# THE PLANETARY SCIENCE AND ASTROBIOLOGY DECADAL SURVEY

Statement of

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The National Academies of Sciences, Engineering, and Medicine

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Chairman Beyer, Ranking Member Babin, and distinguished members of the Subcommittee thank you very much for the opportunity to speak to you today. My name is Philp Christensen, and I am a Regents professor in the School of Earth and Space Exploration at Arizona State University and Co-Chair of the National Academies of Sciences, Engineering, and Medicine's Decadal Survey in Planetary Science and Astrobiology.

**New Flagship Missions**

One of the most important, exciting, and challenging tasks that our committee was given was to identify and prioritize the large, or "Flagship" - planetary science missions that NASA should undertake in the coming decade. As you heard from my co-chair Dr. Canup, there is a remarkable array of key science questions that we would like to answer, and the Flagship missions provide the best means to make fundamental progress toward answering those questions. We carefully studied a half dozen potential missions and selected the Uranus orbiter and probe as our top priority. Uranus is a member of the "ice-giant" class of planets – so called because they have far more ice, and likely rock, than the "gas giants" Jupiter and Saturn. The ice giants may be among the most common class of planets in the universe, yet they remain the only planetary bodies in our solar system that have never been studied with a dedicated orbital tour. Uranus is one of the most intriguing bodies in the solar system. Its low internal energy, active atmospheric dynamics, and complex magnetic field all present major puzzles. A primordial giant impact may have produced the planet's extreme axial tilt and possibly its rings and satellites. It is unclear when and where Uranus formed – it may have swapped positions with Neptune during early solar system migration. This migration would have significantly affected the inner solar system, including the early Earth at the time when life may have been emerging – we need to understand this process much better. Uranus's largest ice-rock moons show surprising evidence of geological activity and are potential ocean worlds. The Uranus orbiter and probe will address a broad range of science questions across the entire Uranian system – from its origin, its interior, atmosphere, and magnetosphere, to its moons and rings. The mission would launch on an existing rocket, with optimal launch opportunities in 2031 and 2032 that utilize a Jupiter gravity assist to shorten cruise time. Finally, there is strong international interest in an ice giant mission, which offers the opportunity for partnership like the highly successful NASA-ESA collaboration on the Cassini/Huygens spacecraft to the saturnian system. Our committee strongly recommends that NASA begin the development of this mission as soon as possible with the goal of launching in 2031.

Our second priority Flagship, which we also advocate starting in the coming decade, is the Enceladus orbiter and lander mission. Enceladus is a small, icy moon of Saturn with active plumes that bring water from its subsurface ocean to the surface. These plumes deliver ocean water, and whatever is in it, to the surface where we can study it. The Orbilander mission will not only determine whether an ocean world *could* support life but will directly address perhaps the most fundamental question in solar system science: *is there life* beyond Earth? The Cassini spacecraft sampled the plumes, so we know that they contain water, methane, ammonia, and other simple organic molecules. However, the Cassini fly through velocity was high, causing the breakup of large organic molecules associated with life. The Orbilander will first orbit Enceladus at much lower velocity than Cassini and then will land and spend two years on the surface directly beneath an active plume. This mission design will provide much better measurements of the fresh plume materials as they rain down upon the lander. In addition to the search for evidence of life, Orbilander will obtain geochemical and geophysical context for the life detection experiments, such as the conditions in the ocean and the dynamics of the interior.

**Medium-class New Frontiers Missions**

In addition to the Flagship missions, our committee evaluated more than 25 medium-class, or New Frontiers, mission concepts and prioritized the most promising candidates for the coming decade. New Frontiers missions are competitively selected and provide the science engineering community with the opportunity to bring forward their most innovative and exciting exploration concepts. I'm sure you can appreciate how difficult it was for us to make our final selections from this amazing suite of candidates, but we have an exceptional set of nine themes.

- The Centaur Orbiter and Lander would study one of the compositionally primitive members of the Kuiper Belt – the ice-rich bodies formed in the outermost solar system - that has been captured into orbit between Jupiter and Neptune. Such objects provide crucial information on the nature of the compositional reservoirs in the protoplanetary disk.
- The Ceres Sample Return would return samples to Earth from the largest asteroid and most ice rich body in the inner solar system and investigate how it formed and assess its habitability.
- The Comet Surface Sample Return would return samples for detailed analyses to understand comet formation and activity, the mechanisms of primordial mixing in the early solar nebula, and the role of comets in delivery of water and organics to Earth.
- The Enceladus Multiple Flyby would characterize the habitability of the subsurface ocean and look for evidence of life via analysis of fresh plume material. This mission would not provide the detailed results of the Orbilander, but we considered the search for life at Enceladus to be of such importance to warrant an alternative mission pathway.
- The Lunar Geophysical Network would examine the Moon with a global, long-lived network of geophysical landers to better understand the Moon's geological processes, bulk composition, distribution of heat-producing elements, and interior state and thermal evolution.
- The Saturn Probe would obtain direct measurements of Saturn's atmosphere from an entry probe in order to understand conditions in the protosolar nebula, constrain giant planet formation mechanisms, including when and where Saturn formed, and study what governs the diversity of giant planet climates, circulations, and meteorology.
- The Titan Orbiter would characterize Titan's ice shell and subsurface ocean, its dense nitrogen atmosphere, and study its methane seas and hydrological cycle to assess its potential habitability and prebiotic chemistry relevant to the early Earth.
- The Venus In Situ Explorer would investigate global atmospheric cycles, surface-atmosphere interactions, and surface properties that cannot be characterized from orbit or from a single descent profile, in order to better understand the origin and evolution of terrestrial planets, including our Earth.
- The Triton Ocean World Surveyor would orbit Neptune and complete numerous flybys of Triton, a captured Kuiper Belt Object that has a geologically young surface and active plumes and is a potential ocean world.

Our recommended program for the decade would include the selection of three New Frontiers missions, each of which will provide breakthroughs in our understanding of the solar system that we live in.

**Planetary Defense**

Planetary defense is an international enterprise aimed at providing protection to the people of the world from devastating asteroid and comet impacts. By using the knowledge and tools gained through planetary science and exploration, it is now possible to develop realistic and cost-effective detection and mitigation strategies against these natural disasters. As awareness of the hazard posed to life and property by Earth-approaching asteroids and comets has grown, NASA, NSF, and other government agencies are pursuing activities in support of planetary defense. Advancement in planetary defense will require enhancements in asteroid detection and characterization, an assessment of potential mitigation techniques, and the ability to rapidly characterize newly identified hazardous objects. Our report recommends that NASA should fully support the development and timely launch, of the NEO Surveyor mission to achieve the highest priority planetary defense goal of asteroid detection (and characterization?). Furthermore, we recommend a follow-on rapid-response, reconnaissance mission targeted to an approximately 100-m diameter asteroid – the class that poses the highest probability of a destructive Earth impact - to better prepare for a short-warning-time threat.

**A Balanced Planetary Exploration Portfolio for the Coming Decade**

Our report outlines a prioritized portfolio of research activities that will significantly advance the frontiers of planetary science and astrobiology in the coming decade. Our recommended program defines an integrated suite of flight projects, research activities, and technology development that will produce transformative advances in our knowledge and understanding. This program follows directly from our priority science questions and captures the highest priorities of the planetary science community. It is balanced across activities of varied scale and scientific focus and includes key areas for cooperation with NASA's human exploration program and U.S. agency, industry, and international partners. The recommended program is both aspirational and inspirational and enables the robust training and development of a diverse science and engineering workforce, drives technology development, and maintains strong U.S. leadership in space exploration across the solar system.

Thank you for the opportunity to testify. I welcome any questions the Subcommittee might have.

# Summary of National Academies of Sciences, Engineering, and Medicine's Decadal Survey in Planetary Science and Astrobiology

This report identifies a research strategy to maximize advancement of planetary science, astrobiology, and planetary defense in the 2023-2032 decade. Federal investment in these activities occurs primarily through NASA's Planetary Science Division (PSD); important activities are also conducted by the National Science Foundation (NSF). The decadal committee evaluated potential activities by their capacity to address the priority science questions identified by the committee (Table S.1), cost and technical readiness as assessed through independent evaluation, programmatic balance, and other factors. This summary highlights the committee's top findings and recommendations.

## STATE OF PROFESSION

The state of the profession (SoP), including issues of diversity, equity, inclusivity, and accessibility (DEIA), is central to the success of the planetary science enterprise. Its inclusion here, *for the first time in a planetary science decadal survey*, reflects its importance and urgency. Ensuring broad access and participation is essential to maximizing excellence in an environment of fierce competition for limited human resources, and to ensuring continued American leadership in planetary science and astrobiology (PS&AB). A strong system of equity and accountability is required to recruit, retain, and nurture the best talent into the PS&AB community. The committee applauds the hard-earned progress that has been made – most notably with respect to the entry and prominence of women in the field – as well as the exemplary goals and intentions of NASA science leadership with respect to DEIA. However, much work remains to be done, in particular to address persistent and troubling issues of basic representation by race/ethnicity.

The committee's eight SoP recommendations address:

1. *An evidence gathering imperative*. Equity and accountability require accurate and complete data about the SoP. There is an urgent need for data concerning the size, identity, and demographics of the PS&AB community; and workplace climate. Without such data, it cannot be known if the best available talent is being utilized, nor how involvement may be undermined by adverse experiences.
2. *Education of individuals about the costs of bias and improvement of institutional procedures, practices, and policies*. The committee recommends that the PSD adopt the view that bias can be both unintentional and pervasive and provides actionable steps to assist NASA in identifying where bias exists and in removing it from its processes.
3. *Broadening opportunities to advance the SoP*. Engaging underrepresented communities at secondary and college levels to encourage and retain them along PS&AB career pathways is essential to creating and sustaining a diverse community.
4. *Creating an inclusive and inviting community free of hostility and harassment*. Ensuring that all community members are treated with respect, developing and enforcing codes of conduct, and providing ombudsperson support to address issues is important for maintaining healthy and productive work environments.

Together, the SoP findings and recommendations aim to assist NASA's PSD in boldly addressing issues that concern its most important resource: the people who propel its planetary science and exploration missions.

## MISSION CLASSES, BALANCE, AND ONGOING ACTIVITIES

The committee's Statement of Task defines missions in three cost classes — small, medium, and large. The Discovery program supports small, PI-led missions that address focused science objectives with a high launch cadence. Medium-class New Frontiers missions are PI-led and address broader science goals. Large ("Flagship") missions address broad, high-priority science objectives with sophisticated instrument payloads and mission designs. Balance across these classes is important to enable a steady stream of new discoveries and the capability to make major scientific advances.

Currently operating PSD spacecraft include the ongoing Mars orbiter missions, Curiosity and Perseverance Mars rovers; the Lunar Reconnaissance Orbiter; the InSight and Lucy Discovery missions; and the New Horizons, Juno, and OSIRIS-REx New Frontiers (NF) missions. Missions in development include four small SIMPLEx missions, the Psyche, DAVINCI, and VERITAS Discovery missions, the Dragonfly NF mission, and the Europa Clipper large strategic mission. NASA also contributes to international missions (e.g., ESA's BepiColombo, JUICE, and EnVision and JAXA's MMX). The committee strongly supports *i*) continuation of these missions and contributions in their current operational or development phases, and *ii*) the Senior Review process for evaluating the merit of additional extended mission phases.

TABLE S.1: The twelve priority science questions.

| Scientific Themes | Priority Science Question Topics and Descriptions |
|---|---|
| A) Origins | Q1. Evolution of the protoplanetary disk: What were the initial conditions in the solar system? What processes led to the production of planetary building blocks, and what was the nature and evolution of these materials? |
| | Q2. Accretion in the outer solar system: How and when did the giant planets and their satellite systems originate, and did their orbits migrate early in their history? How and when did dwarf planets and cometary bodies orbiting beyond the giant planets form, and how were they affected by the early evolution of the solar system? |
| | Q3. Origin of Earth and inner solar system bodies: How and when did the terrestrial planets, their moons, and the asteroids accrete, and what processes determined their initial properties? To what extent were outer solar system materials incorporated? |
| B) Worlds and Processes | Q4. Impacts and dynamics: How has the population of solar system bodies changed through time, and how has bombardment varied across the solar system? How have collisions affected the evolution of planetary bodies? |
| | Q5. Solid body interiors and surfaces: How do the interiors of solid bodies evolve, and how is this evolution recorded in a body's physical and chemical properties? How are solid surfaces shaped by subsurface, surface, and external processes? |
| | Q6. Solid body atmospheres, exospheres, magnetospheres, and climate evolution: What establishes the properties and dynamics of solid body atmospheres and exospheres, and what governs material loss to space and exchange between the atmosphere and the surface and interior? Why did planetary climates evolve to their current varied states? |
| | Q7. Giant planet structure and evolution: What processes influence the structure, evolution, and dynamics of giant planet interiors, atmospheres, and magnetospheres? |
| | Q8. Circumplanetary systems: What processes and interactions establish the diverse properties of satellite and ring systems, and how do these systems interact with the host planet and the external environment? |
| C) Life and Habitability | Q9. Insights from Terrestrial Life: What conditions and processes led to the emergence and evolution of life on Earth, what is the range of possible metabolisms in the surface, subsurface and/or atmosphere, and how can this inform our understanding of the likelihood of life elsewhere? |
| | Q10. Dynamic Habitability: Where in the solar system do potentially habitable environments exist, what processes led to their formation, and how do planetary environments and habitable conditions co-evolve over time? |
| | Q11. Search for life elsewhere: Is there evidence of past or present life in the solar system beyond Earth and how do we detect it? |
| Cross-cutting A-C linkage | Q12. Exoplanets: What does our planetary system and its circumplanetary systems of satellites and rings reveal about exoplanetary systems, and what can circumstellar disks and exoplanetary systems teach us about the solar system? |

## MARS SAMPLE RETURN

The Perseverance rover on Mars is collecting samples from Jezero crater, a former lake basin carved into >3.7-billion-year-old stratigraphy. This was the highest priority large mission in the prior decadal survey, *Vision and Voyages*. NASA, with ESA partnership, is now undertaking Mars Sample Return (MSR) to return those samples to Earth. Sedimentary, igneous, water-altered, and impact-formed rocks accessible in the Jezero region will provide a geological record crucial for understanding Mars's environmental evolution and, potentially, its prebiotic chemistry and biology, in ways that cannot be addressed in situ or with martian meteorites. MSR will provide an invaluable sample collection to the benefit of future generations.

**Recommendation: The highest scientific priority of NASA's robotic exploration efforts this decade should be completion of Mars Sample Return as soon as is practicably possible with no increase or decrease in its current scope.**

**Recommendation: Mars Sample Return is of fundamental strategic importance to NASA, US leadership in planetary science, and international c cooperation and should be completed as rapidly as possible. However, its cost should not be allowed to undermine the long-term programmatic balance of the planetary portfolio. If the cost of MSR increases substantially (≥ 20%) beyond the $5.3 billion[1] level adopted here or goes above ~35% of the PSD budget in any given year, NASA should work with the Administration and Congress to secure a budget augmentation to ensure the success of this strategic mission.**

## MARS EXPLORATION PROGRAM

The Mars Exploration Program (MEP) has a record of success in advancing our understanding of Mars and the evolution of terrestrial planets, technology development, joint mission implementations, and public enthusiasm for planetary science. The committee strongly supports the continuation of MEP and prioritizes Mars Life Explorer (MLE) as the next medium-class Mars mission.[2] While ancient biosignatures are a focus of MSR, MLE will seek extant life and assess modern habitability through examination of low latitude ice. MLE will characterize organics, trace gases, and isotopes at a fidelity suitable for biosignature detection; and assess ice stability and the question of modern liquid water via chemical, thermophysical, and atmospheric measurements.

**Recommendation: Subsequent to the peak-spending phase of MSR, the next priority medium-class mission for MEP should be Mars Life Explorer**

## LUNAR DISCOVERY AND EXPLORATION PROGRAM

The Lunar Discovery and Exploration Program (LDEP) supports industry partnerships and innovative approaches to accomplishing exploration and science goals, including the Commercial Lunar Payload Services (CLPS) program for lunar landing services. LDEP is funded within PSD, but budgetary responsibility is split between PSD and the Exploration Science Strategy and Integration Office (ESSIO). No single organizational chain has authority for executing lunar science and missions; as a result, LDEP activities are currently not optimized to accomplish high-priority science. A structured, science-led approach to setting goals and measurement objectives for the Moon is needed for LDEP and to provide scientific requirements for Artemis.

[1] All dollar amounts are real-year dollars unless otherwise indicated

[2] The full Mars Life Explorer mission study report is available at https://tinyurl.com/2p88fx4f

**Recommendation: PSD should execute a strategic program to accomplish planetary science objectives for the Moon, with an organizational structure that aligns responsibility, authority, and accountability.**

**Recommendation: The advancement of high priority lunar science objectives, as defined by PSD based on inputs from this report and groups representing the scientific community, should be a key requirement of the Artemis human exploration program. Design and implementation of an integrated plan responsive to both NASA's human exploration and science directorates, with separately appropriated funding lines, presents management challenges; however, overcoming these is strongly justified by the value of human-scientific and human-robotic partnerships to the agency and the nation.**

The committee prioritizes the medium-class Endurance-A lunar rover mission. Endurance-A will traverse diverse terrains in the South Pole Aiken (SPA) basin, collect ~100 kg of samples, and deliver the samples to a location for return to Earth by astronauts. Endurance-A will address the highest priority lunar science, revolutionizing our understanding of the Moon and the early history of the solar system recorded in its most ancient impact basin. Return of Endurance-A samples by Artemis astronauts is the ideal synergy between NASA's human and scientific exploration of the Moon, producing flagship-level science at a fraction of the cost to PSD through coordination with Artemis.

**Recommendation: Endurance-A should be implemented as a strategic medium-class mission as the highest priority of the Lunar Discovery and Exploration Program. Endurance-A would utilize CLPS to deliver the rover to the Moon, a long-range traverse to collect a substantial mass of high-value samples, and astronauts to return them to Earth.**

## RESEARCH AND ANALYSIS

Robotic solar system exploration is driven by the desire to increase knowledge. Strong, steady investment in research and analysis (R&A) is needed to ensure *i*) maximal return from mission data; *ii*) that data drives improved understanding and novel, testable hypotheses; *iii*) that advances feed into future mission development; and *iv*) training a diverse workforce. The fraction of PSD's budget devoted to R&A has decreased from 14% in 2010 to a projected 7.7% by FY23. It is essential to the nation's planetary science efforts that this trend be reversed. The openly competed R&A programs drive innovation, provide rapid response to new discoveries, identify the most meritorious ideas, and attract new and increasingly diverse investigators.

**Recommendation: PSD should increase its investment in R&A activities to achieve a minimum annual funding level of 10% of the PSD total annual budget. This increase should be achieved through a progressive ramp-up in funding allocated to the openly competed R&A programs, as defined in this decadal survey. Mid-decade, NASA should work with an appropriately constituted independent group to assess progress in achieving this recommended funding level.**

## PLANETARY DEFENSE

The Planetary Defense Coordination Office within PSD coordinates and supports activities to protect Earth from impacts by Near Earth Objects (NEOs). Congressionally directed NEO detection goals will be ideally advanced by NEO Surveyor, a dedicated, space-based mid-IR survey currently pending confirmation. Advancement in planetary defense will require assessment of mitigation techniques, as well as the ability to characterize newly identified hazardous objects. NASA's DART mission, scheduled to impact the moonlet of the binary asteroid 65803 Didymos in 2022, will demonstrate one approach to asteroid deflection.

**Recommendation: NASA should fully support the development, timely launch, and subsequent operation of NEO Surveyor to achieve the highest priority planetary defense NEO survey goals.**

**Recommendation: The highest priority planetary defense demonstration mission to follow DART and NEO Surveyor should be a rapid-response, flyby reconnaissance mission targeted to a challenging NEO, representative of the population (~50-to-100 m in diameter) of objects posing the highest probability of a destructive Earth impact. Such a mission should assess the capabilities and limitations of flyby characterization methods to better prepare for a short-warning-time NEO threat.**

## DISCOVERY PROGRAM

The Discovery program supports relatively frequent missions that address any science achievable within a specified cost cap, with a central goal to maximize innovative science per total mission cost. The program has made fundamental contributions to planetary exploration and the committee strongly supports its continuation. The committee assessed the cost cap and structure needed to *i*) address decadal-level science[3] questions, *ii*) more clearly anticipate mission life cycle cost, and *iii*) maximize science return per dollar.

**Recommendation: The Discovery Phase A through F cost cap should be $800 million in FY25 dollars, exclusive of the launch vehicle, and periodically adjusted throughout the decade to account for inflation. This cap will enable the Discovery Program to continue to support missions that address high-priority science objectives, including those that can reach the outer solar system.**

## NEW FRONTIERS PROGRAM

New Frontiers missions address broader and/or more technically challenging scientific questions, with higher costs and less frequent launches. NF missions are managed by a limited number of centers, and extensive resources are required for NF mission proposals. It is thus essential that NF missions be strategically designed to address the most important science. Decadal

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[3] Decadal-level science is that which results in significant, unambiguous progress in addressing at least one of the survey's 12 priority science questions.

surveys provide the ideal opportunity for a large, diverse group representing the community to prioritize NF mission themes.

**Recommendation: Mission themes for the NF-6 and NF-7 calls should continue to be specified by the decadal survey. Additional concepts that may arise mid-decade due to new discoveries should be evaluated by an appropriately constituted group representing the scientific community and considered for addition to NF-7.**

Mission life cycle costs are the primary factor in determining launch cadence for a cost-bounded program like New Frontiers. In evaluating the NF cost structure, the committee prioritized enabling access to all targets across the solar system at the potential expense of launch cadence. New Frontiers missions in development, as well as the most scientifically compelling new concepts considered by the committee, have estimated life cycle costs substantially greater than the prior NF cost cap. These missions are representative of the nature and breadth of science optimally addressed in the NF program.

**Recommendation: New Frontiers should have a single cost cap that includes both Phase A-D and the primary mission Phase E-F costs, with a separate, additional cost cap allocation for a mission's quiet cruise phase. This approach will enable the NF Program to optimize mission science, independent of cruise duration.**

**Recommendation: The NF Phase A-F cost cap, exclusive of quiet cruise phase and launch vehicle costs, should be increased to $1.65 billion in FY25 dollars. A quiet cruise allocation of $30 million per year should be added to this cap, with quiet cruise to include normal cruise instrument checkout and simple flyby measurements, outbound and inbound trajectories for sample return missions, and long transit times between objects for multiple-target missions.**

## NEW FRONTIERS MISSIONS

The committee considered a broad range of medium-class missions, and from these prioritized the following eight mission themes for the New Frontiers 6 (NF-6) call:

- Centaur orbiter and lander
- Ceres sample return
- Comet surface sample return
- Enceladus multiple flyby
- Lunar Geophysical Network
- Saturn probe
- Titan orbiter
- Venus In Situ Explorer

The themes recommended for New Frontiers 7 (NF-7) include all those not selected from the above list, with the addition of:

- Triton Ocean World Surveyor

Theme descriptions are provided in the report.

## NEW LARGE MISSIONS

**The committee prioritizes the Uranus Orbiter and Probe (UOP) as the highest priority new Flagship mission for initiation in the decade 2023-2032.** UOP will deliver an in situ atmospheric probe and conduct a multi-year orbital tour that will transform our knowledge of ice giants in general and the Uranian system in particular. Uranus is one of the most intriguing bodies in the solar system. Its low internal energy, active atmospheric dynamics, and complex magnetic field all present major puzzles. A primordial giant impact may have produced the planet's extreme axial tilt and possibly its rings and satellites, although this is uncertain. Uranus's large ice-rock moons displayed surprising evidence of geological activity in limited Voyager 2 flyby data, and are potential ocean worlds. UOP science objectives address Uranus' *i*) origin, interior, and atmosphere, *ii*) magnetosphere; and *iii*) satellites and rings. UOP will provide ground-truth relevant to the most abundant, similarly sized class of exoplanets. UOP can launch on an existing launch vehicle. Optimal launch opportunities in 2031 and 2032 utilize a Jupiter gravity assist to shorten cruise time; other opportunities from 2032 through 2038 (and beyond) utilize inner solar system gravity assists with an increased cruise time.

**The second highest priority new Flagship mission is the Enceladus Orbilander.**[4] Enceladus is an ice-rock world with active plumes of gas and particles that originate from its subsurface ocean. Study of plume material allows direct study of the ocean's habitability, addressing a fundamental question: is there life beyond Earth and if not, why not? Orbilander will analyze fresh plume material from orbit and during a two-year landed mission. Its main science objectives are: *i*) to search for evidence of life; and *ii*) to obtain geochemical and geophysical context for life detection experiments. Commencing Orbilander late in the decade supports arrival at Enceladus in the early 2050s when optimal illumination of the south polar region begins. Should budgetary constraints not permit initiation of Orbilander, the committee includes the Enceladus Multiple Flyby (EMF) mission theme in NF. EMF provides an alternative pathway for progress this decade on the crucial question of ocean world habitability, albeit with greatly reduced sample volume, higher velocity of sample acquisition and associated degradation, and a smaller instrument component to support life-detection.

## REPRESENTATIVE FLIGHT PROGRAMS

The committee developed two representative programs for the 2023-2032 decade. The *Level Program* assumes currently projected funding for PSD, including inflation at 2%/yr, while the *Recommended Program* can be achieved with ~17.5% higher decade funding. Decision Rules are provided to accommodate significant budgetary deviations. Both programs continue missions in operation and in development; initiate the Uranus Orbiter and Probe Flagship mission; increase R&A funding to 10% or more of the annual PSD budget by mid-decade; incorporate cost realism and cost cap recommendations for Discovery and New Frontiers; and maintain support for

[4] Mission study report available at https://science.nasa.gov/solar-system/documents.

planetary defense, including at least one new mission start (Table S.2); supports the Lunar Discovery and Exploration Program with a mid-decade start of the Endurance-A rover; and continues the Mars Exploration Program.

The two programs differ in their support for new initiatives. The *Recommended Program* is aspirational and inspirational: it enables robust development of diverse science and engineering communities, drives technology development, and maintains U.S. leadership in solar system exploration. It begins the UOP Flagship in FY24 to support a launch in the early 2030s that minimizes cruise length and complexity and initiates the Orbilander Flagship late in the decade to reveal the astrobiological conditions of an ocean world. It also restores the *Vision and Voyages* recommendation, endorsed by the committee, for two NF missions per decade, with NF-5 (which was to be the second NF mission from the prior decade) completed early in the decade, followed by a mid-decade selection of two NF missions in NF-6. The Mars Life Explorer would be initiated late in the decade through the Mars Exploration Program.

TABLE S.2 Comparison of Representative Programs

| Recommended Program | Level Program |
|---|---|
| Continue Mars Sample Return | Continue Mars Sample Return |
| Five new Discovery selections at recommended cost cap | Five new Discovery selections at recommended cost cap |
| Support LDEP with mid-decade start of Endurance-A | Support LDEP with mid-decade start of Endurance-A |
| R&A increased by $1.25 billion | R&A increased by $730 million |
| Continue Planetary Defense Program with NEO Surveyor and a follow-on NEO characterization mission | Continue Planetary Defense Program with NEO Surveyor and a follow-on NEO characterization mission |
| Gradually restore MEP to pre-MSR level with late decade start of Mars Life Explorer | Gradually restore MEP to pre-MSR level in late decade with no new start for Mars Life Explorer |
| New Frontiers 5 (1 selection)<br>New Frontiers 6 (2 selections) | New Frontiers 5 (1 selection)<br>New Frontiers 6 (late, or not included) |
| Begin Uranus Orbiter and Probe in FY24 | Begin Uranus Orbiter and Probe in FY28 |
| Begin Enceladus Orbilander in FY29 | No new start for Enceladus Orbilander this decade |

## MISSION TRACEABILITY TO SCIENCE GOALS

The large- and medium-class strategic and PI-led missions prioritized and recommended in this report were selected based on their ability to address the priority science questions, as well as programmatic balance, technical risk and readiness, and cost. After these missions had been selected, the committee evaluated this portfolio of new missions to assess how well they covered the breadth of the priority science questions (Q1-Q12) discussed in Chapters 4-15. The committee considered whether each mission would likely contribute to a ‘substantial’, ‘breakthrough’ or ‘transformative’ advance for each of the sub-questions in Q1 through Q12. The tabulated and normalized results are displayed in a mission portfolio assessment matrix (Table S.3) on a scale of modest (yellow) to high (dark green) contribution. This matrix illustrates that the collective suite of prioritized missions in the Recommended Program does an excellent job of addressing the full breadth of the priority planetary science questions and does so at a diverse set of destinations.

## KEY ADDITIONAL RECOMMENDATIONS

**Recommendation: NASA should evaluate plutonium-238 production capacity against the mission portfolio recommended in this report and other NASA and national needs, and increase it, as necessary, to ensure a sufficient supply to enable a robust exploration program at the recommended launch cadence.**

**Recommendation: NASA should continue to invest in maturing higher efficiency radioisotope power system radioisotope power system technology to best manage its supply of plutonium-238 fuel.**

**Recommendation: NASA PSD should strive to consistently fund technology advancement at an average of 6% to 8% of the PSD budget.**

| Table 3 | Priority Science Questions | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mission Name** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| **Mars Sample Return** | | | | | | | | | | | | |
| **Uranus Orbiter and Probe** | | | | | | | | | | | | |
| **Enceladus Orbilander** | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| **Endurance-A** | | | | | | | | | | | | |
| **Mars Life Explorer** | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| **Centaur Orbiter/Lander** | | | | | | | | | | | | |
| **Ceres Sample Return** | | | | | | | | | | | | |
| **Comet Sample Return** | | | | | | | | | | | | |
| **Enceladus Multi-Flyby** | | | | | | | | | | | | |
| **Lunar Geophys. Network** | | | | | | | | | | | | |
| **Saturn Probe** | | | | | | | | | | | | |
| **Titan Orbiter** | | | | | | | | | | | | |
| **Triton OWS** | | | | | | | | | | | | |
| **Venus In Situ Explorer** | | | | | | | | | | | | |

TABLE S.3. Mission Portfolio Assessment Matrix. Assessment of the science questions addressed by MSR and each of the other large- and medium-class missions prioritized in this report. The top rows include MSR and the two new large strategic missions prioritized here. Endurance-A and Mars Life Explorer are highly ranked medium-class missions recommended for the LDEP and MEP programs, respectively. The remaining rows are the prioritized New Frontiers mission themes in alphabetical order. Yellow represents a modest contribution—typically a "substantial" advance in addressing one to a few of a priority science question sub-questions—whereas the increasing intensity of green indicates increasing levels of 'breakthrough' or 'transformative' advances—i.e., addressing an increasing number of sub-questions. Note that Q9 focuses on terrestrial life and is therefore not the primary focus of most planetary missions, but rather is supported through astrobiology research programs.

PHILIP R. CHRISTENSEN is a Regents Professor and the Ed and Helen Korrick Professor in the School of Earth and Space Exploration at Arizona State University. His research interests focus on the composition, processes, and physical properties of Mars, Earth, asteroids, Europa, and other planetary surfaces. Dr. Christensen uses spectroscopy, radiometry, field observations, and numerical modeling to study the geology and history of planets and moons. A major facet of his research is the development of spacecraft instruments, and he has built seven science instruments that have flown on NASA's Mars Observer, Mars Global Surveyor, Mars Odyssey, Mars Exploration Rover, OSIRIS-REx, and Lucy missions and the UAE's Hope Mars orbiter. He is currently developing an infrared camera for the Europa Clipper missions. Over the past 20 years he has developed an extensive K-12 education and outreach program to bring the excitement of science and exploration into the classroom and has mentored 32 outstanding Ph.D. students. Dr. Christensen is a Fellow of the American Geophysical Union and the Geological Society of America and received the AGU's Whipple Award in 2018, the GSA's G.K. Gilbert Award in 2008, NASA's Public Service Medal in 2005, and NASA's Exceptional Scientific Achievement Medal in 2003. He received his Ph.D. in geophysics and space physics from the University of California, Los Angeles. Dr. Christensen is the co-chair of the National Academies Planetary Science and Astrobiology Decadal Survey and has previously served as the chair of the Mars Panel of the Planetary Science Decadal Survey in 2010-2011 and as the co-chair of the NRC's Committee on Astrobiology and Planetary Science from 2012-2015.

**PHILIP R. CHRISTENSEN**

## Education

| | | | |
|---|---|---|---|
| B.S. | Geology | 1976 | University of California, Los Angeles |
| M.S. | Geophysics and Space Physics | 1978 | University of California, Los Angeles |
| Ph.D. | Geophysics and Space Physics | 1981 | University of California, Los Angeles |

## Professional Employment

| | |
|---|---|
| 2004-present | *Regents Professor*, Arizona State University |
| 2000-present | *Ed and Helen Korrick Professor*, Arizona State University. |
| 1995-2000 | *Professor*, Department of Geology, Arizona State University |
| 1990-1995 | *Associate Professor*, Department of Geology, Arizona State University |
| 1986-1990 | *Assistant Professor*, Department of Geology, Arizona State University |
| 1981-1986 | *Faculty Research Associate,* Department of Geology, Arizona State University |

## Selected Funded Research Projects

Instrument Principal Investigator, L'TES, NASA Lucy Discovery Mission, 2017-present.

Principal Investigator, E-THEMIS, NASA Mars Europa Mission, 2015-present.

Instrument Lead, EMIRS, UAE Emirates Mars Mission, 2015-present.

Instrument Lead, OTES, NASA OSIRIS-REx New Frontiers Mission, 2010-present.

Principal Investigator, Thermal Emission Imaging System (THEMIS), NASA Mars 2001 Orbiter Mission, 1997-present.

Principal Investigator, Miniature Thermal Emission Spectrometer (Mini-TES), NASA Mars 2001/2003 Rover Mission, 1997-2018.

Principal Investigator, NASA, Mars Instrument Develop. Program 2008-2013.

Principal Investigator, NASA, THEMIS Imaging Facility and Student Imaging Project 2000-present.

Principal Investigator, NASA, JMARS Data Analysis Tool, 2005-present

Co-Investigator, NASA, Eos ASTER investigation 1990-present

Principal Investigator, Thermal Emission Spectrometer (TES), NASA Mars Observer/Global Surveyor Mission, 1986-2007.

Principal Investigator, NASA, Mars Fundamental Research Program, 2007-present.

Principal Investigator, NASA, Planetary Geology Program, 1986-present.

Principal Investigator, NASA, Mars Data Analysis Program, 1999-present.

Principal Investigator, NASA, Planetary Instrument Definition and Development Program, 1084-1987; 1996-1998.

## Selected National Service

Co-Chair, National Research Council Planetary Science Decadal Survey, 2020-present

Co-Chair, NRC Committee on Astrobiology and Planetary Science (CAPS) 2011-2016

Chair, Mars Panel, National Research Council Planetary Science Decadal Survey, 2010-2011

Chair, NASA Mars Architecture Tiger Team (2008-2010)

MEPAG Executive Committee, 2007-present

Chair, NASA Mars Reconnaissance Orbiter MOS/GDS Review Board (2003-2006)

NASA Mars Reconnaissance Orbiter Science Definition Team (2001)

Lunar and Planetary Institute (LPI) Science Council (2001-2002)

Chair, NASA Planetary Geology and Geophysics Review Panel (1994-1995)

National Academy of Sciences Committee on Planetary and Lunar Exploration (1994-1997)

NASA Mars Exploration Program Assessment Group (1999-205)

NASA Mars Science Working Group (1994-1996)
NASA Planetary Geology and Geophysics Review Panel (1989-1990); (1993-1995)
NASA Earth Observing System Science Steering Committee (1985-1987)

**Professional Societies**

American Geophysical Union
American Astronomical Society, Division of Planetary Science
Geological Society of America

**Selected Honors and Awards**

Whipple Award, American Geophysical Union, 2018
2016 Robert H. Goddard Honor Award, OSIRIS-REx Thermal Emission Spectrometer
Distinguished Teaching Award, Arizona State University 2014
Fellow, Geological Society of America, 2009
G.K. Gilbert Award, Geological Society of America, 2008
NASA Public Service Medal, 2005
Fellow, American Geophysical Union, 2004
NASA Exceptional Scientific Achievement Medal, 2003
ASU College of Liberal Arts and Science Distinguished Faculty Award, 2002
ASU Alumni Association Distinguished Faculty Award for Research, 1998
ASU Liberal Arts and Sciences Alumni Association Outstanding Faculty Award, 1995
23 NASA Group Achievement Awards, 1993-present

**Selected Recent Publications**

Khuller, A., and **P. R. Christensen** (in press), Evidence of Exposed Dusty Water Ice within Martian Gullies *Journal of Geophyisical Research*.

Hamilton, V., A. Simon, **P. R. Christensen**, D. Reuter, B. Clark, M. Barucci, N. Bowles, W. Boynton, J. R. Brucato, and E. Cloutis (2019), Evidence for widespread hydrated minerals on asteroid (101955) Bennu, *Nature Astronomy*, *3*(4), 332-340.

Coles, K.S., Tanaka, K.L. and **Christensen, P.R.**, (2019), The Atlas of Mars: *Mapping its Geography and Geology*. Cambridge University Press.

**Christensen, P. R.**, et al., (2018), The OSIRIS-REx Thermal Emission Spectrometer (OTES) Instrument, *Space Science Reviews, 214*(5), p.87.

Mitchell, J. L., and **P.R. Christensen** (2016), Recurring slope lineae and chlorideson the surface of Mars, *J. Geophys. Res*, *121*, doi:10.1002/2016JE005012.

Klug-Boonstra, S., and **P. R. Christensen** (2013), Mars Student Imaging Project: Real research by secondary students, *Science*, *339*, 920-921.

**Christensen, P. R.**, J. L. Bandfield, R. L. Fergason, V. E. Hamilton, and A. D. Rogers (2008), The Compositional Diversity and Physical Properties Mapped from the Mars Odyssey Thermal Emission Imaging System (THEMIS), in The Martian Surface: Composition, Mineralogy, and Physical Properties, edited by J. F. Bell, III, Cambridge University Press.

**Christensen, P. R.**, J. L. Bandfield, A. D. Rogers, T. D. Glotch, V. E. Hamilton, S. W. Ruff, and M. B. Wyatt (2008), Global Mineralogy Mapped from the Mars Global Surveyor Thermal Emission Spectrometer, in The Martian Surface: Composition, Mineralogy, and Physical Properties, edited by J. F. Bell, III, Cambridge University Press.

Kieffer, H. H., **P. R. Christensen**, and T. N. Titus, CO2 jets formed by sublimation beneath translucent slab ice in Mars' seasonal south polar ice cap, Nature, 442, 793-796, doi:710.1038/nature04945, 2006.