERITAS spacecraft is via low-gain UHF band antennas, which taken together are omnidirectional, with no pointing requirement. Cupid's Arrow technical requirements are summarized in Table 1, while the flight configuration is depicted in Figure 2.

Table 1. Cupid's Arrow Technical Requirements

Key Technical Parameters	
Mass	Flight Vehicle 16 kg, 8.2 kg deployer + relay avionics = 24.2 kg MEV total
Power	28 vdc, ~3W supplied to heater and battery charger prior to deployment
Data interface	RS422, SPC, I2C, or GPIOs for command/ telemetry. SpaceWire for high speed/volume data
Thermal	TDO package to be thermally isolated from VERITAS
Mechanical I/F	Deployer is new design for 1.25 m/s deployment velocity and 5 RPM spin
Payload	Ultra-compact, quadrupole ion trap mass spectrometer (QITMS)
CubeSat Avionics*	• Radiation tolerant dual-core to 200 MIPS processor • INSPIRE UHF-band radio and LGAs • 150-Wh battery
Flight software	RTOS supports telecom, CMD & TLM functions, QITMS data processing

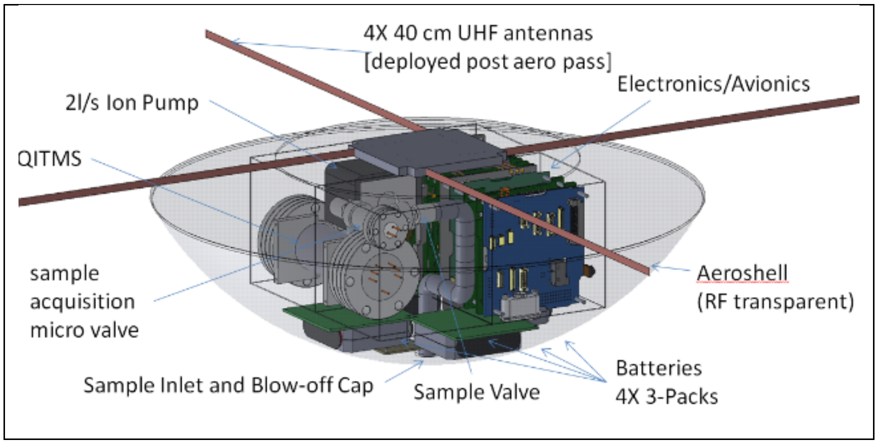

Figure 2. Cupid's Arrow flight system configuration.

QITMS Instrument

Inventorying Venus's noble gases is the highest-priority investigation for Goal I/Objective A identified by the VEXAG. Specifically, to sample the Venus atmosphere and measure the noble gases (^{4}He, ^{20}Ne, ^{36}Ar, ^{40}Ar, ^{84}Kr, ^{130}Xe) abundances and their isotopic ratios with precision <1-5%.

Noble gases are tracers of planetary evolution, illuminating 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 a planet's interior, and its timing. For Venus a major observational missing link in understanding the evolution of its atmosphere is the elementary and isotopic pattern of noble gases and stable isotopes, which remain poorly known [Chassefiere et al. 2012]. These measurements strongly complement VERITAS's science goals, which seek to understand another key aspect of the history of volatiles on Venus: how they are cycled between Venus's atmosphere and interior, through evidence of past tectonic activity at the surface, and present-day volcanic outgassing.

The performance and accommodation specifications for the Cupid's Arrow QITMS are summarized in Table 2. Meeting the science objectives for Cupid's Arrow relies heavily on the QITMS' high sensitivity and peer-reviewed noble-gas isotope-ratio performance, which is better than 0.1% precision and 0.3% accuracy [Madzunkov and Nikolic, 2014]. The QITMS has been under continuous development at JPL for the last 15 years. As VCAM (Vehicle Cabin Atmosphere Monitor), it attained TRL 9 on the ISS in 2009 [Darrach et al. 2012]. The successor flight instrument to VCAM, the Spacecraft Atmosphere Monitor (S.A.M), was awarded in October 2014. The S.A.M instrument, based on the QITMS, will be delivered to the International Space Station and ORION in 2017 to monitor the astronaut atmosphere on all future crewed spaceflight missions.

In 2013 the QITMS received an ICEE (Instrument Concepts for Europa Exploration) grant and was proposed to the Europa Instruments competition where it was evaluated as Category-II. Also in 2015 it received the NASA New Frontiers Homesteader award for maturation into an atmospheric probe instrument for both Venus and Saturn. Obviously the Homesteader award enables significant leveraged development of the Cupid's Arrow QITMS.

The QITMS technology offer key benefits for planetary flight applications:

a. Today's smallest flight MS. Instrument size is an unusually critical parameter for atmosphere probe missions since the size of the probe vessel is determined by the volume of enclosed instruments and minimization of pressure-vessel structural mass. Probe size is especially sensitive to instruments' longest irreducible dimension. For Cupid's Arrow, the largest QITMS subassembly is 21 cm long, only 16% and 40% of size of a time-of-flight or and linear-quadrupole MS, respectively.

b. Acquires full-range mass spectra at full sensitivity. Unlike linear-quadrupole mass spectrometers that must measure individual mass lines sequentially, the QITMS measures the entire mass range with full sensitivity and resolution. The Cupid's Arrow performance model, even with a de-rating factor of 5 in both operating pressure and sensitivity, indicates that 1% (for ppm) and 20% (for ppb) accuracies can be determined every 40 seconds. This high-speed, full-range measurement ensures that no

Table 2. QITMS Performance and Accommodation Specifications.

Performance	QITMS Value
Sensitivity	10^{14} counts/torr/sec (axial ionization mode)
Mass range	3-140 amu
Mass resolution[1]	m/Δm (full width half maximum) = 700 @ 130 Dalton
Isotopic precision	Major isotope abundances – ^{4}He, ^{20}Ne, ^{36}Ar, ^{40}Ar, ^{84}Kr, ^{130}Xe: <5% Isotope ratios – ^{3}He/^{4}He, ^{20}Ne/^{22}Ne, ^{36}Ar/^{38}Ar, ^{82,83,86}Kr/^{84}Kr, ^{129,136}Xe/ ^{130}Xe: <1 – 3% (Values are for Cupid's Arrow Instrument; Ion Trap MS Alone is <0.1%[2])
Mass	4 kg, including 30% contingency
Power	31W, including 30% contingency
Volume	20 cm x 20 cm x 10 cm, including 15% cont. (equivalent to 4U CubeSat form factor)

[1]*Mass instability mode, no cooling or buffer gas;*
[2]*Madzunkov & Nikolić 2014.*

species are missed from having to anticipate which mass channels are important to monitor.

c. Highest native partial-pressure sensitivity of any flight MS. The QITMS does not require special-trapping ion sources or cryotrapping of trace noble gases, both of which can introduce measurement error and bias. Cupid's Arrow will measure the noble gases directly without cryotrap pre-processing, enabling real-time and altitude-profile measurements.

The QITMS and its electronics are shown in Figures 3 and 4, respectively. The "wireless" QITMS configuration accommodates the high G-load environments experienced during atmospheric entry and landing. Shown in Figure 5 are high-resolution spectra obtained using the QITMS.

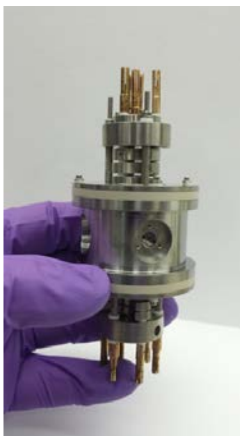

Figure 3. "Wireless" QITMS All electrical contacts are made through support rods, without any discrete wires. The QITMS is held in compression between two vacuum flanges enabling a robust, compact, flight instrument.

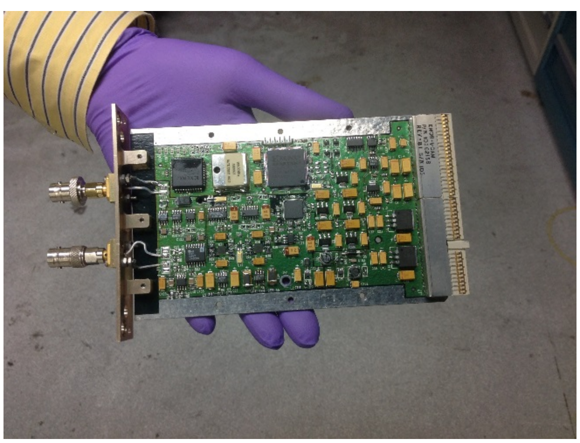

Figure 4. QITMS Electronics for Cupid's Arrow

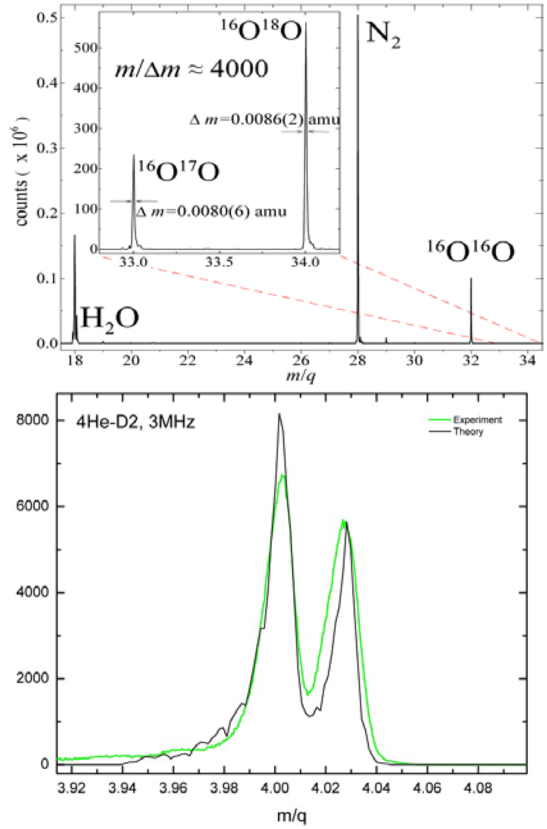

Figure 5. QITMS mass resolution allows unambiguous identification. Left: QITMS spectrum of oxygen isotopes demonstrates m/Δm = 4000 FWHM. Right: QITMS spectrum demonstrating mass resolution at low mass. The black curve represents theoretical model developed at JPL for the mass spectral lineshapes, which has excellent agreement with the experimental data (green curve).

3. CONCLUSIONS

Cupid's Arrow is a TDO proposed to fly on the VERITAS spacecraft. While most solid body in-situ atmospheric missions descend well into the increasingly dense atmosphere, Cupid's Arrow skims through the upper Venus atmosphere to an altitude of 125 km, where its QITMS instrument ingests a sample and measures noble gases and key isotropic ratios. This economical investigation provides valuable Venus atmospheric data at a fraction of the cost of a dedicated atmospheric probe mission.

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BIOGRAPHY

Bernie Bienstock *received a B.S. in Engineering from UCLA in 1968, an M.S. from UCLA in 1970 and an Engineer's Degree from USC in 1977. After a 32-year career in systems engineering and program management at Hughes and Boeing, he decided to begin anew with his second career at JPL in February, 2007. He specializes in formulation across the various JPL areas of Solar System, Earth Science and Astrophysics investigations. To date, he has managed four JPL Venus proposals, with the latest, VERITAS, selected as one of five Discovery 14 proposals by NASA for a Phase A study. Bernie's other passion is planetary probe missions. He has chaired the last seven yearly International Planetary Probe Workshops (IPPWs) and is currently planning IPPW-13, scheduled for June, 2016 at the Applied Physics Laboratory (APL) in Laurel, Maryland.*

Murray Darrach *received his PhD in Physics from the University of Windsor (Canada) in 1990 and joined JPL in 1993. He leads the JPL Planetary Surface Instruments Group, a collection of 12 scientists and engineers developing a variety of miniature sensors for planetary exploration. Dr. Darrach has delivered two JPL flight mass spectrometers, the Trace Gas Analyzer in 2000 and the Vehicle Cabin Air Monitor in 2009. He is the Principal Investigator (PI) for the VCAM follow-on, the Spacecraft Atmosphere Monitor (S.A.M), which will be launched to the International Space Station in 2017.*

Stojan Madzunkov *received his PhD in Physics from the University of Stockholm in 2004. In 2005 he joined JPL where he is currently a Senior Technologist in the Planetary Surface Instruments Group. Dr. Madzunkov was an Instrument Scientist for VCAM and solely responsible for developing the major constituents hardware and analysis capabilities for the instrument. He is the D-PI for the Spacecraft Atmosphere Monitor and the Instrument Scientist for the Cupid's Arrow investigation.*

Christophe Sotin *received an Engineer's Degree in*

Geology and Geophysical Engineering from 'Ecole Nationale Superieure de Geologie, Nancy" in 1981 and a "Doctorat es Sciences" from University of Paris VII in 1986. After creating a laboratory in planetary geology and geophysics at the University of Nantes (period 1989-2007) where he was Professor, he moved to JPL where he is presently Chief Scientist for Solar System Exploration. He has published more than 170 papers on the interior structure and dynamics of planets and moons. He has been Inter-Disciplinary Scientist on the Venus-Express mission, and Co-I of the Visual and Infrared Mapping Spectrometer (VIMS) onboard the Cassini spacecraft for which he implements the Titan observations. He was awarded the Runcorn-Florensky medal of the European Geoscience Union in 2008.