

**Planetary Mission Concept Studies**  
**Abstracts of Selected Proposals**  
**(NNH18ZDA001N-PMCS)**

Below are the abstracts of proposals selected for funding for the Planetary Mission Concept Studies program. Principal Investigator (PI) name, institution, and proposal title are also included. **54** proposals were received in response to this opportunity. As of October 5, 2019, 10 proposals have been selected for funding.

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**Wendy Calvin/University Of Nevada, Reno**  
**Mars Orbiter for Resources, Ices, and Environments (MORIE)**

This proposed study will seek to integrate multiple community efforts to identify the most compelling and effective mission concept to address high priority Mars science questions and provide detailed cost estimates to achieve these objectives.

In 2015, MEPAG commissioned a Science Analysis Group to consider the Next Mars Orbiter NEX-SAG. In addition to conducting new scientific investigations, the strawman solar-electric propulsion orbiter concept was tasked with providing the capability to act as a telecommunications relay and to rendezvous with and capture a sample-return canister. Since that study (NEX-SAG, 2015) was completed, many additional activities have highlighted the need for a new orbiter to address high priority science questions at Mars. Emerging from the NEX-SAG report were five areas of new compelling science. We will focus on two of the NEX-SAG synergistic science objectives, (S-A): Map and quantify shallow ground ice deposits across Mars along with shallow layering of volatile ices at the poles to better understand the global water inventory, and (S-D): Characterize the occurrence and timing of major environmental transitions recorded in compositional stratigraphic records. Simultaneously, we will explicitly address the human exploration strategic knowledge gaps related to water resources by detecting shallow water ice, determining properties of its protective overburden, and mapping the distribution and nature of hydrated minerals.

The 2017 report by the Committee on Astrobiology and Planetary Science and the NASA 2018 mid-term Planetary Decadal review reiterated and re-emphasized the importance of the science goals identified by NEX-SAG. In other venues, additional mission concepts have been proposed for a Mars orbiter. In 2017, two workshops at the Keck Institute for Space Studies (KISS) were dedicated to Unlocking the Climate Record Stored within Mars Polar Layered Deposits. The final KISS report identified four mission concepts, one of which was an orbiter focusing on both the ice layering and the fluxes and forcings of wind and atmosphere-surface interchange. Furthermore, one key product of the MEPAG-commissioned Ice and Climate Evolution Science Analysis Group (ICE-SAG) is an orbital mission concept (NF5) to map shallow ice, topography and surface composition (ICE-SAG, 2019).

Additional study is necessary to determine the most cost effective and scientifically productive mission concept to meet the needs of Mars science in the upcoming decade, as neither the NEX-SAG nor the ICE-SAG orbiters have been studied or costed in detail. Based on strawman payload estimates, we believe that addressing the key climate and geological science of buried ice, surface composition of key rock stratigraphies, polar layer stratigraphy, and ongoing surface changes such as the time-varying thickness of seasonal ice, can be provided in a focused medium-class mission concept.

Specific goals for our concept study are to:

1. Discuss the science goals and define measurement requirements emerging from our discussions and the NEX-SAG and ICE-SAG reports that focus on resources, ice distribution and quantity, and environmental transitions.
2. Develop a list of strawman instruments to achieve those measurement requirements.
3. Decide on the optimal mission orbital parameters to achieve the stated science goals and any changes needed during the course of the mission.
4. Work with a NASA Design Lab to provide an overall mission design of the spacecraft, instruments and interfaces, and cost estimate.
5. Document the mission concept study in a final report.

### **Julie Castillo/Jet Propulsion Laboratory**

#### **Assessing Dwarf Planet Ceres Past and Present Habitability Potential**

The dwarf planet Ceres has more water than any other body in the inner solar system after Earth (in absolute amount). Abundant ammonia and carbon species on its surface suggests it is likely an interloper from the outer solar system. Between 2015-2018, the Dawn mission performed extensive geological, compositional, and geophysical observations of Ceres on a global scale. These observations revealed a body that has been subject to pervasive aqueous alteration, with a chemically- and physically-layered interior resulting from ice-rock fractionation. Ceres surface is a globally homogeneous mixture of phyllosilicates and carbonates with a dark agent, likely consisting of iron compounds and amorphous carbon. Ceres low-density and high-strength crust suggests a rich mixture of ice, hydrates (salts and gas), silicates, and likely organics. Numerous local sites are compositionally distinct, with carbonate-rich deposits, organic-rich areas, and landmarks testifying of recent geological activity.

Dawn painted the portrait of an exceptional dwarf planet, likely a former ocean world that might still hold a relict ocean and has lost a significant amount of ice. The mission revealed the role of brines in driving long-term activity in an otherwise heat-starved object and the role of impacts in creating local liquid environments that could represent potential habitable niches.

This, combined with an apparent abundance of organics in the shallow subsurface, leads to key questions about Ceres past and present habitability potential that cannot be resolved with Dawn observations:

Did Ceres originate between the orbits of the giant planets or in the Kuiper belt? What is Ceres' crustal composition and the structure of its upper crust? Has Ceres lost a significant amount of water ice? What are the characteristics of the Ceres' volatile cycle, including the role of impacts and the origin and attributes of the vapor plumes? What were the environmental conditions in Ceres' early ocean? Were these amenable to prebiotic chemistry? What are the origin and nature of Ceres' organics? Does Ceres still contain liquid, and in which form and extent? Is cryovolcanism ongoing at Occator or Ahuna Mons? Are there regions in Ceres (e.g., source of the faculae) where chemical energy is still available?

Their resolution will require a combination of high-resolution geological and geophysical observations from orbit with in situ chemical measurements (elemental, mineralogical, isotopic) at multiple sites, possibly in combination with sample return. The proposed study will focus on a multi-element architecture (orbiter with one or multiple deployable elements) and address (1) the definition of testable hypotheses leading to quantitative measurement requirements (i.e., a science traceability matrix); (2) various payload options based on existing and emerging techniques that can address these requirements; (3) the design of in situ investigations and mobile platform and the feasibility and risk of accessing multiple sites; (4) the approach for and cost impact of returning samples to Earth; (5) the aspects and cost of planetary protection; (6) an end-to-end mission design for possible launch dates. These activities will include an assessment of technologies that can be readily leveraged from previous and ongoing projects (e.g., Dawn, Mars missions, Europa lander), and provide an assessment of technology needs in the next decade to enable future Ceres exploration.

This study will lead to a spectrum of architectures ranging from the New Frontiers to small flagship (\$1.5+B) cost caps. This will allow the Decadal Survey committee to assess science return vs. cost for sensible implementations that can determine the astrobiological significance of the closest dwarf planet to Earth.

### **Barbara Cohen/NASA Goddard Space Flight Center In Situ Geochronology for the Next Decade**

Geochronology, or determination of absolute ages for geologic events, underpins many inquiries into the formation and evolution of planets and our Solar System. The bombardment chronology inferred from lunar samples has played a significant role in the development of models of early Solar System and extrasolar planet dynamics, as well as the timing of volatile, organic, and siderophile element delivery. Absolute ages of ancient and recent magmatic products provide strong constraints on the dynamics of magma oceans and crustal formation, and the longevity and evolution of interior heat engines and distinct mantle/crustal source regions. Absolute dating also relates habitability markers to the timescale of evolution of life on Earth. Major advances in planetary science can thus be driven by absolute geochronology in the next decade, calibrating body-specific

chronologies and creating a framework for understanding Solar System formation, the effects of impact bombardment on life, and the evolution of planets and interiors.

Absolute ages for multiple worlds are a desire in both the 2003 and 2013 Planetary Science Decadal Surveys, but in these two decades, only sample return was considered a viable method for geo-chronology. The Decadal Surveys recommended mission lists reflect the reality for those decades that sample return is the only way to yield reliable and interpretable geochronology. In the last two decades, NASA has also invested in the development of in situ dating techniques, increasing the technology readiness levels of instruments using complementary radiogenic isotopic systems (K-Ar and Rb-Sr) to TRL 6. The time is right to consider how the precision achievable with in situ geochronology can advance important science goals for the next Decadal Survey, the most fruitful way to deploy them in missions to key planetary destinations, and to consider how these technologies complement sample-return efforts for the Moon and Mars.

For this Planetary Mission Concept Study, we will formulate and cost a medium- or flag-ship-class mission for Solar System chronology. The aim of this proposal is to give the next Decadal Survey panel a viable alternative or addition to sample return missions to accomplish longstanding geochronology goals within a New Frontiers envelope. Our Science Definition Team (SDT) has expertise across the Moon, Mars, and small bodies communities to identify the most important science questions that can be answered in the next decade using the first generation of in situ dating techniques and examine mission-level requirements, trades, and instrumentation for answering these questions. By conducting this study, we will provide the next Decadal Survey panel with several options for how geochronology might be accomplished in the inner Solar System within the Planetary Science portfolio, the synergies these measurements have with other high-priority science goals, and the technology investments required to implement such missions.

### **Carolyn Ernst/Johns Hopkins University Mercury Lander**

MESSENGER revealed that Mercury's highly chemically reduced and unexpectedly volatile-rich composition is unique among the terrestrial planets and unlike any predictions of previously proposed hypotheses of the planet's origin. These surprising results have led to a reexamination of the planet's formation and history. As an end-member of terrestrial planet formation, Mercury holds unique clues about the original distribution of elements in the earliest stages of the solar system and how planets (and exoplanets) form and evolve in close proximity to their host stars. In situ measurements from the surface are needed to address fundamental science goals about Mercury's origin, evolution, and ongoing processes.

Our multidisciplinary science team has identified four main science goals that will guide a mission concept study of a landed mission to Mercury:

- 1) Investigate the highly chemically reduced, unexpectedly volatile-rich mineralogy and chemistry of Mercury's oldest terrain type to understand the earliest evolution of this end-member of rocky planet formation.
- 2) Investigate Mercury's interior structure and magnetic field to unravel the planet's differentiation and evolutionary history and understand the magnetic fields at the surface.
- 3) Investigate the active processes that produce Mercury's exosphere and alter its surface to understand planetary processes on rocky airless bodies, including the Moon.
- 4) Characterize the landing site in order to understand the processes that have shaped its evolution, place the in situ measurements in context, and enable ground truth for global interpretations of Mercury.

We plan for a two- to three-week effort to perform a complete, end-to-end Mercury Lander mission concept study. This study will examine key payload and spacecraft trades, incorporating technology advancements over the last decade, to establish if a Mercury Lander mission is feasible as a New Frontiers class mission, and therefore able to be considered for a New Frontiers candidate mission list by the 2023 Decadal Survey.

A decade is needed to go from project start to landing on Mercury, including a cruise comparable in duration to an outer solar system mission. Performing a high-fidelity Mercury lander mission concept study now enables proper consideration by the 2023 Decadal Survey, while the long lead time still allows a future proposal team to adapt to BepiColombo's orbital findings. Postponing a study until the 2030s would break the continuity of Mercury exploration and lead to a multi-decade gap between spacecraft visits to the planet. The active and engaged Mercury community is ready to build upon the legacy of MESSENGER and the forthcoming investigation by BepiColombo to address the next stage of Mercury exploration by defining the framework for the first landed mission to the innermost planet.

### **Martha Gilmore/Wesleyan University Venus Flagship Mission Study**

We propose to define science objectives and develop a Flagship-class mission to Venus that can be executed in the 2023-2033 decade. The proposal team purposely includes a diverse range of specialties (geoscience, atmospheric science, exoplanets and astrobiology); many levels of experience with the Venus community, NASA, NAS and mission work, and is also diverse demographically. This team critically enables a fresh and open assessment of the range of Venus mission concepts that could be accomplished in a Flagship class.

The science goals of the mission are to constrain the: 1) history of volatiles and liquid water on Venus and determine if Venus was habitable, 2) composition and climatological history of the surface of Venus and the present-day couplings between the surface and atmosphere and 3) the geologic history of Venus and whether Venus is active today. These goals are derived from study and discussion of the VEXAG Goals, Objectives and Investigations (GOI) Document currently under revision and are linked directly to the

crosscutting themes of the Decadal Survey and NASA Science Plan. Our goal is to address scientific objectives representative of priorities of Venus the community, which integrates new data from Venus by Venus Express, Akatsuki, Arecibo, ground-based observations, new discoveries in the Magellan data, new laboratory studies (e.g., GEER), as well as consider new technologies supported by the HEEET and HOTTech programs and new mission concepts such as Smallsats. These advances in scientific understanding and technology require a new look at a Venus Flagship mission since the Venus Climate Orbiter was endorsed in the last Planetary Decadal. This Venus Flagship mission will be considered in light of proposed Venus missions in Discovery and New Frontiers and international missions including Venera-D, EnVision and ISRO. Our goal is to provide a compelling Venus mission that advances key planetary science and can be promoted as a top priority in the coming Decadal Survey.

This team will develop one or more mission concepts that we request be studied by Goddard. We anticipate 2 face to face team meetings as well as at least two week-long runs at the GSFC MDL design lab in addition to ~weekly telecons.

### **Carly Howett/Southwest Research Institute Pluto Orbiter and Kuiper Belt Exploration Mission**

The exploration of the Pluto system and the Kuiper Belt Object (KBO) 2014 MU69 by New Horizons has proven the scientific worth of KBO targets and made a compelling case for follow-up missions. The mission concept proposed here is to send a single small Flagship-class spacecraft to orbit in the Pluto system for approximately two terrestrial years, then break orbit and explore at least one small KBO and one other KBO dwarf planet. Feasibility studies conducted at SwRI have shown this mission to be possible with planned capability launch vehicles and existing electric propulsion systems but has not addressed science focus, instrument trades, costing, and other important issues. The mission will carry a more capable remote sensing instrument suite than that of New Horizons, allowing new investigations of Pluto, all its moons and the Kuiper Belt.

The proposed mission concept will address three key questions: Is Pluto an ocean world? What is the history of the Pluto system? What is the diversity of objects in the Kuiper Belt? To answer these questions, the proposed mission will explore both new objects and Pluto system terrains that New Horizons did not observe. An orbiter also allows time domain studies and allows Pluto's global gravity to be assessed in order to definitively determine whether Pluto has a subsurface liquid water ocean. In the Pluto system, the mission will provide new types of atmospheric investigations, including in situ studies of Pluto's atmosphere. Comparing these new results with those obtained by New Horizons will enable an in-depth understanding of Pluto's temporal changes due to active geology and the interaction of the surface and atmosphere.

We have identified multiple additional KBO targets after Pluto, including the option for multiple small-target flybys, and the ability to orbit or fly by at least one other KBO

dwarf planet, depending on which target is chosen all within existing electric propulsion capabilities.

There are many aspects of this mission still to be developed; we outline the specific work still to be done, which includes the numerous trades needed to ensure this mission has the highest and most cost effective science return. We require inputs from NASA's Design Lab to complete our work, to assist with issues such as (but not restricted to) full mission costing, payload, integration, communications, and trajectory analysis.

This mission concept is fully in line with the priorities of both the Committee on Astrobiology and Planetary Sciences (CAPS), the National Academies Decadal Survey and NASA's Roadmap to Ocean Worlds (ROW): CAPS lists a dwarf planet mission to Pluto as a priority area for large- and medium-class mission studies; the mid-term review of the planetary decadal survey, Vision and Voyages, lists a Kuiper Belt mission to be important, specifically one that visits a large and small KBO; and The Roadmap to Ocean Worlds (ROW) recommends that mission studies should be performed to address technology advances enhancing exploration of the Kuiper belt or a return to Pluto with an orbiter .

**Robert Lillis/University of California, Berkeley**

**MOSAIC: Mars Orbiters for Surface-Atmosphere-Ionosphere Connections**

The Mars lower and middle atmosphere is a highly dynamic physical and chemical gaseous envelope that bridges the martian surface below to the thermosphere, ionosphere and space environment above, and through which atmospheric gas escapes, shaping the evolution of Mars climate.

Orbital and surface-based assets have been exploring and characterizing important, but limited pieces of the atmosphere for some time; however these efforts have been insufficient to characterize key properties of its dynamics globally, particularly the diurnal evolution of weather systems and the processes connecting the atmosphere to the surface and subsurface as well as atmospheric regions to one another. Understanding these connections is important not just as a scientific and exploration endeavor, forecasting orbital and surface hazards to and identifying sub-surface resources for future human explorers.

Such synergistic understanding requires a novel approach to observing the surface/atmosphere/space linkages, which includes measurements from multiple vantage points: areostationary, polar, and elliptical orbits. Thus, we propose to investigate a concept for a Mars orbiter constellation consisting of a focused suite of independent instruments aboard a mothercraft and several small satellite daughtercraft in carefully chosen complementary orbits. These instruments include shallow subsurface radar, atmospheric remote sensing via a) lidar and sub-mm sounding, b) NUV, visible and thermal infrared imaging, and c) satellite-satellite radio occultations, and d) MUV and FUV spectroscopy plus space environment monitoring (solar UV, coronal EUV/FUV,

magnetic fields and plasma flows). The proposed mission concept is called Mars Orbiters for Surface, Atmosphere and Ionosphere Connections (MOSAIC).

Such a constellation will both greatly advance the scientific understanding of the dynamic Mars system as a whole while demonstrating several key technologies/capabilities that will enable a paradigm change in the robotic exploration at other planetary bodies. Among these capabilities are a) delivery of SmallSats to diverse orbits from a single mothership in a reasonable time (< 24 months from launch), b) spacecraft-to-spacecraft communication for radio science and data exchange in Mars orbit, c) continuous Earth-to-Mars-surface communication (via relay), d) disruption-tolerant networking, e) optical communication to Earth from Mars f) next generation spaceflight computing and g) computing and data storage support for resource constrained orbiters. Given the significant number of orbiters involved, and the technological challenge of designing an efficient multi-platform network, we anticipate the scope/cost of this mission to be significantly beyond the Discovery (\$500M) level.

As part of the proposed concept study, we will bring together a talented and diverse team of scientists, knowledgeable in spaceflight instrumentation and specializing in surface-atmosphere interactions, global atmospheric circulation, lower-to-upper atmosphere connections, and atmospheric escape, in addition to engineers familiar with these technologies. This team will work with a mission design team from JPL, APL or GSFC to develop this idea into an end-to-end mission concept with a) a clear flowdown from science and technology goals and objectives to requirements for measurements, instruments and subsystems and b) an indicative estimate of schedule and cost. The proposed work is relevant to ROSES Appendix C.30 because it will develop scientific, technical, and cost information to be used as input to the 2023 Decadal Survey.

### **Shannon MacKenzie/Johns Hopkins University Flagship Concepts for Astrobiology at Enceladus**

Enceladus contains the best characterized ocean environment beyond Earth. We propose to investigate large-sized mission concepts that leverage the astrobiological opportunity Enceladus offers to search for biosignatures and constrain the processes that drive ocean habitability and plume activity. Our goal is to provide a prioritized set of science objectives that ensures even a non-detection of life provides meaningful results. While an orbiter with various small landers and solo orbiters were some of the concepts studied in 2010, the increased understanding of the Enceladus environment from Cassini extended mission data and technological advancements in instruments over the last nine years make a new evaluation essential for providing accurate assessments to the National Academies.

Since the last decadal survey, Cassini provided more evidence that Enceladus ocean meets the basic requirements for habitability: liquid water, chemical building blocks, and energy sources. The inferences from the fracture history and gravity field of a global subsurface ocean were confirmed by observations of physical libration. Simple and



complex organics have been detected amongst the water ice and vapor plume material. The presence of salts, silica, and molecular hydrogen in the plume suggest that the ocean is geochemically interacting with a rocky core, which provides chemical energy akin to the activity that sustains ecosystems at Earth's seafloor. Both the ejection and fallout of Enceladus plume material have been mapped, providing new insight into the ease of accessibility of fresh oceanic material both in flight and on the surface.

Recent investment in technologies suitable for surface and subsurface science at Europa (e.g. ICEE and SESAME programs) can be leveraged at the more radiation-benign Enceladus surface. The Europa Lander Science Definition Team laid the ground work for designing biosignature detection strategies and identifying compelling landing sites with limited data. Mars2020 and ExoMars have driven advancements in technologies capable of identifying geochemical and isotopic biosignatures. Sample acquisition systems are also currently being studied for comet sample return, lunar landers, the Europa Lander study, and a rotorcraft on Titan. Lessons learned from these developments will facilitate planning for sampling at Enceladus in the next decade.

This confluence of the properties of the ocean and the ease of access to the samples makes a pressing case for exploring Enceladus in the next decade. The plumes are active now and have been since at least Voyager; a return to Enceladus as soon as possible ensures the freshest samples even in the unlikely event that the plumes become inactive. The imperative of studying Enceladus as an astrobiological target was demonstrated in the New Frontiers 4 competition with two medium-class mission concepts submitted for consideration. By including extensive participation from both NF4 teams, as well as additional team members from a range of career levels, planetary specialties and mission expertise, this proposal takes advantage of a cross-disciplinary pool of expertise to represent the interests of the broader Enceladus and astrobiology communities.

With direct access to fresh plume samples and the high habitable potential of its ocean, Enceladus thus offers the unique and unparalleled potential for answering the fundamental questions surrounding life elsewhere in the solar system. In this proposal, we seek to provide options for fulfilling that potential in the next decade. Specifically, we will elucidate the science cost associated with trades between lander +/- orbiter architectures in the \$1-2.5B cost range. We will identify the key science objectives specifically enabled by, key risks associated with, and key technologies required for each architecture and combinations thereof. A skeleton point design will be evaluated for the option with greatest science return per dollar.

**Clive Neal/University Of Notre Dame**  
**Developing the Lunar Geophysical Network Mission**

RELEVANCE: Understanding the interior of the Moon through the development of a Lunar Geophysical Network (LGN) mission is supported by:  
National Academies (2007) Scientific Context for the Exploration of the Moon;  
National Academies (2013) Vision and Voyages (Planetary Decadal Survey);

National Academies (2017) Committee on Astrobiology and Planetary Science report on Getting Ready for the Next Planetary Science Decadal Survey;  
National Academies (2018) Vision into Voyages (decadal survey mid-term review)  
NASA Strategic Plan (2018) Objective 1.1;  
Lunar Exploration Analysis Group LEAG (2016) Lunar Exploration Roadmap (Objective Sci-A-5);  
LEAG (2018) Advancing Science of the Moon (Concept 2);  
LEAG (2018) Next Steps on the Moon (Missions Needed).

**LGN GOALS:** The main goal of the LGN mission is to understand early/initial terrestrial planet evolution through defining the global interior structure and composition of the Moon. Secondary goals include understanding the origin(s) and locations of the shallow moonquakes (the largest events recorded by the Apollo instruments to assist in the location of surface assets away from such areas), defining the current impact flux on the Moon, and understanding the variability in the plasma environment at the LGN sites. Tertiary goals include adding value to other mission datasets (e.g., GRAIL and LRO). In order to constrain the magnitude of the study, the LGN mission should contain the following characteristics: it must be better than Apollo; operate through the night with a long-life time (up to 10 years); contain robust instrumentation that can measure seismic events/energy, magnetic fields, and heat flow; and facilitate laser ranging measurements.

**PROPOSED WORK:** The LGN Mission Concept Study (LGN-MCS) is intended to reduce risk in the implementation of this mission as part of the New Frontiers-5 competition. Therefore, this study will include fundamental concepts such as the number and distribution of landers (including on the farside) that will fit within the New Frontiers cost cap, as well as the complement of instruments that are needed to achieve mission goals (including a candid assessment of TRL and possible international contributions). It will also undertake trade studies such as power (solar vs. RTGs), instrument deployment strategies (understanding if a robotic arm is necessary), and the need for a farside communication asset (e.g., Gateway) to be included in the mission design. We will also consider secondary payloads/instruments as they relate to the mission (e.g., gravimetry, ground-penetrating radar). These studies will be vital for reducing risk to the success of the mission and will focus upon redundancy in systems and instrumentation. It should be noted that each LGN lander will contain identical payloads that are highly focused on the mission's Level-1 science goals. A streamlined payload design is required to enable the maximum number of small, low-mass LGN landers.

The funds for the LGN-MCS will be used primarily to bring US Co-Is together for two face-to-face team meetings. The first will be right after the proposal is funded to examine the constraints on the mission, evaluate available instruments (and their TRLs), and better constrain the needed power budget and data transmission rates. The second meeting will be close to the end of the project to finalize the report for submission to NASA and plan for future proposal development. LGN-MCS will leverage team expertise and lessons learned during the development of the LUNETTE lunar geophysical mission that was submitted to Discovery 2010.

**Mark Robinson/Arizona State University**  
**Intrepid Planetary Mission Concept**

We propose a long-lived roving lunar explorer, Intrepid, to collect essential measurements to address key scientific and exploration questions, and demonstrate technologies required for future robotic and human exploration of the Moon, Mars and other terrestrial bodies. Intrepid will investigate over 100 major (and hundreds of minor) scientific sites over a ~1800 km traverse during four Earth years. Extended mobility will enable Intrepid to acquire measurements over broad areas that address key scientific goals, including:

- 1) Determine the nature of the Reiner Gamma magnetic anomaly and associated albedo feature
- 2) Determine magma compositions and evolution (and thus mantle processes and heterogeneities) over 3 billion years of lunar history, in a region far from the Apollo and Luna sites
- 3) Determine ray formation mixing systematics (local material vs ejected material)
- 4) Determine the nature and extent of explosive volcanism (bulk volatile content of mantle)
- 5) Document target material dependence of impact crater formation
- 6) Investigate contemporary changes (since 2009) to the surface
- 7) Determine the large scale chemical and mineralogic heterogeneities exposed within Aristarchus crater
- 8) Document key landforms diagnostic of impact mechanics (meter to 50 km scale craters)
- 9) Test the hypothesis of young volcanism (Aristarchus IMP; <100 myrs or >1byr)
- 10) Inventory H abundance across a broad range of regolith compositions
- 11) Investigate compositional and textural heterogeneities (laterally and vertically) within a single orbital remote sensing pixel
- 12) Document the surface radiation and solar wind environment in time and location

Intrepid is designed to address high-priority questions from the Planetary Decadal Survey, Scientific Context for the Exploration of the Moon, Lunar Exploration Roadmap and other relevant NASA planning documents (e.g., the LEAG Next Steps on the Moon Special Action Team report). The scientific return from Intrepid will redefine our understanding of fundamental planetary processes (including impact cratering, volcanology, crustal formation, and regolith processes) while making existing (and future) orbital remote sensing measurements more valuable. The Intrepid mission concept takes a holistic view of lunar exploration relying on high TRL hardware and a disciplined concept of operations to ensure mission success.

Intrepid will touch down fifty kilometers south of the Reiner Gamma magnetic anomaly (and associated swirl) and traverse across and along the swirl collecting a suite of measurements to definitively test origin hypotheses for the anomaly and swirl. Intrepid will then continue on to the Marius Hills volcanic complex where it will investigate cones, flows, and putative ash deposits. The observations collected here will not only

explain the unique clustering of landforms but also provide insight to large scale magmatic processes. Next, Intrepid will head north across some of the youngest (1.5 byr) lunar mare deposits, making a suite of compositional observations of the mare and spectacular rays from Aristarchus crater that cross the region. Once on the Aristarchus plateau Intrepid will investigate the largest pyroclastic deposit on the Moon prospecting for H deposits. After the plateau, Intrepid will traverse the rim of the spectacular Aristarchus crater, assessing one of the most compositionally and geologically diverse regions of the Moon. Finally, Intrepid will investigate a newly discovered type of volcanic landform, Irregular Mare Patches (IMP), which may represent very young (<100 my) volcanism.

Intrepid also provides a unique opportunity to excite and involve the public in NASA Solar System exploration by providing dramatic planetary surface imaging and scientific discoveries at an unprecedented pace.

**Abigail Rymer/Johns Hopkins University**  
**Odyssey: A Large Strategic Class Mission Study for the Exploration of the Neptune-Triton System.**

Ice giants are the only major category of Solar System object never to have had a dedicated mission and represent one of the largest groups of detected exoplanets. The complex Neptunian system provides the unique opportunity to simultaneously study an Ice Giant world and a large captured satellite (Triton) that might be host to a sub-surface ocean. Such a mission represents a wealth of cross-cutting science objectives that can ideally be addressed with a Flagship mission.

Ice giants challenge our understanding of planetary formation, evolution and physics. For example, models suggest that they have a narrow time window for formation: their rock/ice cores must become large enough to gravitationally trap hydrogen and helium gas just as the solar nebula is being dissipated by the early Sun. Forming earlier would cause them to trap large amounts of gas and become like Jupiter, and forming later would not allow them to trap the gas they have (perhaps 10% of their total mass). But if their formation requires such special timing, why are they so common?

Triton's youthful surface geology and the south polar plumes that were imaged by Voyager 2 suggest that it may be an ocean world, possessing either a global ocean or other liquid reservoirs of some form. The extent to which cryovolcanism, which is inclusive of plume activity with an endogenic origin, has recently occurred on Triton could also reveal much about the icy moon's internal heat budget, and how it has evolved over time.

A carefully planned Neptune orbit would enable our first real understanding of Neptune's structure and Triton's geoscience. The multiple vantage points and duration of the tour would allow observing of the components of the Neptune-Triton system under varying geometries and conditions, as well as allowing for serendipitous discovery and follow-up. Additional mission elements we propose to consider are: 1) a Neptune atmospheric probe

to measure heavy noble gases, isotopic ratios, and the bulk abundance of certain species and, 2) a Triton lander to provide synergistic observations from the geologic outcrop scale to provide ground truth for the orbiter's observations. Geochemical laboratories on the lander could permit correlating surface composition with multi- or hyperspectral imaging by the orbiter. Public engagement would benefit from inspiring views from the surface, perhaps with Neptune appearing in the sky and views of weather from Triton's surface would complement different perspectives from the orbiter.

A mission to the Neptune-Triton system would allow next-generation comparative studies of Kuiper Belt Objects and advance Ocean Worlds, heliophysics, and exoplanet objectives. We have identified a talented, diverse and multi-disciplinary team to carry out the concept study, leveraging the full spectrum of intellectual talent in the country. Our team includes international collaboration as well as members of the exoplanet and heliophysics community in order to place the science in appropriate broader context. Uranus was chosen over Neptune in the current V&V because of issues involving technology readiness and the availability of appropriate spacecraft trajectories this changes in the next decade and has led OPAG to support Neptune over Uranus for a flagship mission owing to Triton, a captured dwarf planet itself and also a high priority Ocean World target. For these reasons and others, exploration of the Neptune-Triton system is a priority for the near future.

The launch window to Neptune using chemical propulsion only is optimal from 2029 to 2030. For a Neptune flagship to be a viable first choice flagship mission in the next decadal survey, and to meet this launch window, the project must be ready to go before the ink is dry on the decadal survey. That means that the science objectives, mission architecture, launch vehicle and international partners should be clear. This study will illuminate the optimal path.