Planetary Science Deep Space SmallSat Studies

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Lunar Planetary Science Conference Special Session
March 18, 2018
The Woodlands, Texas

SMD CubeSat/SmallSat Approach

National Academies Report (2016) concluded that CubeSats have proven their ability to produce high-value science:

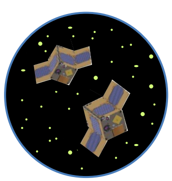
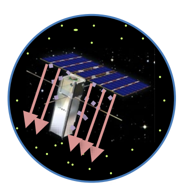
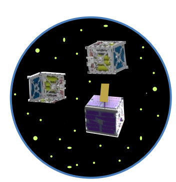
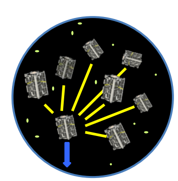
- Useful as targeted investigations to augment the capabilities of larger missions
- Useful to make highly-specific measurements
- Constellations of 10-100 CubeSat/SmallSat spacecraft have the potential to enable transformational science

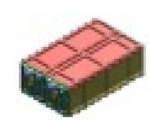
SMD is developing a directorate-wide approach to:

- Identify high-priority science objectives in each discipline that can be addressed with CubeSats/SmallSats
- Manage program with appropriate cost and risk
- Establish a multi-discipline approach and collaboration that helps science teams learn from experiences and grow capability, while avoiding unnecessary duplication
- Leverage and partner with a growing commercial sector to collaboratively drive instrument and sensor innovation

Planetary Science Deep Space SmallSat Studies (PSDS3)

- NASA Research Announcement released August 19, 2016
- Solicited concept studies for potential CubeSats and SmallSats
  - Concepts sought for 1U to ESPA-class missions
  - Up to $100M mission concept studies considered
  - Not constrained to fly with an existing mission
- Objectives:
  - What Planetary Science investigations can be done with SmallSats?
  - What technology development is needed to enable them?
  - What's the anticipated cost range?
- Received 102 proposals
- Funded 19 Studies



Planetary Science
Deep Space SmallSat Studies: Awards

Mars

Robert Lillis, Mars Ion and Sputtering Escape Network (MISEN)
Anthony Colaprete, Aeolus - to study the thermal and wind environment of Mars
Luca Montabone, Mars Aerosol Tracker (MAT)
Michael Collier, PRISM: Phobos Regolith Ion Sample Mission
David Minton, Chariot to the Moons of Mars

Venus

Valeria Cottini, CUVE - Cubesat UV Experiment
Christophe Sotin, Cupid's Arrow
Attila Komjathy, Venus Airglow Monitoring Orbiter for Seismicity (VAMOS)
Tibor Kremic, Seismic and Atmospheric Exploration of Venus (SAEVe)

Icy Bodies and Outer Planets

Robert Ebert, JUpiter MagnetosPheric boundary ExploreR (JUMPER)
Kunio Sayanagi, SNAP: Small Next-generation Atmospheric Probe

Small Bodies

Beau Bierhaus, Ross (formerly CAESAR)
Jeffrey Plescia, APEX: Asteroid Probe Experiment
Tilak Hewagama, Primitive Object Volatile Explorer (PrOVE)

Moon

Suzanne Romaine, CubeSat X-ray Telescope (CubeX)
Charles Hibbitts, Lunar Water Assessment, Transportation, and Resource Mission (WATER)
Noah Petro, Mini Lunar Volatiles (MiLUV) Mission
Timothy Stubbs, Bi-sat Observations of the Lunar Atmosphere above Swirls (BOLAS)
David Draper, Irregular Mare Patch Exploration Lander (IMPEL)

Small Innovative Missions For Planetary Exploration (SIMPLEx)

- **Solicit formulation and development of planetary science investigations that require a spaceflight mission that can be accomplished using small spacecraft**
  - ESPA-Class or smaller (< 180Kg)
  - Solicitation for secondary payload on specific primary missions, which will determine:
    - Launch readiness date
    - Initial release trajectory
  - Cost-capped missions: $15M to $55M
  - Continuously Open call with mission-specific deadlines

https://soma.larc.nasa.gov/simplex

SIMPLEx Process (Section 3)

Soon: Release Open Call for proposals
(public comment period on draft closed March 14)

On-going: Regular Panel Reviews of submitted proposals

Mission Specific Milestones:

- L-4 years: Cut-off consideration for a specific mission
  - Select and award ~1 year Phase A/B studies; expected product is PDR-level design
  - Launch Vehicle is unknown
- L-3 years: Down-select secondary mission(s) for specific primary mission
  - May be possible to select multiple secondaries for a given primary mission
  - Selectability coordination with LV selection
  - Provided for Phase C design/build:
    - More detailed Launch Vehicle trajectory, environments and interfaces
- L-2 years: Build/test secondary payload
- L-1 years: Build/test/integrate secondary payload

SIMPLEx Launch Opportunities

Table A-1 https://soma.larc.nasa.gov/simplex

Primary Mission	SIMPLEx Proposal Cut-off Date	Payload Integration /Launch Readiness Dates	Launch Site	Primary Payload Destination	Launch Orbit	Allowed Elements					Po-tential Launch Vehicle
						CubeSat Deployer	ESPA Ring	ESPA Grande	Propulsive ESPA ring	Radioactive elements	
LEO or GTO	On-going	On-going	Various	N/A	LEO or GTO	Y	Y	Y	Y	N	
Lucy	1 July 2018	August 2021 / 16 October 2021	Cape Canaveral Air Force Station	Jupiter L4 and L5 Trojan Swarms	Helio-centric Escape	Y	Y	N	N	N	Atlas V, Falcon 9, Antares, …
Psyche	1 July 2018	June 2022 / August 2022	Cape Canaveral Air Force Station	(16) Psyche, with Mars gravity assist	Elliptic Helio-centric	Y	Y	N	N	N	Atlas V, Falcon 9, Antares, …
IMAP*	TBA	TBD	TBD	TBD	TBD	N	Y	N	N	N	TBD
EM-x	TBA	TBD	Kennedy Space Center	Lunar Orbit	TBD	Y	N	N	N	N	SLS

SIMPLEx Technology

It is expected that new technologies may be required to accomplish planetary science missions proposed under this PEA. Proposals must justify how the proposed technology will contribute to mission success.

For technologies and subsystems that **do not have flight heritage**, the proposal must include a reference to the details and the results of testing and/or analysis that demonstrate performance in a **relevant environment under conditions that simulate all known significant failure modes** of the technology to demonstrate technical maturity of TRL 6. If a combination of this testing and analysis is proposed to be accomplished in Phase A/B, then a reference must be included describing what testing/analysis is planned or has been completed at the time of proposal submission to demonstrate a plan for maturing these systems to TRL 6 by PDR. A summary of the test/analysis should be included in the body of the proposal. Proposals must include a limited life item list and for those items show plans for how they can **meet 1.5 times the worst-case expected operating life of the proposed mission.**

For technologies and subsystems that **do have flight heritage**, claims of heritage must be supported by a description of the **similarities in design and flight environments between the heritage and the proposed mission.**

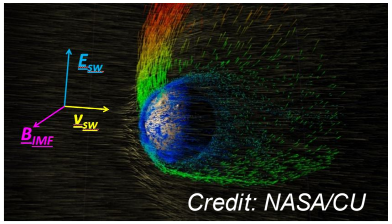
Section 4.6.1 https://soma.larc.nasa.gov/simplex

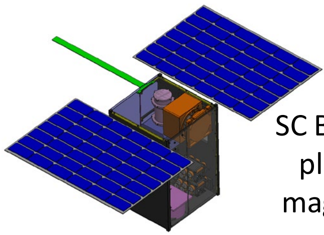
MISEN

Mars Ion and Sputtering Escape Network

Planetary Science Deep Space SmallSat Studies

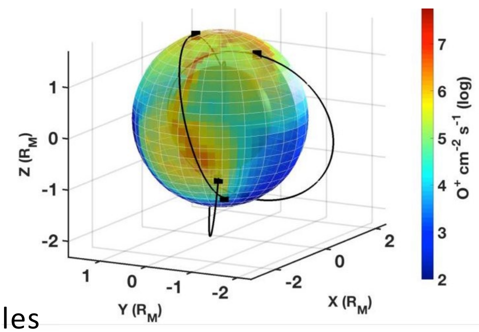
Ion dynamics drives escape and hence climate evolution





SC Bus enables plasma and magnetic field measurements

ion escape flux @ 3000 km



3-5 spacecraft. Orbits chosen to maximize coverage

Team Members/Institutions:

UC Berkeley SSL
Principal Investigator: Rob Lillis
Systems Engineer: Dave Curtis
Ion Analyzer Lead: D. Larson
Ion Dynamics: S. Curry, J. Luhmann, D. Brain (collaborator, U. Colorado)

UCLA ESS
Magnetometer lead: Christopher Russell

Tyvak LLC
Lead spacecraft engineer: Jordi Suig-Puari

Advanced Space LLC
Lead mission designer: Jeffrey Parker

Science Objectives:

Use multi-point simultaneous measurements to characterize the magnitude, global patterns, variability, and real-time response to space weather, of:

i) ion escape at Mars
ii) ion precipitation-driven sputtering escape at Mars

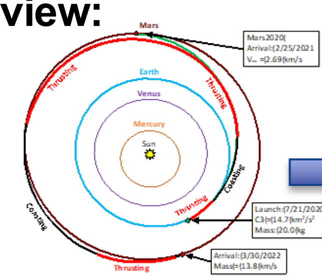
Measurements:

- Ion and electron energy, direction, flux
- Magnetic field

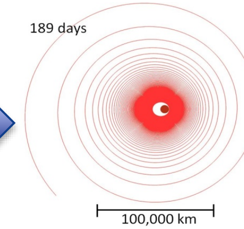
As multi-point measurements have revolutionized our understanding of the Earth's magnetosphere, MISEN will build on MAVEN's legacy for a fraction of the cost and, for the first time, reveal the dynamic global picture of ion escape and precipitation at Mars.

Mission Overview:

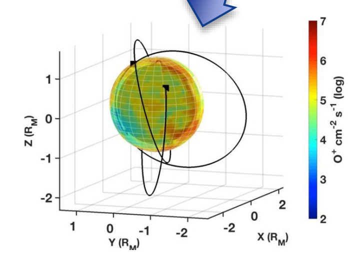
Ride-along SEP cruise to Mars with Psyche (15 months)



11-month spiral down to final orbits

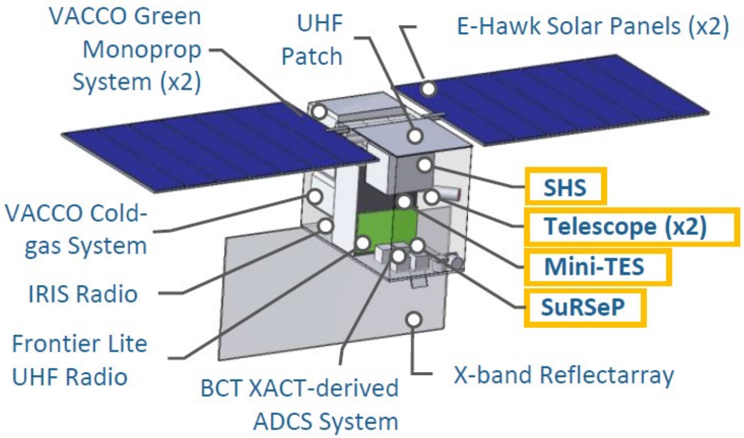


- 2-year primary science mission.
- Navigation: final orbits should precess, no station-keeping.
- Simple ops: spinning spacecraft, constant data collection.
- Telemetry: relay and direct-to-earth options available



The Aeolus Spacecraft

28kkg / 24U / 117W-OAP Spacecraft



Team Members/Institutions:

- PI: Anthony Colaprete (ARC)
- Deputy-PI: Amanda M. Cook (ARC)
- Co-I: Melinda Kahre (ARC)
- Co-I: Robert Haberle (ARC)
- Co-I: Phillip Christensen (ASU)
- Co-I: Greg Mehall (ASU)
- Co-I: David Landis (Draper)
- Mission Design Center Engineering Team (ARC)

Aeolus will make the first direct observations of day and nighttime winds at all local times

Aeolus Science Objectives:

1. Produce a vertically resolved global wind speed map
2. Determine the global energy balance of Mars
3. Correlate wind speeds and surface temperatures with CO_2 and H_2O clouds and dust column densities

Mission Overview:

- Aeolus's inclined orbit allows observations between ±75° and at all local times
- Spatial Heterodyne Spectrometers (SHS) and Mini-TES scan the atmosphere limb providing wind vectors, temperatures and aerosol/cloud densities
- SurSeP (Surface Radiometric Sensing Package) looks nadir measuring the total upwelling solar and thermal radiance as well as the surface temperature and column aerosol/cloud density

6U Payload

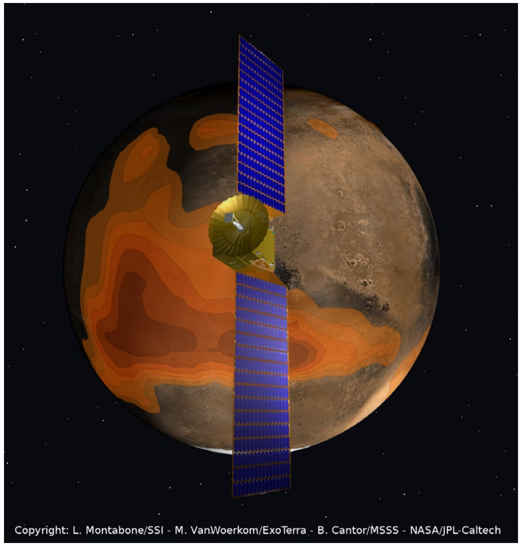


Figure: The MAT SmallSat overviews a regional dust storm on Mars from areostationary orbit, obtaining visible images in daytime and column dust optical depth measurements in daytime as well as nighttime.

Team Members/Institutions:

Principal Investigator:

Luca Montabone (Space Science Institute, CO)

Co-Investigators:

Michael VanWoerkom (ExoTerra Resource LLC, CO)
Bruce A. Cantor (Malin Space Science Systems, CA)
Michael J. Wolff (Space Science Institute, CO)

Collaborators:

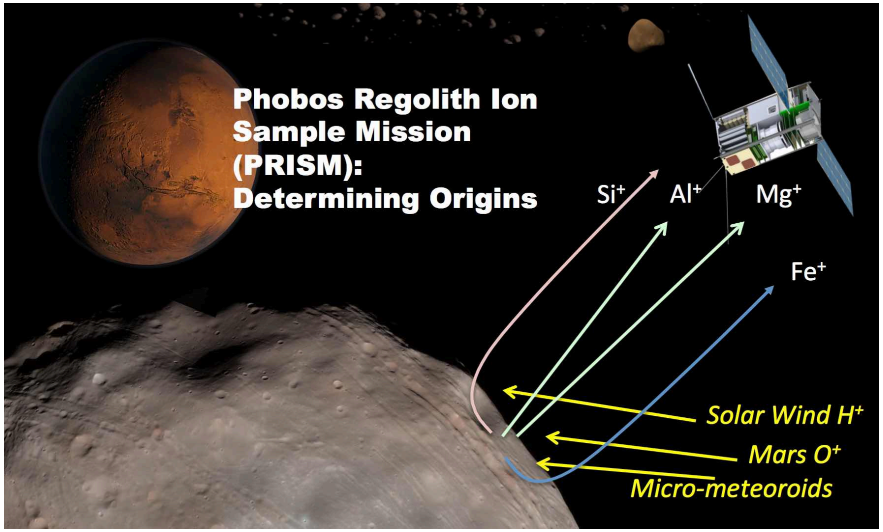
Michael D. Smith (NASA GSFC, MD)
François Forget (CNRS/LMD, France)
Michel Capderou (CNRS/LMD, France)

Science Objectives:

- Monitor a **large, fixed region** of the planet where dust storms and water ice clouds are likely to occur, **using visible and infrared wavelengths** with a **high sampling rate**;
- Observe the **temporal evolution of dust storms and water ice clouds** in the monitored area **throughout the diurnal cycle**;
- Detect **changes in surface physical properties** (e.g. thermal inertia and albedo) **throughout the diurnal cycle**, and particularly after the occurrence and decay of large dust storms.

Mission Overview:

- **Spacecraft**: ESPA-class orbiter; 45 kg; electric propulsion (micro Hall thrusters, Xe gas propellant).
- **Payload**: 1 visible and 2 thermal infrared cameras; filters for 6 IR spectral ranges, from 7.9 to 16 μm.
- **Journey to Mars**: Rideshare on a primary mission to Mars; deployment before Mars capture (baseline).
- **Orbit**: Areostationary (i.e. equatorial, circular, planet-synchronous orbit) at 17,031.5 km above the equator at one of the 2 stable longitudes (baseline).
- **Duration**: 1 Martian year (primary mission).



Team Members/Institutions:

- ***NASA/GSFC:*** *Michael R. Collier, William M. Farrell, David Folta, John Keller, Richard Vondrak, Timothy Stubbs, Rosemary Killen, Menelaos Sarantos*
- ***Morehead St. University, KY:*** *Ben Malphrus*
- ***JHU/APL:*** *Andy Rivkin, Scott Murchie, Dana Hurley*
- ***University of Iowa:*** *Jasper Halekas*
- ***Georgia Institute of Technology:*** *Micah Schaible*
- ***JPL:*** *Pamela Clark*

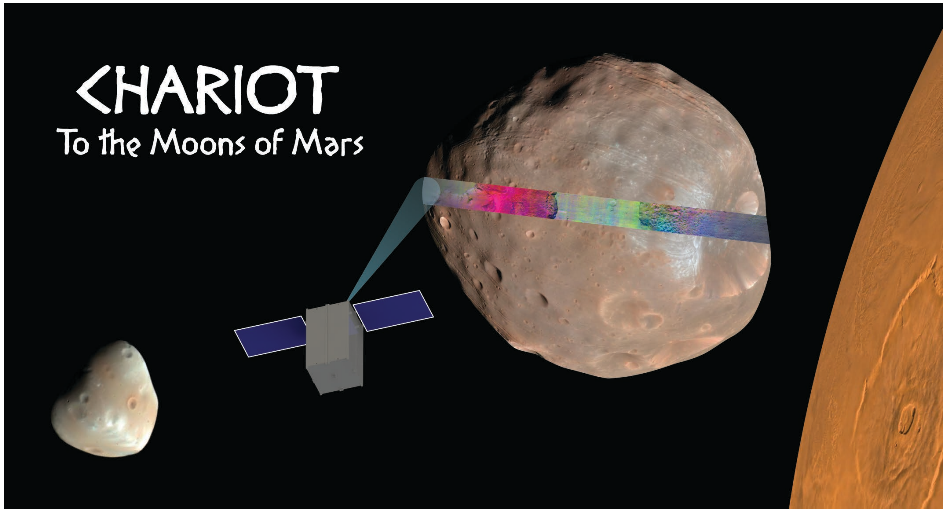
Science Objectives:

The PRISM CubeSat mission will determine the origin of Phobos: Did it form in the outer solar system or *in situ* near Mars, perhaps through a collision or by coalescence of a debris disk left over from the formation of Mars? PRISM will measure Phobos' surface composition using secondary ion mass spectrometry or SIMS and answer this critical question.

Mission Overview:

PRISM, a 12U CubeSat, will be ejected from the upper stage of the launch vehicle a few days after launch and, using a low thrust Solar Electric Propulsion system, will arrive at Mars in about two years and begin taking data during an approximately six-month spiral-in period. At the end of this spiral-in phase, PRISM will be in a Phobos co-orbit, making a pass and measurements near Deimos in the process. PRISM will probe the surface in a Phobos retrograde orbit at a distance as low as 27 km including the Mars facing and far sides of Phobos, both red and blue units, and craters on the leading edge.

Chariot to the Moons of Mars



Team Members/Institutions:

PI: David Minton (Purdue)
Co-Is:
Briony Horgan (Purdue)
David Spencer (Purdue)
Philip Christensen (Arizona State University)
Zachary Putnam (Univ. of Illinois at Urbana-Champaign)
Austin Williams (Tyvak Inc.)
Graduate Students
Jacob Elliot (Purdue), Rohan Deshmukh (Purdue)
Collaborators
Andrew Rivkin (JHU/APL), Matija Cuk (SETI),
Francesca DeMeo (MIT), Erik Asphaug (ASU)

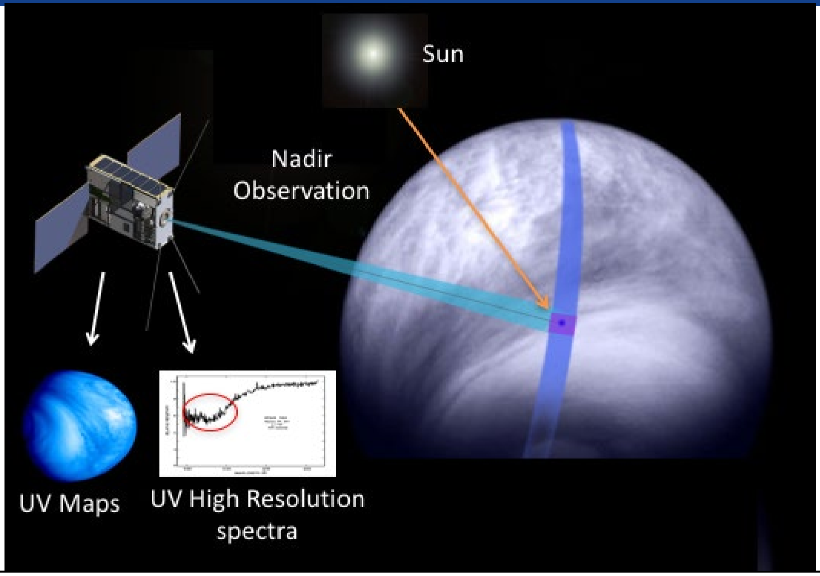
Science Objectives:

1. Determine the origin of moons of Mars, Phobos and Deimos
2. Evaluate the potential for resource extraction to support human exploration on the moons
3. Observe the effects of geologic processes contributing to the ongoing evolution of the Phobos-Deimos system

Mission Overview:

- Will piggyback on another Mars mission for launch, but will be a free flier after separation from the upper stage
- Cruise/aerocapture vehicle with drag modulation trajectory control
- 12U CubeSat, 3-axis stabilized, electric propulsion
- One Mars year mapping mission of Phobos & Deimos
- Remote sensing instrument suite
  - Spectroscopy and visible imaging
- Mission Operations Center at Purdue University
- Science Operations Center at Arizona State University

CUVE Cubesat UV Experiment: Unveil Venus' UV Absorber with Cubesat UV Mapping Spectrometer



Team Members/Institutions:

Principal Investigator:
Valeria Cottini *(University of Maryland College Park)*

Co-Investigators:
Shahid Aslam *(NASA, GSFC)*
Nicolas Gorius *(Catholic University of America)*
Tilak Hewagama *(University of Maryland College Park)*
Giuseppe Piccioni *(INAF-IAPS, Italy)*

Collaborators:
Lori Glaze *(NASA, GSFC)*
Nikolay Ignatiev *(IKI RAN, Russia)*
Emiliano D'Aversa *(INAF-IAPS, Italy)*

Science Objectives:

- Nature of the "Unknown" UV-absorber (range 320 – 490 nm) which drives Venus' thermal radiative balance
- Abundances and distributions of SO2 and SO at and above Venus's cloud tops and their correlation with the UV absorber (range 190 – 320 nm)
- Atmospheric dynamics at the cloud tops using wind tracking (190 – 490 nm) and structure of upper clouds
- Nightglow emissions: NO (190-300 nm), CO (205-240 nm), O2 (400-500 nm)

Mission Overview:

Baseline Spacecraft Configuration

6U to 12U Cubesat (e.g. Morehead or Dellingr)

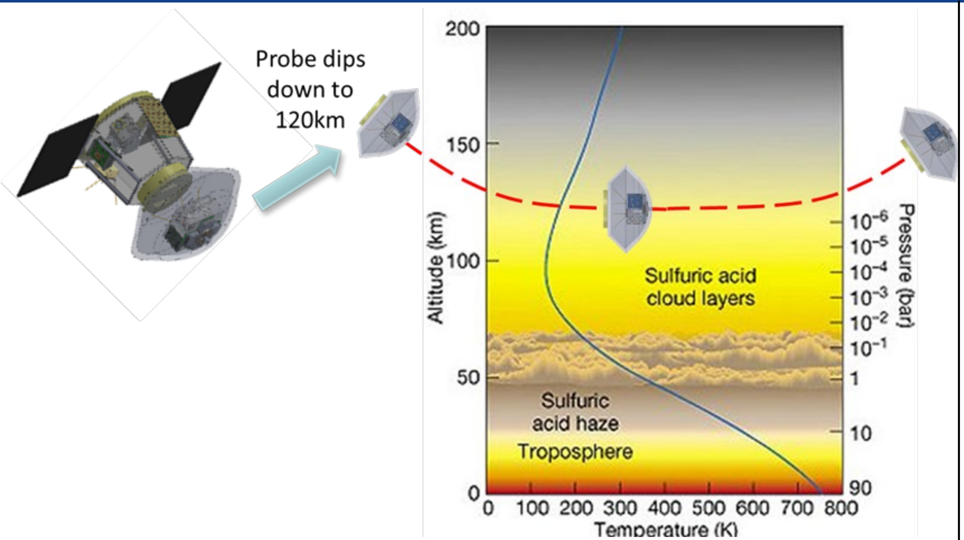
- Cruise < 1.5 year, Science phase > 0.5 year
- Propulsion: Chemical, EP, cold gas
- Power Generation: solar arrays
- Polar orbit around Venus
- Nadir dayside and nightside observations

Payload includes (2U, 2kg)

- UV spectrometer 190 – 570 nm, 0.3 nm spectral resolution
- UV imager broadband centered at 365 nm

Cupid's Arrow

A small satellite to measure noble gases in Venus' atmosphere



Team Members/Institutions:

Christophe Sotin	JPL
Guillaume Avice	Caltech
John Baker	JPL
Murray Darrach	JPL
Anthony Freeman	JPL
Glenn Lightsey	Georgia Tech
Bernard Marty	Univ. Nancy
Stojan Madzunkov	JPL
Daniel Wenkert	JPL
Sterling Peet	Georgia Tech
Terry Stevenson – graduate std.	Georgia Tech
Atelier team	JPL

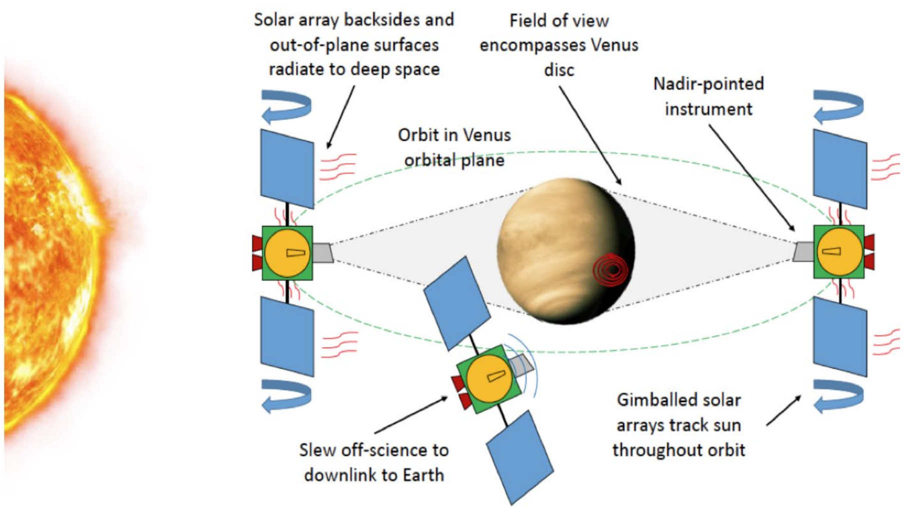
Science Objectives:

1. Determine how did the atmosphere of Venus form and evolve?
2. Compare the primordial volatile compounds of the Earth, Mars, and Venus?
3. Determine the volcanic history of Venus

These objectives are achieved by measuring the abundances of noble gases (Ne, Ar, Kr, Xe) and their isotopic ratios in Venus' atmosphere below the homopause (well mixed atmosphere)

Mission Overview:

- Several Venus-bound trajectory options to be studied:
  - a) Free-flyer launched directly from Earth
  - b) Drop-off on a gravity assist flyby
  - c) Drop-off from orbit
- Probe (mass <30 kg; diam. 60 cm) skims *through* the atmosphere
- At closest approach (below the homopause), spin-stabilized probe grabs a sample of the atmosphere
- Sample is analyzed in a compact mass spectrometer (4 kg, 31 W, 4U CubeSat form factor)
- Sample analysis data are relayed back to Earth



Team Members/Institutions:

- Principal Investigator: A. Komjathy of JPL
- Team JPL: engineering, science
- U. of Illinois, U. of Michigan: modeling, signal processing
- IPGP, CNES, and Geoazur, France: modeling, science
- DLR, Germany: instrument design

Science Objectives:

- Determine the global seismic activity of Venus (± 1 Moment magnitude)
- Determine the thickness of the crust
- Determine oxygen atom abundance and variability at 90-110 km altitude from O_2 emission
- Determine horizontal wind velocity amplitude (±30 m/s) and direction (±30°) from gravity waves detected in O_2 emission

Mission Overview:

- Launch SmallSat (<180 kg) into high earth orbit as rideshare with larger spacecraft
- Inject into trajectory to Venus using SEP (one Earth flyby and one Venus flyby)
- Insert into 24 hour Venus circular orbit in the Sun-Venus plane
- Infrared imaging in two channels: 1.17 μm and 4.3 μm building of atmospheric and ionospheric waves emanating from Venus quakes

SAEVe revolutionizes our paradigm for exploring the deep atmosphere, surface, and geophysical activity of Venus via enabling new technologies

- Leverages recent advances in high-temp electronics & systems
- Focuses on temporal science and incorporates innovative operations approach to make first ever long-duration measurements from the surface of Venus

Team Members/Institutions:

Tibor Kremic	NASA Glenn
Richard Ghail	Imperial College London
Martha Gilmore	Wesleyan University
Gary Hunter	NASA Glenn
Walter Kiefer	Lunar and Planetary Institute
Sanjay Limaye	University of Wisconsin
Michale Pauken	Jet Propulsion Lab
Colin Wilson	University of Oxford

Science Objectives:

1) Determine if Venus is seismically active and characterize the rate and style of activity
2) Determine the thickness and composition of the crust
3) Acquire temporal near surface meteorological data to guide global circulation models
4) Estimate moment exchange between the planet and its atmosphere
5) Measure atmospheric chemistry variability
6) Determine current rate of heat loss from the Venus interior
7) Examine rock and soil distribution and morphology

Mission Overview:

Two probes delivered to Venus via ride along

- Probes enter Venus atmosphere via Stardust-like entry capsule
- Descend to surface through the thickening atmosphere
- Turn on and autonomously implement operations

Probes will

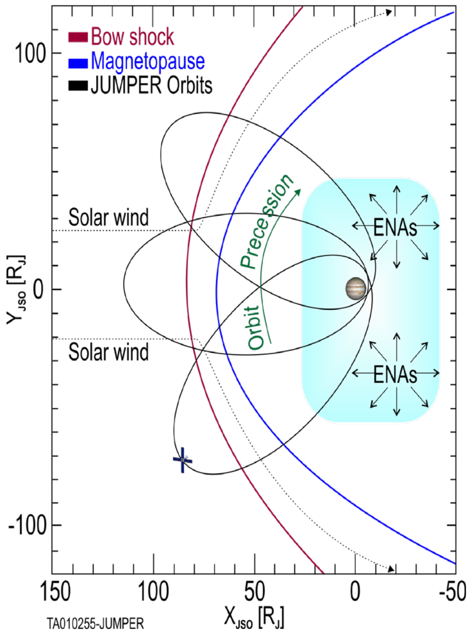
Measure seismic data, heat flux, wind speed and direction, abundance of atmospheric elements, radiance, temperature and pressure.
Landers will also return images supporting context, morphology and instrument coupling information

Transmit data to orbiting spacecraft / comm relay at pre-set intervals for an **unprecedented 120 days, over 3 orders of magnitude > current record!**

Validate capabilities and technologies paving the way for larger, more complex Venus lander missions in the future

JUMPER A SmallSat to Explore Jupiter's Magnetospheric Boundaries and Image its Energetic Neutral Atom Emissions

Planetary Science Deep Space SmallSat Studies



JUMPER is a Jupiter orbiting SmallSat mission concept to (i) understand the solar wind's interaction with Jupiter's magnetosphere and (ii) quantify the contribution from energetic neutral atoms (ENAs) to mass loss from Jupiter's space environment.

JUMPER will ride to Jupiter onboard another spacecraft such as NASA's Europa Clipper.

Team Members/Institutions:

NASA Planetary Science Division

Key
- SwRI
- JPL
- CU/LASP

JUMPER PI R. Ebert

JUMPER PM J. Hanley

Sys. Eng. D. George

Science Team
- **Jupiter Sci.** F. Bagenal
- **Plasma Science** M. Desai
- **Magnetic Fields** N. Murphy
- **ENA Science** F. Allegrini

Mission Design A. Wolf

Mechanical Lead C. Beebe

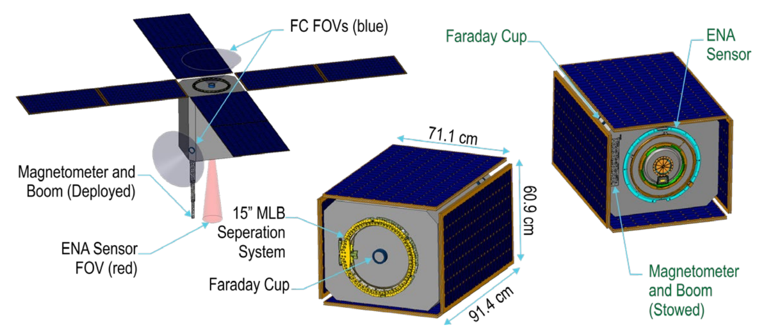
Science Objectives:

1. Characterize the solar wind upstream of Jupiter's magnetosphere and provide additional context for studying magnetospheric dynamics by the primary spacecraft.

2. Investigate the modes of solar wind coupling (e.g. magnetic reconnection, Kelvin-Helmholtz waves) along Jupiter's dayside magnetopause.

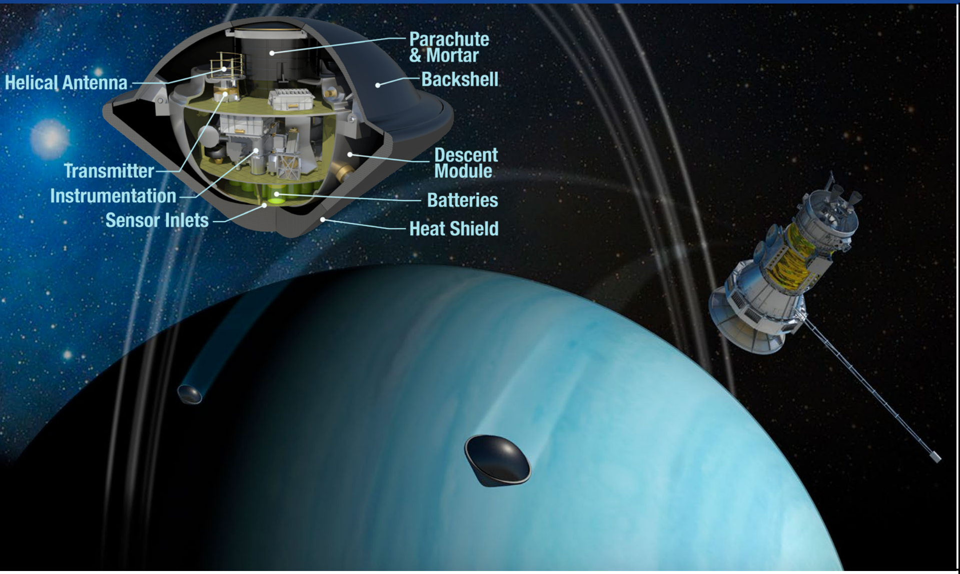
3. Determine the flux, energy spectra, and spatial distribution of energetic neutral atoms (ENAs) escaping from Jupiter's magnetosphere.

Spacecraft Overview:



The spacecraft consists of an ESPA frame supporting four double-deployed solar array panels, and four science instruments. A CubeSat sized electronics vault will house a majority of the electronics, shielding them from radiation.

SNAP Small Next-Generation Atmospheric Probe



Team Members/Institutions:

Kunio M. Sayanagi / Hampton University
Robert A. Dillman / NASA Langley Research Center
David H. Atkinson / Jet Propulsion Laboratory
Amy A. Simon / NASA Goddard Space Flight Center
Michael H. Wong / University of California, Berkeley
Thomas R. Spilker / Independent Consultant
James M. Longuski / Purdue University
Sarag J. Saikia / Purdue University
Jing Li / NASA Ames Research Center
Drew Hope / NASA Langley Research Center

Supported by
NASA Langley Research Center Engineering Design Studio

Science Objectives:

SNAP will examine the physical and chemical processes in the atmosphere of Uranus to understand the origin and evolution of the giant planets and the Solar System.

Tier-1 Objectives

Determine spatial differences of the following atmospheric properties from the Main Probe entry site:

1. Vertical distribution of cloud-forming molecules
2. Thermal stratification
3. Wind speed as a function of depth

Tier-2 Objectives

Augment Main Probe Science Objectives:

4. Measure abundances of the noble gases (He, Ne, Ar)
5. Measure isotopic ratios of H, C, N, and S

Mission Overview:

Baseline SNAP Mission Configuration

Add SNAP to Uranus Orbiter and Probe Mission
Orbiter delivers Main Probe and SNAP to Uranus

Baseline Probe Configuration

Mass: 30 kg
Aeroshell Diameter: 50 cm
Probe Power: Primary Batteries
Heatshield Material: HEEET
Target Atmospheric Pressure: 5 bar

Notional Payload

Atmospheric Structure Instrument: Measures thermal profile
NanoChem: Detects cloud-forming molecules
Ultrastable Oscillator: Measures wind speeds

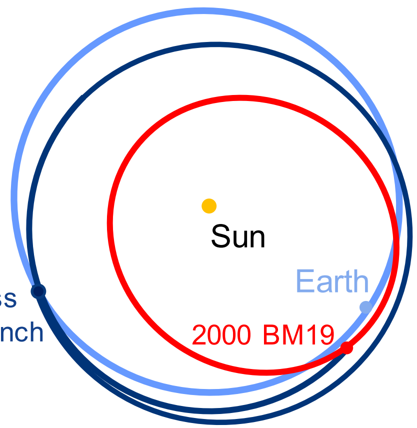
Ross (Formerly CAESAR)

Build and launch several identical 12U CubeSats with Lucy or Psyche to encounter small Near Earth Asteroids.

Obtain fundamental data on size, shape, structure, and regolith properties during flyby

Example mission to asteroid 2000 BM19 shown

Dozens of feasible targets with low ΔV & encounter velocity



Team Members/Institutions:

Beau Bierhaus, P.I., Lockheed Martin
Robert Jedicke, Co-I, University of Hawaii
Michael Ravine, Co-I, Malin Space Science Systems Inc.
Driss Takir, Co-I, SETI Institute
Benton Clark, Co-I Lockheed Martin

Science Objectives:

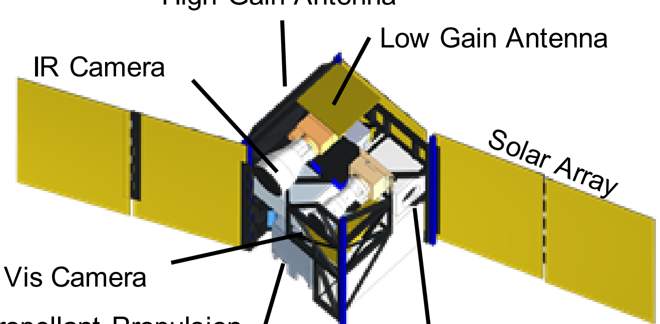
1. Evaluate bulk physical characteristics (size, shape, spin period, surface morphology) of several small Near Earth Asteroids to provide constraints on their formation and evolution
2. Determine the thermal properties of these asteroids to evaluate Yarkovsky and YORP effects on trajectory dispersions.
3. Characterize objects that may pose a threat to Earth or offer resources for exploration

Mission Overview:

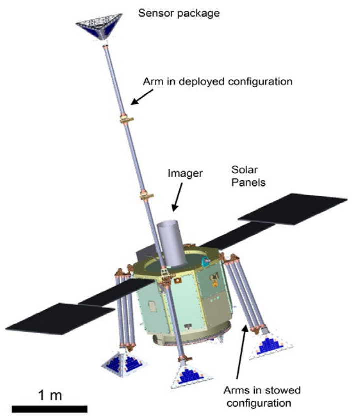
12U cubesats each with 1 Visible and 1 IR Camera

24 kg launch mass, with margin

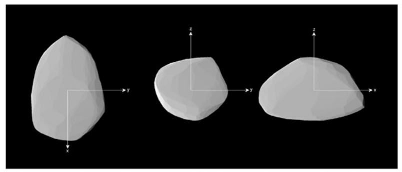
X-band IRIS radio

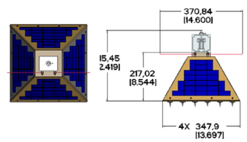


APEX Asteroid Probe Experiment



Possible spacecraft configuration with deployment arm extended.


Apophis shape model (Pravec, 2014)



Seismometer draft configuration – includes sensor, solar cells, electronics and comm.

Team Members/Institutions:

Eric Asphaug – Arizona State Univ.
Olivier Barnouin – JHU/APL
Mark Boslough – Sandia National Lab.
Brett Denevi – JHU/APL
Carolyn Ernst – JHU/APL
Jeff Plescia – JHU/APL
Derrick Richardson – Univ. Maryland
Andy Rivkin – JHU/APL
Nicholas Schmerr – Univ. Maryland
Hongyu Yu – Arizona State Univ.

Science Objectives:

1. Determine the structure of Apophis and observe the tidal deformation during encounter with Earth 2029
   1. Determine rotational dynamics
   2. Establish physical dimensions
   3. Determine topography
   4. Determine interior structure
   5. Define surface morphology
2. Map Apophis before encounter to define the body
3. Remap Apophis after encounter to detect changes resulting from tidal forces during encounter

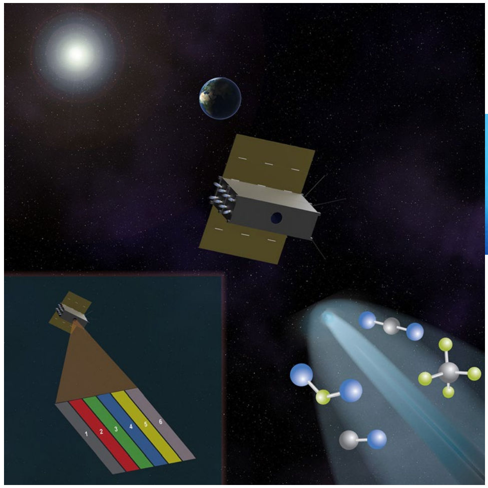
Mission Overview:

Baseline Spacecraft Configuration
- *3 axis stabilized, solar power*
- *Solar electric propulsion (or possible chemical)*
- *Arm to deploy seismometer on surface*

Baseline Instrument Payload
- *Panchromatic imager*
- *Seismometer*

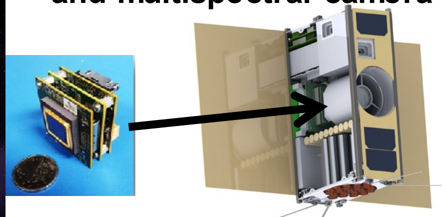
Conops
- *Rendezvous with Apophis before encounter*
- *Map and characterize Apophis*
- *Deploy the seismometer*
- *Observe deformation during encounter*
- *Remap and recharacterize Apophis*

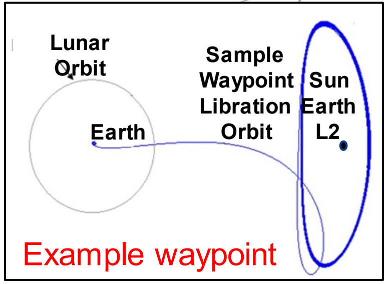
PrOVE Primitive Object Volatile Explorer



PrOVE payload will measure volatiles and temperatures

Deep Space Spacecraft and multispectral camera





Team Members/Institutions:

University of Maryland *PI:* T. Hewagama *CoI:* L. Feaga, J. Sunshine; *Collab:* T. Livengood

GSFC *CoI:* S. Aslam, D. Folta, C. Nixon, G. Villanueva; *Collab:* T. Hurford, M. Mumma,

Catholic University of America *CoI:* N. Gorius

Morehead State University *CoI:* B. Malphrus

JPL: *CoI:* P. Clark

York University: *Collab:* M. Daly

Science Objectives:

PrOVE will perform a close flyby of a Jupiter-family or new comet near perihelion when volatile activity is maximum, to probe the origin of the nucleus and the formation and evolution of our Solar System.

- *Investigate* chemical heterogeneity of nucleus by quantifying volatile species abundances and how these depend on solar insolation;
- *Map* spatial distribution of volatiles, especially CO_2 (which cannot be measured from ground based telescopes), and determine any variations;
- *Determine* the frequency and distribution of outbursts.

Mission Overview:

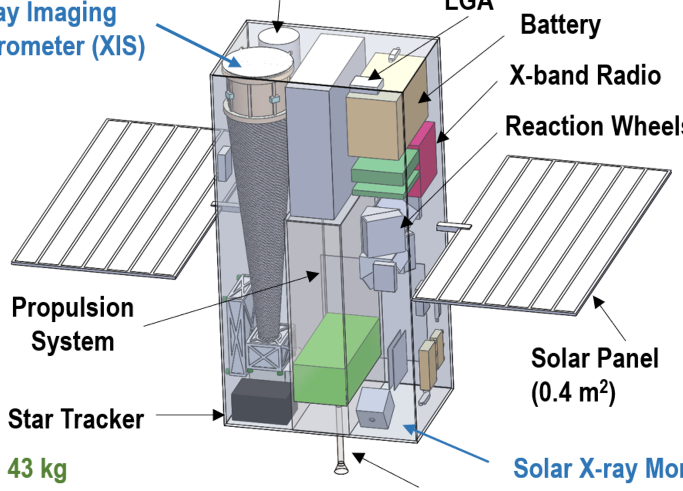
- *PrOVE* will be deployed from any launch platform and released above Earth's gravity well.
- Using onboard propulsion, *PrOVE* will navigate to a waypoint in space.
- *PrOVE* will remain at the waypoint until commanded to a transfer trajectory to intercept a known comet as it approaches encounter or hibernate indefinitely until an opportunistic new comet is identified and transfer orbit is uploaded.
- The *PrOVE* trajectory will be designed to encounter the comet at the ascending/descending node to mitigate large off-plane distances.

CubeX

CubeSat X-ray Telescope for Elemental Abundance Mapping of Airless Bodies and X-ray Pulsar Navigation

NASA SAO

Planetary Science Deep Space SmallSat Studies



Team Members/Institutions:

Management, SOC and MOC

Suzanne Romaine (SAO) PI; MiXO
Jaesub Hong (Harvard) Deputy-PI; Instrument Design
Janet Evans (SAO) SOC
NASA ARC Mission & S/C Design; MOC

Lunar and XRF Science

Ian Crawford (Birkbeck) **David Kring** (LPI)
Noah Petro (GSFC) **Larry Nittler** (Carnegie)

Instruments

Ralph Kraft (SAO) XIS
Almus Kenter (SAO) CMOS
Gregory Prigozhin (MIT) SDD
Rebecca Masterson (MIT) Instr Mgmt, SXM

XNAV and GEONS

Keith Gendreau (GSFC)
Jason Mitchell (GSFC)
Luke Winternitz (GSFC)

Science Objectives:

1. Measure the **vertical and regional composition variation of the lunar crust** by determining the chemical compositions of crater central peaks, basin peak-rings, and ejecta blankets from a wide range of crater sizes (~10–200 km).

2. Identify **outcrops of lunar mantle** on the surface (e.g., through anomalously high Mg/Si ratios), which then become possible targets for future sample return missions.

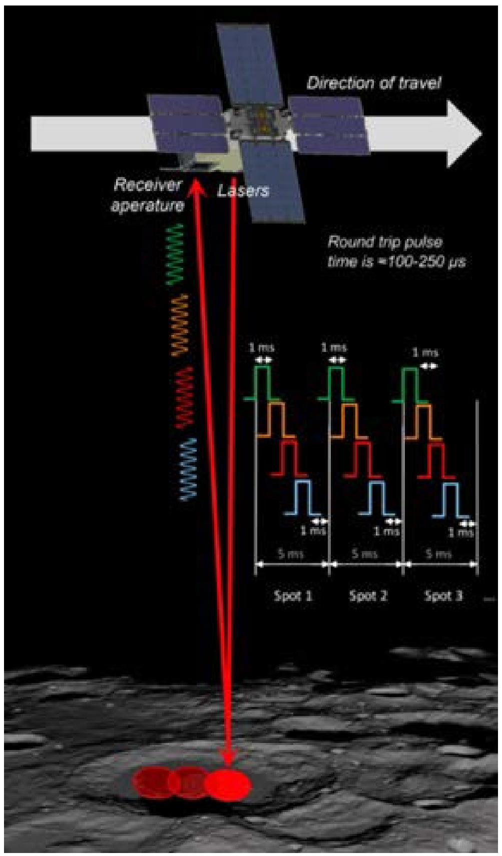
3. Conduct **X-ray pulsar based deep space navigation (XNAV)** and measure its performance.

Mission Overview:

- **Type, Mass:** Secondary Mission, 43 kg in 35 x 23 x 68 cm
- **Mission Lifetime:** 1.5 year; 1 year science operation from a 2023 – 2027 launch for solar max
- **Science Orbit:** Quasi Frozen Circular Polar Lunar Orbit with ~17 hr period at 6000 km after insertion to 500 x 5000 km orbit via primary
- **Payload: [1] X-ray Imaging Spectrometer (XIS):** Miniature X-ray Optics (MiXO, >25 cm^2 at 1 keV) + 2 CMOS X-ray sensors (<200 eV at 6 keV) + 1 high timing resolution SDD (1 μs)
  [2] Solar X-ray Monitor (SXM): SDD
- **Spacecraft (CBE, margin):** wet mass (43 kg, 41%), ADN (7 kg, 22%), R134a (2.2 kg, 31%), energy (136Wh, 46%), power draw (72 W, 35%), pointing knowledge (6″, 60%) & control (30″, 50%) and link margin (7 dB for LGA)

WATER

Lunar Water Assessment, Transport, Evolution, and Resource



Evaluate mission, payload and CONOPS feasible with a small Lunar orbiter to characterize the water on the Moon.

Science Objectives:

- What are the chemical form(s) of water on the Moon, including the PSRs, and how are they distributed spatially?
- How does surficial lunar water evolve over space and time?
- Is solar wind implantation responsible for the OH on the illuminated Moon?

Team Members/Institutions:

PI: C.A. Hibbitts, JHU-APL

D. Blewett, P. Brandt, B. Clyde, D. Hurley, R. Klima, D. Lawrence, A. Mirantes, D. Moessner, W. Patterson, J. Plescia, J. Sunshine, J. Westlake; all JHU-APL

L. Burke, NASA GRC

B. Cohen, NASA GSFC

J. Dankanich, NASA MSFC

Mission Overview:

Solar electric propulsion spacecraft,

3-axis stabilized with instruments on nadir facing deck

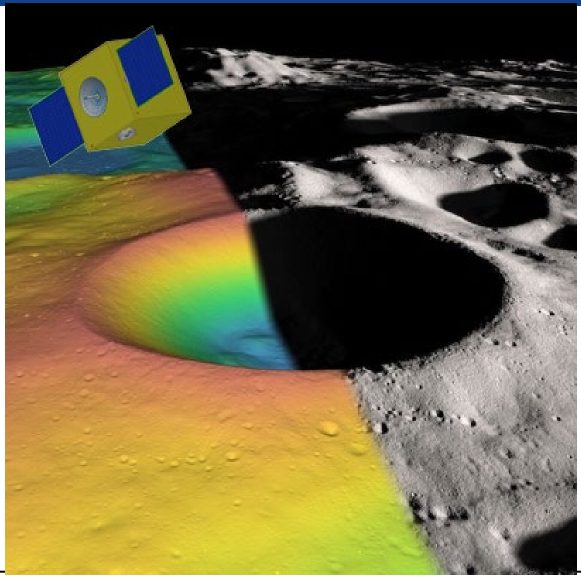
Transit GTO to weakly captured lunar orbit, then spiral in

Instrument suite:

- Mid-Infrared Multi-Spectral Imager (MIMSI)
- Active Multiband IR Reflectometer (WattIR)
- Neutron Spectrometer (NS)

Map surficial water and hydroxyl,

and near-surface polar hydrogen.



Team Members/Institutions:

- N. E. Petro, NASA GSFC
- E. Mazarico, X. Sun, J. Abshire, G. Neumann, P. Lucey
- Mission Study Team: GSFC and WFF Mission Design Labs

Science Objectives:

Mapping lunar volatiles at the 3.0 and 1.5 μm spectral absorption bands from pole to pole in nadir direction in day and night and in permanent darkness

- Detecting water ice on surface above 100 parts per million concentration
- Measuring distribution of surface volatiles in areas of permanent shadow
- Mapping the global distribution of H_2O/OH from pole to pole
- Monitoring diurnal cycle of surface H_2O/OH frost

Mission Overview:

ESPA-class spacecraft

GTO deployment to ~100 km circular lunar polar orbit

Orbit allows for dense coverage of the poles

Instrument suite:

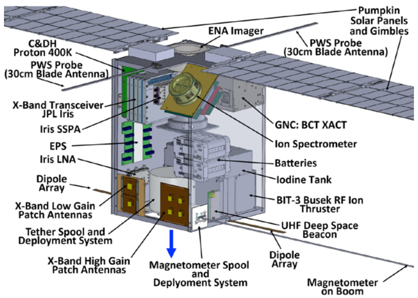
- Lunar Ice LIDaR Spectrometer (LILIS)
- Two bands to maximize water detection and discriminate multiple phases of water

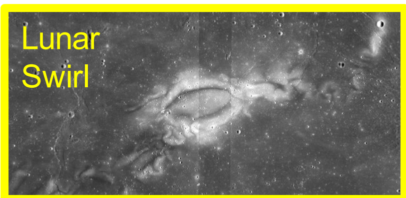
Map the moon for 1 year (12 lunations)

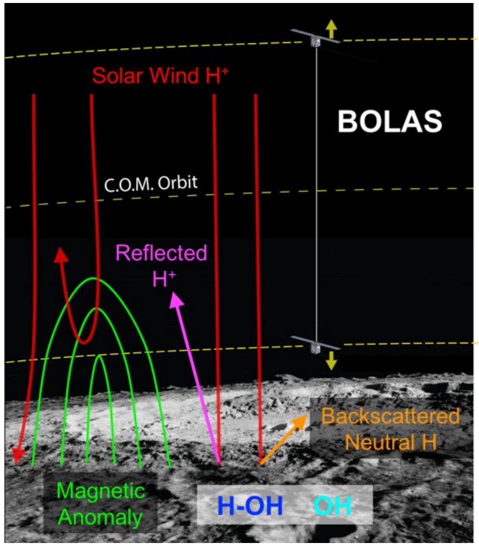
Can act as a communications relay

BOLAS Bi-sat Observations of the Lunar Atmosphere above Swirls

Planetary Science Deep Space SmallSat Studies







Team Members/Institutions:

- *PI:* Timothy J. Stubbs *(NASA/GSFC, 695)*
- *GSFC Co-Is:* Michael R. Collier, William M. Farrell, John W. Keller, Jared Espley, Michael A. Mesarch, Dean J. Chai, Michael K. Choi
- *Morehead State Univ. Co-I:* Benjamin K. Malphrus
- *Tethers Unlimited Co-I:* Robert P. Hoyt
- *Busek Co., Inc. Co-I:* Michael Tsay
- *GSFC Collaborator:* Richard R. Vondrak

Science Objectives:

Investigate the hydrogen cycle (including surface hydroxylation/hydration) at the Moon by determining:

1. the mechanisms and dynamics of lunar hydrogen implantation, and their dependence on composition, regolith properties, local topography, plasma conditions, time-of-day, and crustal magnetic fields.
2. how this relates to the formation of the lunar "swirls" collocated with magnetic anomalies (crustal fields) and space weathering.

Requires repeated *in situ* measurements at very low altitudes (<10 km) – orbit-maintenance propulsion requirements are prohibitive for conventional SmallSats.

Mission Overview:

Flight Configuration: BOLAS will deploy a thin, tens of km-long tether between two CubeSats enabling them to fly in a gravity gradient formation.

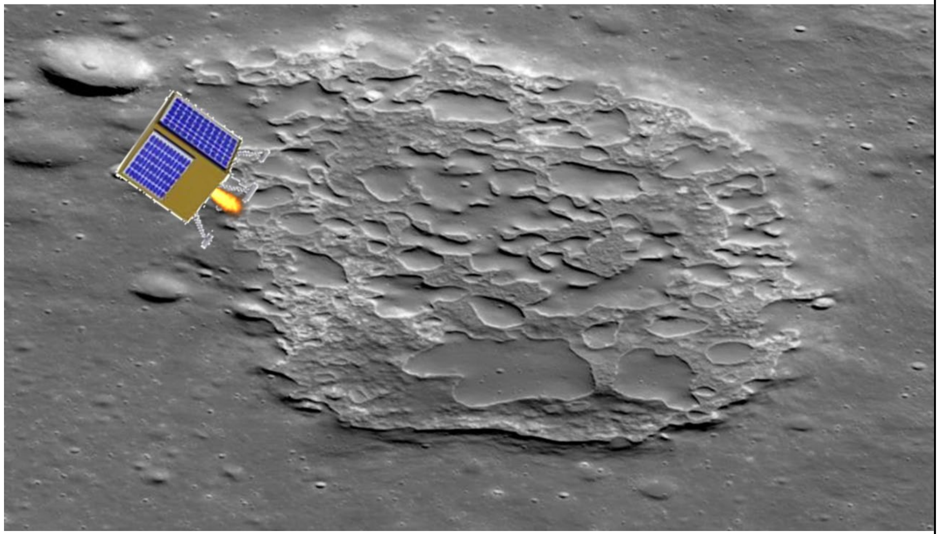
The BOLAS center-of-mass (C.O.M.) will be in a quasi-stable, low maintenance orbit, such that the lower CubeSat can remain at low altitudes for long durations.

Mission Architecture: Two similar 12U CubeSats (24U total), leveraging existing bus and miniaturized subsystems.

Instrument Payload: Ion Spectrometer, Energetic Neutral Atom Imager, Plasma Wave System, and Magnetometer.

Orbit: Low inclination to observe magnetic anomalies/swirls that are clustered around the equator on short timescales.

Mission Lifetime: 1 year (desirable), 1 lunation (minimum).



Team Members/Institutions:

PI: Dr. David Draper (NASA-JSC)
Dr. Samuel Lawrence (NASA-JSC)
Dr. Brett Denevi (JHUAPL)
Dr. Julie Stopar (LPI/USRA)
Dr. Kristen John (NASA-JSC)
Lee Graham (NASA-JSC)
Zachary Fletcher (JHUAPL)
Joseph Hamilton (NASA-JSC)
John Gruener (NASA-JSC)
Susan Bertsch (NASA-JSC)

Science Objectives:

- **Sub-meter-scale imaging** (<40 cm/pixel) to definitively discern small fractures or pits in Ina-D
  - *This will enable determination of whether IMPs are made of young volcanic lavas*
- ***Determine grain sizes and regolith components*** *to understand the age and formation mechanism of Ina-D*

Mission Overview:

- IMPEL will explore a site of potentially recent volcanism (an "Irregular Mare Patch") on the Moon, answering the question of when and how the materials found at Ina-D formed
- IMPEL consists of two 180 kg, tethered spacecraft (science module and descent module) attached to an ESPA ring
- The Descent Module deorbits the Science Module for a soft landing on the Moon, enabling a short, focused science mission