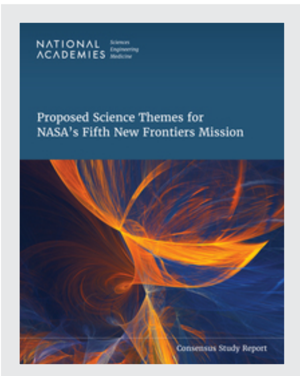


# Proposed Science Themes for NASA's Fifth New Frontiers Mission (2025)

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# Proposed Science Themes for NASA's Fifth New Frontiers Mission

Committee on Proposed Science Themes for NASA's Fifth New Frontiers Mission

Committee on Astrobiology and Planetary Sciences

Space Studies Board

Division on Engineering and Physical Sciences

Consensus Study Report

**NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001**

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# Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

**JAMES H. CROCKER (NAE),** Lockheed Martin Corporation (retired)
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**JAMES J. WRAY,** Georgia Institute of Technology

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **MICHAEL MANGA (NAS),** University of California, Berkeley, and **ROGER D. BLANDFORD (NAS),** Stanford University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

# Contents

# Preface

The Space Studies Board (SSB) of the National Academies of Sciences, Engineering, and Medicine has been involved in shaping U.S. space science policy for 60 years. Through those years, the National Aeronautics and Space Administration (NASA) has sponsored studies through the SSB, seeking independent, scientific advice on how to craft its planetary science program through both the planetary science decadal surveys and individual reports by ad hoc committees.

At the request of NASA and under the auspices of the SSB, the National Academies appointed an ad hoc committee with the purpose of serving as an independent forum for identifying and discussing issues in astrobiology and planetary science between the research community, the federal government, and the interested public. As a result of this charge, the Committee on Astrobiology and Planetary Sciences (CAPS) was organized.

This report was completed in response to a request from NASA Planetary Science Division (PSD) to draft a report evaluating scientific and technical progress since the last planetary science decadal survey and how that may impact selection of the next New Frontiers class mission.

To gather information on this issue, CAPS held three open session meetings in 2024 to address this topic: February 13, February 20, and May 20. The Committee on Proposed Science Themes for NASA's Fifth New Frontiers Mission discussed these issues in closed session.

The committee would like to thank Lori Glaze (NASA-PSD), Curt Niebur (NASA-PSD), Robin Canup (Southwest Research Institute), Philip Christensen (Arizona State University), Lori Feaga (University of Maryland), Ben Greenhagen (Johns Hopkins University Applied Physics Laboratory), Amanda Hendrix (Planetary Science Institute), and Noam Izenberg (Johns Hopkins University Applied Physics Laboratory) for their presentations and discussions with CAPS during its open sessions.

# Executive Summary

NASA's New Frontiers (NF) program plays a crucial role in solar system exploration by soliciting principal investigator (PI)-led missions at a more frequent cadence of ~two per decade than flagship missions, but with a larger budget and scope (~$1 billion) than Discovery missions. Since the NF program inception in 2002, four missions have been selected. Mission themes for the New Frontiers 5 (NF-5) announcement of opportunity (AO) were evaluated in the 2011 planetary science decadal survey *Vision and Voyages for Planetary Science in the Decade 2013–2022* (NRC 2011; hereafter, *V&V*) and reevaluated in *Report Series—Committee on Astrobiology and Planetary Science: Options for the Fifth New Frontiers Announcement of Opportunity* (NASEM 2020; hereafter, *ONF5*). The most recent planetary science decadal survey, *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023; hereafter, *OWL*), recommended mission themes for NF-6 and NF-7 for the current decade (2023–2032). Since the completion oof the *OW*L report, the timing for the upcoming NF-5 AO has been delayed to no earlier than 2026, overlapping with the timeframe expected for NF-6. Therefore, NASA requested that the National Academies investigate and report on any scientific, programmatic, and technological advances that have a significant impact on the mission themes prioritized for the next NF AO.

There were 10 mission themes listed in *OWL* for NF-5 and NF-6. The missions, in alphabetical order, are as follows: Centaur Orbiter and Lander (CORAL), Ceres Sample Return, Comet Surface Sample Return (CSSR), Enceladus Multiple Flyby (EMF), Io Observer, Lunar Geophysical Network (LGN), Lunar South Pole–Aitken (SPA) Basin Sample Return, Saturn Probe, Titan Orbiter, and Venus In Situ Explorer (VISE). The additional NF-7 mission theme, Triton Ocean World Surveyor, was considered outside the remit of the statement of task of the Committee on Proposed Science Themes for NASA's Fifth New Frontiers Mission. The committee evaluated each of the 10 themes for updates in scientific understanding, programmatic developments, and technological advances since *OWL*, with consideration of the new NF timeline outlined above. The committee's deliberations were informed by open community input, including from each of the relevant assessment groups (LEAG, OPAG, SBAG, and VEXAG),[1] as well as the *OWL* decadal survey committee co-chairs and NASA Science Mission Directorate (SMD) stakeholders. In assessing the significance of any changes, the committee was guided by the decadal survey priority science questions developed by *OWL*. Additionally, the fact that only three flight centers can develop NF-class mission proposals, and that such resource-intensive activities can limit the number of themes proposed, was an important consideration as the committee developed mission theme priorities for the NF-5 AO.

Recent major programmatic and scientific developments identified as relevant to the mission theme prioritization for the next NF AO were the outcome of the Endurance-A concept study, the recent flight history of the Commercial Lunar Payload Services (CLPS) program and the Lunar Discovery and Exploration Program (LDEP), the scientific priorities outlined for the Artemis missions, the selection and readjusted timeline of the NF-4 Dragonfly mission, the selection and readjusted timelines of the DAVINCI and VERITAS missions to Venus, and the science results of the Juno flyby of Io. A summary of each mission theme under consideration for the next NF-5 AO is found in Chapter 2 of this report.

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[1] Lunar Exploration Analysis Group, Outer Planets Assessment Group, Small Bodies Assessment Group, and Venus Exploration Analysis Group.

Additionally, the significance of these advancements for each mission theme is outlined in Findings 1 through 7 and discussed in Chapter 3.

Finding 1: Endurance-A, identified in *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023) as the highest-priority medium-class mission for the Lunar Discovery and Exploration Program (LDEP), addresses multiple decadal survey priority science questions. Because the Endurance-A mission scope encompasses the objectives outlined in the New Frontiers (NF)-5 draft announcement of opportunity (AO) Lunar South Pole–Aitken Basin Sample Return mission theme, the absence of this theme from the next NF AO is warranted.

Finding 2: The science proposed by the Lunar Geophysical Network (LGN) addresses multiple decadal survey priority science questions. There are currently no programmatic avenues, including the NASA Lunar Discovery and Exploration Program (LDEP) and the Commercial Lunar Payload Services, that could accomplish LGN other than the New Frontiers (NF) program. Therefore, the inclusion of LGN as a theme in the next NF announcement of opportunity is warranted.

Finding 3: Comet Surface Sample Return, Centaur Orbiter and Lander, and Ceres Sample Return address multiple decadal survey priority science questions. Inclusion of these missions in the next New Frontiers announcement of opportunity is warranted.

Finding 4: Enceladus Multiple Flyby and Saturn Probe address multiple decadal survey priority science questions. Inclusion of these missions in the next New Frontiers announcement of opportunity is warranted.

Finding 5: The broad objectives of Io Observer continue to address multiple decadal survey priority science questions. Recent advances in Io science, including those from the Juno flybys, do not warrant reconsideration or removal of Io Observer from the next New Frontiers (NF) announcement of opportunity (AO). Therefore, inclusion of Io Observer in the next NF AO is warranted.

Finding 6: Titan Orbiter addresses several decadal survey priority science questions that are distinct from the Dragonfly mission to Titan selected in the New Frontiers (NF)-4. However, to maintain programmatic balance, the absence of Titan Orbiter from the next NF announcement of opportunityis warranted. Titan Orbiter remains a high priority for future NF mission opportunities as recommended by *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023).

Finding 7: Venus In Situ Explorer (VISE) addresses several decadal survey priority science questions that are distinct from those addressed by recently selected missions (DAVINCI, VERITAS, and EnVision) to Venus. However, to maintain programmatic balance, the absence of VISE from the next New Frontiers (NF) announcement of opportunity (AO) is warranted. VISE remains a high priority for future NF mission opportunities as recommended by *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023).

The committee recognizes that a healthy NF program is critical to NASA's Planetary Science portfolio. The cadence of NF missions, the growth in the number of mission themes, the resource limitations on developing mission proposals, and the budgetary constraints on the program are all crucial aspects of the program's success and were considered in developing the committee's findings.

Finding 8: Given that NASA anticipates that the New Frontiers (NF)-5 announcement of opportunity will be announced no earlier than 2026, it is important to assemble a mission list for this upcoming call that can address the broadest range of priority science questions identified in *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023).

Finding 9: Based on the findings of the committee, the next New Frontiers announcement of opportunity would be most effective if it includes the following themes, listed alphabetically:

- Centaur Orbiter and Lander
- Ceres Sample Return
- Comet Surface Sample Return
- Enceladus Multiple Flyby
- Io Observer
- Lunar Geophysical Network
- Saturn Probe

Finding 10: New Frontiers (NF) mission cadence is critical to programmatic balance. Without a predictable cadence aligned with the decadal surveys, the NF mission theme list will continue to expand without accomplishing previously prioritized missions, jeopardizing decadal survey priorities.

Finding 11: Due to factors such as inflationary pressure and supply chain challenges, the draft New Frontiers (NF)-5 announcement of opportunity cost cap is likely insufficient for many of the mission themes considered here and therefore merits reconsideration by NASA.

# 1
# Introduction

## STUDY BACKGROUND

In 2023, the National Academies of Sciences, Engineering, and Medicine released *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023; hereafter, *OWL*). To maximize the advancement of the scientific fields under its purview, *OWL* outlined 12 priority science questions to guide planetary science and astrobiology within this decade (Box 1-1). To address these key questions, *OWL* proposed a recommended program that included a balanced portfolio of missions across ranges of both size and cadence.

The principal investigator (PI)-led New Frontiers (NF)-class (NASA n.d.-d) missions bridge the gap between the directed Large Strategic Science Missions (otherwise known as NASA flagship missions; NASEM 2017) and the smaller, but more rapidly responsive, PI-led missions under the Discovery program (NASA n.d.-a). The NF missions occupy a middle ground, having both a relatively longer timeline (nominally twice per decade) and higher budget (~$1 billion) than the Discovery program (nominally three times per decade, <$1 billion) although not as expansive as the NASA flagship missions. This allows more ambitious decadal survey science objectives to be accomplished by targeted missions that are smaller in scale than a NASA flagship.[1]

NF mission selection occurs through an AO that provides the community a proposal mechanism to respond to priority mission themes recommended and specified by the decadal surveys. The scope of these mission themes can be broad—for example, the NF-4 mission themes ranged from target-specific missions to Saturn and Venus to a more open call to tour and rendezvous with multiple Trojan asteroids without mandating a specific target (NASA 2016). What unites these mission themes are the key decadal science objectives that the proposed missions are intended to address. Proposals to the NF program must address one of the mission themes, making selection of what themes to include in an AO an important strategic decision.

The planetary science and astrobiology decadal survey develops the list of NF mission themes for NASA based on scientific merit, programmatic balance, technical readiness and feasibility, and other factors. Because only three entities can manage an NF proposal (Johns Hopkins University Applied Physics Laboratory, NASA Goddard Space Flight Center, and the California Institute of Technology's Jet Propulsion Laboratory), this list must maximize potential benefit to the field while bearing in mind the significant resources necessary to propose, implement, and manage an NF-class mission. *OWL* assumed that the NF-5 AO would be solicited prior to the decade covered by *OWL* and did not reevaluate the themes outlined for NF-5 in *V&V*. *OWL* recommended eight mission themes for the NF-6 and one additional mission theme for NF-7 to be included in the two AO's anticipated to be solicited in the 2023–2032 decade.

[1] Discussion with the NASA Planetary Science Division Director, Committee Meeting No. 1 on the New Frontiers Task, February 13, 2024.

**BOX 1-1**
**Priority Science Questions from *Origins, Worlds, and Life:***
***A Decadal Strategy for Planetary Science and Astrobiology 2023–2032***

*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?

*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?

*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?

*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?

SOURCE: NASEM (2023).

*OWL* contained both a "Recommended Program" assuming a modest increase to the NASA Planetary Science Division's (PSD's) budget and a "Level Program" assuming a flat budget. However, various factors can motivate significant deviations from the decadal survey–recommended program. If these recommended programs were untenable, *OWL* provided a list of prioritized decision rules that advise NASA on how to best accomplish the priority science questions. The fourth of these decision rules was to "Reduce the cadence of New Frontiers in the coming decade" (NASEM 2023). If this contingency came to pass, there would still be the outstanding question of which of these *OWL* mission theme lists to use for the next NF AO.

The National Academies' Committee on Astrobiology and Planetary Sciences (CAPS) "monitor[s] the progress of implementing the priorities in the most recent decadal survey for the most important scientific and technical activities in that report and recommendations."[2] In this role, NASA may request that CAPS undertake a report advising on how best to accomplish decadal scientific priorities, including "consideration of budget and programmatic aspects of the implementation of the decadal survey."

Budget constraints have compelled NASA to delay the AO for NF-5 until no earlier than 2026. Because that timeframe approaches the expected timeframe for NF-6, it becomes necessary to consider which of the decadal survey mission theme lists to use for this next AO. Against this backdrop, the NASA PSD has requested this report via the statement of task below.

## STATEMENT OF TASK

Then NASA PSD Director Lori Glaze requested that CAPS, as part of its role to "[monitor] the progress of implementing the priorities in the most recent decadal survey,"[3] write a report evaluating potential mission themes for the next NF AO.

The statement of task for this activity, completed by the Committee on Proposed Science Themes for NASA's Fifth New Frontiers Mission, was as follows:

> The Committee on Astrobiology and Planetary Sciences (CAPS) of the National Academies of Sciences, Engineering, and Medicine, will address the following questions:
>
> - Has scientific understanding or external factors, such as programmatic developments or technological advances, significantly changed since the New Frontiers 5 (NF-5) mission themes or New Frontiers 6 (NF-6) mission themes were evaluated by the most recent planetary science and astrobiology decadal survey, *Origins, Worlds, and Life* (*OWL*)?
> - Has scientific understanding or external factors, such as programmatic developments or technological advances, been sufficiently substantial since *OWL* to warrant reconsidering or removing any of these mission themes?
> - Given that NASA anticipates the next New Frontiers Announcement of Opportunity (AO) will be released no earlier than 2026, should NASA use the mission themes provided in the draft NF-5 AO (released 1 September 2023 [NASA 2023b]), the NF-6 mission themes as provided in *OWL*, or a hybrid of the these?

It is noted here that the draft NF-5 AO cited in this statement of task was released on September 1, 2022. The committee corrects this editorial error here and uses the actual release date in the remainder of the report.

The committee received this task on January 25, 2024. CAPS held its first open session meeting to address these questions on February 13, 2024.

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[2] The Committee on Astrobiology and Planetary Sciences statement of task is reprinted in Appendix A.

[3] See Appendix A.

**BOX 1-2**
**New Frontiers-7 and Triton Ocean World Surveyor as a Mission Theme**

The National Academies of Sciences, Engineering, and Medicine decadal survey report *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023) recommended eight mission themes for New Frontiers (NF)-6 and that all nonselected missions from NF-6 be included in NF-7. The decadal survey also recommended an additional mission for NF-7—the Triton Ocean World Surveyor.

According to *OWL*, "The recommendation that Triton Ocean World Surveyor be delayed until NF-7 took into consideration launch trajectories, which benefit from a Jupiter gravity assist likely available in the NF-7 timeframe."

The Committee on Astrobiology and Planetary Sciences (CAPS) was specifically charged in its statement of task (reprinted in Appendix A) to evaluate missions included in the NF-5 draft Announcement of Opportunity and NF-6 list as outlined by *OWL*. CAPS was not tasked to evaluate mission themes listed for NF-7. Therefore, the Triton Ocean World Surveyor was considered outside the scope of this report.

## Outline of the Report

This report is organized as follows: The remainder of Chapter 1 outlines a brief history of the NF program and its current state. Chapter 2 responds to the first item in the statement of task by succinctly summarizing each of the mission themes considered by this report and relevant science developments since the release of *OWL*. Chapter 3 addresses the second item in the statement of task, focusing on programmatic changes and balance issues that may justify the reconsideration of a mission theme (see Box 1-2). Last, Chapter 4 answers the final question posed in the statement of task and proposes a list of mission themes for NASA to use in its upcoming AO for NF-5, along with justifications as to why this list would best enable decadal-level science.

## HISTORY OF THE NEW FRONTIERS PROGRAM

The NF program was developed by NASA and approved by Congress in 2002. With a cost cap of ~$1 billion, double that of the Discovery program, NF missions were designed to achieve more ambitious science objectives. The goal of the program was "to explore the solar system with medium-class spacecraft missions that conduct high-science-return investigations that add to our understanding of the solar system" (NASA n.d.-d). A summary of the missions included in the various NF AOs is included in Table 1-1 (found at the end of the chapter) and described in detail here.

The first NF mission was selected before the program existed and was grand sired in as its inaugural mission. The New Horizons mission (NF-1) was launched in 2006 with the goal of understanding the formation of the Pluto system and Kuiper belt objects through a close flyby of Pluto, a first in space exploration, and to continue on to perform reconnaissance of several additional Kuiper belt objects (NASA n.d.-e). It achieved its Pluto objective in 2015, and its second major science objective, a flyby of the Kuiper belt object Arrokoth, in 2019. The mission was further extended in 2022.

After NF-1, missions for the NF program were selected based on the objectives laid out in the planetary science decadal surveys or from follow-up reports by the Space Studies Board (SSB). In 2003, the decadal survey *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NRC 2003; hereafter, *NFSS*) recommended five mission concepts as medium-class missions. A further five were considered high priority but were deferred for various reasons including mission sequencing, technological readiness, or budget.

Out of five recommended mission concepts in *NFSS*, four were included in the second NF AO. One was selected as the second NF mission in 2005: the Jupiter Polar Orbiter with Probe. This mission concept evolved into the Juno mission (NF-2) (NASA n.d.-c). The mission was launched in 2011 to develop a greater understanding of the composition, mass, and magnetic fields of Jupiter. Juno arrived at Jupiter in 2016 and has performed measurements since. Although originally designed to last only 33 orbits, Juno has been extended twice through September 2025.

In 2007, NASA asked the SSB to evaluate all of the unimplemented medium-size missions from *NFSS* in preparation for the third NF-class mission. The resulting report, *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (NRC 2008), recommended that all three missions not selected for NF-2 as well as the five mission concepts considered "deferred" by *NFSS* be included in the third NF AO.

The resulting AO in 2009 included eight mission concepts, resulting in the selection of the Asteroid Rover/Sample Return concept. It should be noted that this particular mission concept was considered "deferred" by *NFSS*. This mission would become the OSIRIS-REx mission (NF-3).

OSIRIS-REx was launched in 2016 with the primary objective of collecting and returning a sample from the asteroid (101955) Bennu, a body with materials that can provide information on the early history of the solar system (NASA n.d.-f). OSIRIS-REx entered Bennu orbit in December 2018, surveyed for potential sample collection sites, successfully collected more than twice the required 60 g of sample in October 2020, and returned those samples to Earth in September 2023. At the time of this writing, sample analysis is ongoing. OSIRIS-REx was extended in April 2022 as OSIRIS-APEX, with the goal of studying the near-Earth asteroid (99942) Apophis shortly after its near-Earth encounter in 2029.

In 2013, the next decadal survey was published—*Vision and Voyages for Planetary Science in the Decade 2013–2022* (NRC 2011; hereafter, *V&V*). *V&V* recommended a total of seven mission concepts as potential NF-class missions, including four mission concepts not selected for NF-3. Of these seven missions, one mission concept was added since the 2008 *Opening New Frontiers in Space* report and two were removed.

In 2015, the U.S. House of Representatives Committee on Appropriations released a report accompanying the Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2016 (Congress.gov 2016). Although the language of this report was not reflected in the final appropriations bill, the report served as "an explanation of the accompanying bill making appropriations for Commerce, Justice, Science, and related agencies for the fiscal year ending September 30, 2016, and for other purposes." This report directed NASA to "to create an Ocean World Exploration Program whose primary goal is to discover extant life on another world using a mix of Discovery, New Frontiers and flagship class missions consistent with the recommendations of current and future Planetary Decadal surveys" (Congress.gov 2016). In response, NASA announced via community announcement that "Ocean Worlds (Titan and/or Enceladus)" would be included as one of six possible mission concepts in the fourth NF AO.

The Ocean Worlds (Titan and/or Enceladus) mission theme was selected in 2017, becoming the Dragonfly mission (NF-4). Dragonfly is a rotorcraft designed for flight in the atmosphere of Titan, the largest moon of Saturn (NASA n.d.-b). Dragonfly will fly hundreds of kilometers in Titan's atmosphere, sampling a wide variety of landing sites with its onboard science payload. This mission is expected to launch no earlier than July 2028.

## CURRENT STATE OF THE NEW FRONTIERS PROGRAM

In 2020, NASA PSD requested a report from CAPS to evaluate four NF mission themes: Ocean Worlds, Trojan Tour and Rendezvous, Io Observer, and Lunar Geophysical Network. The resulting report, *Options for the Fifth New Frontiers Announcement of Opportunity* (NASEM 2020), recommended reconsideration of Ocean Worlds (Titan) and the Trojan Tour and Rendezvous as themes in light of the then recent mission selections, Dragonfly (NF-4) and the Discovery-class mission Lucy, respectively.

A community announcement in November 2020 gave advance notice for the upcoming AO for the NF-5 mission (NASA n.d.-g). This community announcement included the following mission themes as valid proposal targets:

- Comet Surface Sample Return
- Lunar South Pole–Aitken Basin Sample Return
- Ocean Worlds (Enceladus)
- Saturn Probe
- Venus In Situ Explorer
- Io Observer
- Lunar Geophysical Network

Note that this included four mission concepts not selected for NF-4. This community announcement stated that the estimated release of the draft AO would be October 2021, with the final version to be released in October 2022. This timeline was later delayed.

In September 2022, NASA PSD issued a community announcement removing Venus In Situ Explorer from the list of NF-5 proposal targets after two Venus missions were selected in the Discovery mission line (DAVINCI and VERITAS; NASA 2022).

The draft NF-5 AO was released on January 10, 2023 (NASA 2023b), estimating the release of the final version for November 2023. However, owing to budget uncertainty, the conversion of this draft AO to a final AO was delayed to no earlier than 2026 (NASA 2023a).

The delayed timing of the draft AO created an overlap with activities for *NFSS*. As stated in *OWL* (NASEM 2023, p. 586),

> Midway through the decadal process, on May 12, 2021, NASA issued a Community Announcement that the NF-5 announcement of opportunity (AO) was to be delayed until a target release of October 2024. That announcement indicated that NASA intended to use the results of this survey to guide the NF-5 AO. However, when the National Academies initiated this decadal survey, it was with the understanding that the NF-5 mission themes would not be determined by the survey committee. Therefore, committee membership was not designed nor vetted to provide impartial findings and recommendations on NF-5. On May 25, 2021, the survey chairs released a letter notifying the community that the [decadal study steering] committee would not adjust the mission themes for NF-5 and would retain those listed above.

This delay stimulated NASA's PSD request for CAPS to evaluate potential mission themes for the next NF AO in January 2024, which is the basis of this report.

**TABLE 1-1** New Frontiers (NF) Recommended Target List Evolution

| Recommended Mission | Report(s) Containing Recommendation | NF-2 AO 2003 | NF-3 AO 2009 | NF-4 AO 2016 | NF-5 Draft 2023 | NF-6 *OWL* 2023 | Outcome |
|---|---|---|---|---|---|---|---|
| Asteroid Rover/Sample Return | *NOSSE* | | X | | | | OSIRIS-REx (NF-3) |
| Centaur Orbiter and Lander | *OWL* | | | | | X | |
| Ceres Sample Return | *OWL* | | | | | X | |
| Comet Surface Sample Return | *NFSS, NOSSE, V&V, OWL* | X | X | X | X | X | |
| Ganymede Observer | *NOSSE* | | X | | | | |
| Io Observer[a] | *NOSSE, V&V, ONF5, OWL* | | X | | X | | |
| Jupiter Polar Orbiter with Probes | NF | X | | | | | Juno (NF-2) |
| Kuiper Belt–Pluto Explorer | NF | | | | | | New Horizons (NF-1)[b] |
| Lunar Geophysical Network | *V&V, ONF5, OWL* | | | | X | X | |
| Lunar South Pole–Aitken Basin Sample Return | *NFSS, NOSSE, V&V* | X | X | X | X | | *OWL* recommends move mission from NF to LDEP |
| Network Science | *NOSSE* | | X | | | | |
| Ocean Worlds[c] Titan and/or Enceladus | | | | X | | | Dragonfly (NF-4) |
| Enceladus Only | *ONF5* | | | | X | | |
| Enceladus Multiple Flyby | *OWL* | | | | | X | |
| Titan Orbiter | *OWL* | | | | | X | |
| Saturn Probe | *V&V, OWL* | | | X | X | X | |
| Trojan Tour and Rendezvous/Trojan Centaur Reconnaissance | *NOSSE, V&V* | | X | X | | | Lucy (Discovery 13) |
| Venus In Situ Explorer[d] | *NFSS, NOSSE, V&V, OWL* | X | X | X | | X | |
| Total Mission Themes Recommended per NF AO | | 4 | 8 | 6 | 7 | 8 | |

[a] *ONF5* and *OWL* recommended removal of Io Observer if Io Volcano Observer was selected in Discovery.
[b] Grandsired into the NF program.
[c] Program added by Congress.
[d] Removed from 2023 NF-5 Draft Announcement of Opportunity (AO) by NASA's Planetary Science Division after selection of Venus missions in Discovery.

NOTE: Each recommended mission can be found in one or more reports of the National Academies of Sciences, Engineering, and Medicine (published by the National Academies Press):

- *NFSS*, planetary decadal survey 1: *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NRC 2003).
- *NOSSE*, New Opportunities in Solar System Exploration study: *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (NRC 2008).
- *V&V*, planetary decadal survey 2: *Vision and Voyages for Planetary Science in the Decade 2013–2022* (NRC 2011).
- *ONF5*: *Report Series: Committee on Astrobiology and Planetary Science: Options for the Fifth New Frontiers Announcement of Opportunity* (NASEM 2020).
- *OWL*, planetary decadal survey 3: *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023).

An "X" indicates that that mission was included in an NF AO, draft AO or, for NF-6, recommended in *OWL*.

# 2
# Changes Since *Origins, Worlds, and Life*

The first item in the committee's statement of task is repeated here:

> Has scientific understanding or external factors, such as programmatic developments or technological advances, significantly changed since the New Frontiers 5 (NF-5) mission themes or New Frontiers 6 (NF-6) mission themes were evaluated by the most recent planetary science and astrobiology decadal survey, *Origins, Worlds, and Life* (*OWL*)?

This question requires an evaluation of the New Frontiers (NF)-5 draft announcement of opportunity (AO) and NF-6 mission themes included in *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023; hereafter, *OWL*) ahead of an AO for NF-5 that will be released no earlier than 2026. Recommended are 10 mission themes for NF-5 draft AO and NF-6 (from *OWL*), with 5 on both lists: Io Observer, Venus In Situ Sample Return, Saturn Probe, Comet Surface Sample Return, and Lunar Geophysical Network (see Table 1-1). In addition to the 6 mission themes recommended for NF-5, 3 additional mission theme targets were included in *OWL*: Centaur Orbiter and Lander, Ceres Sample Return, and Titan Orbiter. It is noted here that the Ocean Worlds mission theme in NF-5 evolved into the Enceladus Multiple Flyby mission theme in NF-6.

*OWL* did not reevaluate NF-5 mission themes because, at the time of commissioning of the decadal survey, it was expected that the NF-5 AO would be released prior to the completion of *OWL*, as stated in Chapter 1. Therefore, the last detailed review of the 5 NF-5 mission themes carried forward to NF-6 was performed in *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NRC 2003; hereafter, *NFSS*—Venus In Situ Sample Return and Comet Surface Sample Return) or *Vision and Voyages for Planetary Science in the Decade 2013–2022* (NRC 2011; hereafter, *V&V*—Saturn Probe and Lunar Geophysical Network).

In response to the first item of the statement of task, the Committee on Proposed Science Themes for NASA's Fifth New Frontiers Mission reviewed each of these 10 mission themes, with a specific focus on advances in scientific or technological understanding, and/or programmatic developments. Each mission theme is reviewed in the following sections with respect to these topics. Additionally, the contributions of each mission theme to each priority science question as outlined in *OWL* are assessed.

## LUNAR SCIENCE

### Lunar South Pole–Aitken Basin Sample Return

South Pole–Aitken (SPA) Basin Sample Return was recommended as an NF mission in the *NFSS* (2003) and *V&V* (2011) decadal surveys.

The science goals of SPA Basin Sample Return outlined in *V&V* are as follows:

- Determine the chronology of basin-forming impacts and constrain the period of late heavy bombardment in the inner solar system and thus address fundamental questions of inner solar system impact processes and chronology;

- Elucidate the nature of the Moon's lower crust and mantle by direct measurements of its composition and of sample ages;
- Characterize a large lunar impact basin through "ground truth" validation of global, regional, and local remotely sensed data of the sampled site;
- Elucidate the sources of thorium and other heat-producing elements in order to understand lunar differentiation and thermal evolution; and
- Determine ages and compositions of farside basalts to determine how mantle source regions on the far side of the Moon differ from regions sampled by Apollo and Luna.

*OWL* upheld the view of *V&V* that SPA Basin Sample Return addressed the highest priority lunar science. It was also noted that achieving all of the science goals outlined in the NF mission concept would be challenging with a fixed lander. *OWL* instead favored the new mission concept Endurance-A, a long-distance lunar rover that would deliver samples to Artemis astronauts for return to Earth. *OWL* recommended that "Endurance-A should be implemented as a strategic medium-class mission as the highest priority of the Lunar Discovery and Exploration Program (LDEP). Endurance-A would utilize the Commercial Lunar Payload Services Program (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." As such, *OWL* also recommended removal of SPA Basin Sample Return from the NF-6 list.

The science goals of Endurance-A outlined in *OWL* are as follows:

- Determine the age of SPA Basin, to anchor the earliest impact history of the solar system;
- Test the giant planet migration/terminal cataclysm hypotheses, and to better constrain the inner solar system impact chronology;
- Determine the age and mineralogical and geochemical composition of deep and crustal materials exposed in SPA Basin to understand the bulk composition of the Moon, its primordial differentiation and geologic evolution;
- Determine the age and nature of volcanic features and compositional anomalies on the lunar farside to characterize the thermochemical evolution and the origin of the Moon's nearside–farside asymmetry; and
- Determine the geologic diversity of the SPA Terrane to provide geologic context for returned samples and ground truth for orbital measurements.

In addition to *OWL* favoring Endurance-A, new developments warrant further reconsideration of SPA Basin Sample Return with a fixed lander. China's Chang'e-4 mission landed in SPA and studied the landing area in situ using a rover in 2019. The Chang'e-6 fixed lander mission returned samples from SPA and conducted additional in situ science. In contrast, with its long-range rover and capacity to sample from multiple distant locations, Endurance-A could achieve the scientific goals outlined in *OWL*. The Chang'e-4 and Chang'e-6 missions have not achieved the goals of Endurance-A but provide complimentary science.

The Endurance-A science goals would address the three science themes for lunar exploration identified in *OWL* (see Box 22-1 in *OWL*). *OWL* also states: "If timelines or plans for Artemis render this partnership infeasible, NASA, with guidance from CAPS, could evaluate options for a robotic return of the minimum set of samples needed to accomplish the core science objectives, leveraging international partnerships and commercial capabilities as appropriate, while maintaining life cycle costs to NASA commensurate with a medium-class mission" (NASEM 2023, p. 574).

### Lunar Geophysical Network

Lunar Geophysical Network (LGN) was recommended as an NF mission in *V&V* (2011) and *OWL* (2023). This mission includes deployment of a global network of geophysical instruments to monitor the Moon for a minimum of 6 years. As stated in *OWL*,

> LGN will reveal the nature and evolution of the lunar interior and facilitate understanding of the initial solidification and primordial geologic processes that have shaped all terrestrial bodies. These measurements (e.g., seismic, heat flow, laser ranging, and magnetic-field/electromagnetic sounding) will allow the bulk composition of the Moon to be calculated, elucidate the dynamical processes that are active during the early history of terrestrial planets, provide new constraints on the collision process that generated our unique Earth–Moon system, and illuminate processes currently active on the Moon. (NASEM 2023, p. 589)

The science objectives of LGN outlined in *OWL* are as follows:

- Determine the internal structure and size of the crust, mantle, and core to constrain the composition, mineralogy, and lithologic variability of the Moon;
- Determine the distribution and origin of lunar seismic activity in order to better understand the origin of moonquakes and provide insights into the current dynamics of the lunar interior and the interplay with external phenomena such as tidal interactions with Earth; and
- Determine the global heat-flow budget for the Moon in order to constrain more precisely the distribution of heat-producing elements in the crust and mantle, the origin and nature of the Moon's asymmetry, its thermal evolution, and the extent to which it was initially melted.

The LGN mission design includes at least four geophysical stations at different locations operating simultaneously for years, providing critical information on interior composition and structure, which, particularly in combination with global high-resolution gravity by the Gravity Recovery and Interior Laboratory (GRAIL) mission and topography by the Lunar Reconnaissance Orbiter (LRO) data, underlie the estimates of lunar formation, compensation mechanisms, heat distribution, and the history and generation of the lunar dynamo. LGN directly addresses at least 4 of *OWL*'s 12 priority science questions—Q3: "Origin of Earth and inner solar system bodies"; Q4: "Impacts and dynamics"; Q5: "Solid body interiors and surfaces"; and Q8 "Circumplanetary systems." Fundamental questions about the lunar interior require in situ deployment of multiple seismic stations. Seismometers were deployed by astronauts at the Apollo 11, 12, 14, 15, and 16 landing sites. Analysis of these nearside data detected moonquakes that provide the best available constraint on the size and nature of the lunar core, mantle, and crust.

In 2023, India's Chandrayaan-3 mission Vikram lander, carrying the Instrument for Lunar Seismic Activity (ILSA), may have detected a moonquake at the lunar south pole, but this detection has not yet been verified (Turner 2023). Soon, a Draper CLPS lander is expected to carry two seismometers to the lunar farside in 2026, named the Farside Seismic Suite (FSS). The Endurance-A nominal payload includes a magnetometer and laser reflectometer. However, the questions about the lunar interior included in the science objectives of LGN (e.g., cadence and location of seismic events and consequent location, detail and access to the interior) cannot be resolved with sporadic, infrequent, and spatially limited data alone (Sohl and Schubert 2007).

In 2017, Space Policy Directive-1 set a national goal of returning humans to the Moon (Artemis Program) and cooperation with commercial (via CLPS) and international partners. Lunar science objectives can now be met with a combination of robotic and human and government and commercial approaches. The responsibility of achieving decadal survey lunar science objectives falls under SMD's Lunar Discovery and Exploration Program (LDEP), created in 2019. *OWL* emphasizes the need for synergistic partnerships between lunar programs, recommending that "the advancement of high-priority lunar science objectives, as defined by the Planetary Science Division based on inputs from this report and groups representing the scientific community, should be a key requirement of the Artemis human exploration program" (NASEM 2023, p. 573).

*OWL* also recognizes that "No single organizational chain has authority for executing lunar science and missions" (NASEM 2023, p. 571). Furthermore, there is as yet no overall strategy for lunar scientific exploration or a program director or chief scientist to lead such a plan. As a result, despite substantial investment and tremendous potential for innovative lunar exploration, as stated by *OWL*, "LDEP activities are not optimized to accomplish high-priority planetary science goals at the Moon" (NASEM 2023, p. 571). This committee recognizes that one consequence of this approach is that currently the only path for LGN and its decadal survey science priority goals is through the NF Program.

## SMALL BODIES

### Comet Surface Sample Return

The Comet Surface Sample Return (CSSR) mission theme has been a part of the NF mission targets since NF-2 and has been confirmed on the target lists by the relevant decadal surveys (see Table 1-1).

Comets are the icy leftovers of the planetesimals that formed in the distant reaches of our solar system. These bodies, which are composed of dust, rock, organic materials, and ices such as methane, ammonia, and water, are thought to have experienced limited thermal evolution. This means that their compositions may provide powerful constraints on the nature of the solar nebula in the outer solar system. The most accessible comets are those with relatively short orbital periods that reside on unstable orbits within the giant planet zone. Often referred to as Jupiter-family comets, they are thought to have originated in the primordial Kuiper belt, with early dynamical processes sending them into cold storage within Neptune's scattered disk. Many of these bodies are only a few kilometers in size, with some coming close enough to the Sun for their ices to sublimate.

As discussed in *OWL*, the CSSR mission theme

> Seeks to understand the nature of cometary formation and mixing of materials in the protosolar nebula; compositional reservoirs present in the early solar system; the role of comets in the delivery of water and organic molecules to the early Earth, terrestrial planets, and satellites; and evolutionary processes spanning from the protoplanetary disk to current cometary activity. The mission will map the nucleus of a Jupiter-family comet, select an optimal sampling site, and acquire a sample from the surface for return to Earth for laboratory analysis. The sample will be acquired and transported in a manner that preserves organics and prevents aqueous alteration of the sample. Volatile material will be characterized via onboard analysis and/or by capture and return at noncryogenic temperatures. (NASEM 2023, p. 588)

The science objectives of CSSR, as defined by *OWL*, are as follows:

- Determine the elemental, isotopic, and structural composition of the organic and inorganic components on a comet nucleus to understand early compositional reservoirs;
- Sample, preserve, and analyze cometary organic material to determine how complex organic molecules form and evolve in interstellar, nebular, and planetary environments;
- Determine the isotopic composition of cometary water to address the role of comets in delivering volatiles to Earth's atmosphere and interior; and
- Determine if cometary organic matter contributed significantly to prebiotic chemistry and homochirality of life on Earth.

The CSSR mission theme addresses 8 of the 12 priority science questions from *OWL* see Box 1-1). It would yield transformative results on Q1: "Evolution of the protoplanetary disk," and it would produce breakthroughs in Q2: "Accretion in the outer solar system"; Q3: "Origin of the Earth and inner solar system bodies"; Q4: "Impacts and dynamics"; and Q12: "Exoplanets." It would also lead to more modest advances in Q5, Q9, and Q10.

The potential for CSSR to become a viable NF mission was demonstrated by the Comet Astrobiology Exploration Sample Return (CAESAR) mission concept, which was one of the two finalists for NASA's NF-4 call, the other being Dragonfly, which was selected. Its status as an NF-4 finalist suggests that CSSR can plausibly be achieved within the technical and budgetary constraints of the NF program. Furthermore, the successful return of samples by the Hayabusa, Hayabusa2, and OSIRIS-REx missions from near-Earth asteroids have demonstrated that sample return from small bodies is possible for missions whose budgets are NF class or smaller, although comets may require more advanced technology owing to the challenges that those small bodies present.

CAESAR would have targeted comet 67P/Churyumov-Gerasimenko, which was extensively studied in situ by the European Space Agency's (ESA's) Rosetta mission. The orbital location of 67P within the timeframe of NF-5, however, may not be optimum for sample return. If the orbital position is not ideal, this may require future CSSR mission proposals to consider other candidate comets.

Over the next several years, the commissioning of the Vera C. Rubin Observatory (previously known as the Large Synoptic Survey Telescope [LSST]) and NEO Surveyor, and the expected subsequent detection of undiscovered comets, may yield many new targets for CSSR. The concern would be whether the orbits of these new objects are known to sufficient precision to allow for future mission planning. In addition, the superb spectra derived from James Webb Space Telescope (JWST) observations may provide additional information on the composition of possible target bodies, which in turn could help optimize the choice of CSSR targets. The committee finds no significant practical or programmatic challenges that would change the recommendation of the CSSR mission theme.

### Centaur Orbiter and Lander

The Centaur Orbiter and Lander (CORAL) mission was developed as a planetary mission concept study (PMCS) by *OWL* committee members. After science, technical, and cost assessments, it was recommended as one of several prospective NF-6 missions by the *OWL* steering committee.

Centaurs are small bodies with characteristics of both asteroids and comets that reside generally in unstable orbits between Jupiter and Neptune. They are a population of dynamically evolved but compositionally primitive small icy bodies, originally from the primordial Kuiper belt that typically display much less activity than Jupiter-family comets. Owing to their unstable orbits, Centaurs are considered transitory objects that may evolve into Jupiter-family comets, be ejected from the solar system, or collide with the Sun. As described by *OWL*, "CORAL investigates a Centaur from orbit and in situ … [conducting] a comprehensive study of the geochemical and physical properties of primordial ice-rich planetesimals, which trace the composition of nebular volatiles such as $H_2O$, $CO_2$, CO, and $NH_3$, revealing the nature of early solar system compositional reservoirs. The mission will map the surface and measure the ices and organics in situ" (NASEM 2023, p. 587).

The science objectives of CORAL, as defined by *OWL*, are as follows:

- Determine the chemical and physical properties of a Centaur to understand the nature of primitive planetesimals;
- Perform in situ elemental, isotopic, and organic analyses of a Centaur to develop a comprehensive understanding of the composition and initial conditions of the protoplanetary disk;
- Determine the shape, topography, geological landforms, and density of a Centaur to understand the evolutionary history of this population of objects; and
- Determine degree of aqueous alteration of a Centaur to investigate the biological potential of icy planetesimals and potential brine reservoirs.

The CORAL mission theme addresses 10 of the 12 priority science questions from *OWL* (see Box 1-1). It would produce substantial breakthroughs to Q1–Q3, which cover the Origins themes; modest advances to substantial breakthroughs for Q4–Q6 and Q8, which cover the Worlds and Processes themes; modest advances for Q9 and Q10, which cover the Life and Habitability themes; and modest advances for Q12, which is the Exoplanet theme.

Given the recent publication of *OWL*, there has been little scientific advancement on the CORAL objectives and no significant practical or programmatic challenges that would change the recommendation of the CORAL mission theme. However, there could be developments that might increase the number of possible targets. For example, the Centaur target list used in the CORAL PMCS was limited at the time of the study to known objects as of late 2020 through early 2021. Their orbits constrain the choice of the target Centaur by defining where a rendezvous would be possible within a 13-year interplanetary cruise. As discussed in the CSSR mission theme, the commissioning of the Vera C. Rubin Observatory and NEO Surveyor, as well as new data releases from existing surveys, such as ESA's Gaia mission, and the subsequent expected detection of many new Centaurs, may allow CORAL to find rendezvous targets and cruise times superior to those suggested in the CORAL PMCS. However, it is noted that new Centaur detections would require long observation arcs to reduce orbital uncertainties to levels needed for mission planning. In addition, spectra derived from JWST observations, if available, may provide additional information on the composition of possible target bodies, which in turn could help optimize the choice of the target Centaur to visit.

Otherwise, from a programmatic standpoint, CORAL requires two radioisotope thermoelectric generators (RTGs), so availability of RTGs and plutonium may be a consideration in its selection.

## Ceres Sample Return

The Ceres Sample Return mission theme was first discussed in *OWL*. It was developed as a PMCS by *OWL* committee members. After science, technical, and cost assessments, it was recommended as one of several new mission themes for the NF-6 list.

Ceres is a ~940-km-diameter dwarf planet in the asteroid belt that was revealed by NASA's Dawn spacecraft to be a candidate ocean world owing to recent and potential ongoing geologic activity, in the form of cryovolcanism, such as at Ahuna Mons (Sori et al. 2018). Indeed, Ceres presents the feasible opportunity for a sample return from a candidate ocean world. Additionally, Dawn revealed evidence for a protracted history of water, rock, and potentially even organic compound interactions via measurements of the Cerean surface chemistry, such as observed within the 92-km-diameter Occator crater (Raponi et al. 2019). Although Dawn provided key information that transformed our understanding of Ceres, Dawn also provided the foundation for its future exploration because it revealed areas that require further detailed exploration. There are key areas, especially in regard to habitability, that require a future spacecraft; these areas include an assessment of chemical gradients and physico-chemical conditions (Castillo-Rogez et al. 2022).

The composition of Ceres suggests that it may not have formed within the asteroid belt, but rather it may have originated outside the orbit of Jupiter and migrated inward. As such, it presents the opportunity not only to better understand solar system migration mechanisms but also to obtain a sample from an object that formed in the giant planet zone (Burbine and Greenwood 2020).

As described in *OWL*, "Ceres Sample Return focuses on quantifying Ceres's current habitability potential and its origin, which is important for understanding habitability of mid-sized planetary bodies."

The science objectives of the Ceres Sample Return theme as defined by *OWL* are as follows:

- Characterize the depth and extent of potential deep brine layer(s) to determine whether liquid exists beneath Ceres today near hypothesized brine extrusion zones;
- Characterize the nature of Ceres's brines from salt deposits to determine the chemistry of waters and their potential habitability;
- Determine the composition, structure, and isotopic composition of Ceres's organics to understand processes of abiotic organic synthesis and evolution; and
- Determine the elemental abundances and isotopic ratios of Ceres's materials via measurements on returned samples to determine its accretional environment.

The Ceres Sample Return mission theme addresses 7 of the 12 priority science questions identified by *OWL* (see Box 1-1). It would result in substantial breakthroughs to Q5 and Q10, which seek to answer questions related to the themes of “Solid body interiors and surfaces” and “Dynamic habitability.” Indeed, it is one of two NF mission themes that may result in substantial breakthroughs in Q10. Additionally, the Ceres Sample Return mission theme will result in breakthroughs in Q3 and Q4, which seek to answer questions related to the themes of the “Origin of Earth and inner solar system bodies” and “Impacts and dynamics,” respectively. It will additionally result in advances related to priority science questions Q1, Q2, and Q11, which seek to answer questions related to the themes of “Evolution of the protoplanetary disk,” “Accretion in the outer solar system,” and “Search for life elsewhere.”

Several summary reports of the findings of Dawn have been published since the publication of *OWL*; these can be used to inform mission requirements (see Castillo-Rogez et al. 2020; McCord et al. 2022). Additionally, several mission concepts have been published, demonstrating community interest (see Gassot et al. 2021). From a programmatic perspective, NASA and other space agencies have demonstrated the capability of sample return from small solar system bodies (e.g., Hayabusa, Hayabusa2, and OSIRIS-REx) and larger worlds like the Moon (Apollo 11, 12, 14, 15, 16, and 17; Luna 16, 20, and 24; and Chang’e 5 and 6).

## OUTER SOLAR SYSTEM PLANETS AND MOONS

### Enceladus Multiple Flyby/Ocean Worlds—Enceladus

The scientific importance of both Titan and Enceladus were discussed in detail in *V&V*; however, these were not specifically called out as NF mission themes. In the midterm review (NASEM 2018), Enceladus was identified as a potential target for a large mission if additional financial resources were made available to NASA by Congress. Similarly, Titan was identified as the destination for a high-priority, but deferred, large mission. Ultimately, in response to Congress, NASA added the Ocean Worlds theme to the NF-4 call, soliciting missions to explore Titan and/or Enceladus.

According to the NF-4 announcement of opportunity, “ ‘The Ocean Worlds’ mission theme is focused on the search for signs of extant life and/or characterizing the potential habitability of Titan and/or Enceladus. For Enceladus, the science objectives (listed without priority) of this mission theme are: a) Assess the habitability of Enceladus’s ocean; and b) Search for signs of biosignatures and/or evidence of extant life” (NASA 2016).

The science goals of Enceladus Multiple Flyby, studied in and included as a New Frontiers mission by *OWL*, are closely aligned with those of Ocean Worlds—Enceladus, which was not included in a decadal survey. Thus, the committee considers Enceladus Multiple Flyby and Ocean Worlds—Enceladus as one mission theme with the science goals of Enceladus Multiple Flyby superseding and encompassing those of Ocean Worlds—Enceladus.

Enceladus is an icy ocean world currently erupting cryovolcanic plumes of gas and ice grains from its South Polar Terrain. Cassini measurements of the temperature and salinity of Enceladus’s subsurface ocean paired with the detection of elements such as carbon, hydrogen, nitrogen, oxygen, and sulfur in the plume suggest that Enceladus could possess geochemical and geophysical conditions suitable for life (Thomas et al. 2016). As demonstrated by Cassini, a spacecraft can directly sample icy grain materials and molecular gasses erupted from Enceladus’s subsurface ocean to assess the potential for habitability.

As discussed in the *OWL* report, the Enceladus Multiple Flyby (EMF) mission theme:

> Seeks to characterize Enceladus’s habitability and look for evidence of life via multiple flybys and analysis of plume material. Enceladus, an active icy moon with a subsurface ocean in a relatively benign radiation environment, provides the best opportunity to directly sample a potential

> habitable subsurface ocean. Prior Cassini observations demonstrate the presence of alkali and carbonate salts and complex organic molecules in plume icy grains; gas-phase nitrogen- and oxygen-bearing as well as aliphatic and aromatic organic molecules; redox couples (e.g., $H_2$ and $CO_2$), habitable temperature, salinity, and pH; alkaline hydrothermal activity; and water–rock reactions. However, Cassini flyby velocities were high, leading to fragmentation of large compounds, and ambiguity as to the precise identity of the parent organic molecules. (NASA 2023c)

The science objectives of EMF, as defined by *OWL*, are as follows:

- Search for and identify complex organic molecules in Enceladus plume materials, with velocities 4 km/s and sample volume >1 µl with appropriate contamination control to enable life-detection investigations;
- Determine the composition, energy sources, and physicochemical conditions of Enceladus's ocean to assess its habitability; and
- Characterize Enceladus's cryovolcanic activity to determine spatial and compositional variations in plume activity and the processes causing ocean material ejection and modification.

The EMF mission theme addresses 4 of the 12 priority science questions from *OWL*: Q5: "Solid body interior and surfaces"; Q10: "Dynamic habitability"; Q11: "Search for life elsewhere"; and Q12: "Exoplanets." Given the recent publication of *OWL*, there has been little scientific advancement on the EMF objectives and no significant practical or programmatic challenges that would change the recommendation of the EMF mission theme.

### Saturn Probe

The Saturn Probe mission concept was first included in the New Frontiers program in *V&V*. This mission would deploy a probe into Saturn's atmosphere to determine the structure of the atmosphere as well as noble gas abundances and isotopic ratios of hydrogen, carbon, nitrogen, and oxygen. The key mission challenges identified in the *V&V* concept study were development of the entry probe and potential payload requirements growth (see Table ES.1 in *V&V*; NRC 2011). The Saturn Probe mission theme underwent independent cost and technical evaluation as part of *V&V* and was not studied further for *OWL*. Following *V&V*, the Saturn Probe mission theme was included in the NF-4 AO, proposed but not selected in response to the NF-4 call, and included in the NF-5 draft AO and the NF-6 list outlined in *OWL*.

Understanding the initial conditions in the protosolar nebula requires measurements of each of the giant planets' elemental and isotopic compositions. Constraining giant planet formation mechanisms is particularly dependent on knowing when and where Saturn formed, over how long, and if its orbit has migrated over time to stop Jupiter's inward movement. Noble gas abundances are also crucial for determining if helium rain has prolonged Saturn's thermal evolution. Additionally, comparisons of what governs the diversity of giant planet climates, circulation, and meteorology require constraints on the vertical temperature and wind profiles, as well as vertical circulation.

The science objectives of the Saturn Probe mission from *OWL* include the following:

- Determine the in situ noble gas, elemental, and isotopic abundances to understand conditions in the protosolar nebula, as well as constrain Saturn's formation, evolution, and migration;
- Determine the in situ tropospheric temperature–pressure profile to quantify Saturn's heat transport and convective stability;
- Determine the in situ vertical wind shear to characterize Saturn's tropospheric circulation and meteorology; and

- Constrain vertical mixing in Saturn's troposphere to bound transport from the deeper interior.

The Saturn Probe mission theme addresses 5 of the 12 priority science questions from *OWL*: Q1: "Evolution of the protoplanetary disk"; Q2: "Accretion in the outer solar system"; Q7: "Giant planet structure and evolution"; Q8: "Circumplanetary systems"; and Q12: "Exoplanets." It is the only NF mission theme to address Q7: "Giant planet structure and evolution" (NASEM 2023). Although some measurements may be obtained via remote sensing, many of the science objectives require in situ sampling.

The priority science questions addressed by Saturn Probe are still highly compelling and have not been significantly advanced in recent years because an atmospheric probe is required; thus, we find no significant practical or programmatic challenges that would change the recommendation of the Saturn Probe mission theme.

### Io Observer

An Io Observer mission concept was first discussed in the 2003 decadal survey *NFSS* (NRC 2003). While this concept was deemed worthy of flight based on its science goals, it was not initially prioritized as a medium-class (NF) mission for that decade based on reasons of "mission sequencing, technological readiness, or budget." However, the 2008 report *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (NRC 2008) recommended that the mission be added to the NF-3 candidate mission list, and it was subsequently included as a mission concept in NASA's NF-3 AO released in 2009.

*V&V* reiterated the high scientific priority of the questions that would be addressed by Io Observer in the decade from 2013–2022, and the *V&V* committee commissioned an Io mission concept to be studied in detail. The subsequent cost and technical evaluation (CATE) analysis of this study demonstrated that the mission was a plausible candidate for the New Frontiers program. The report prioritized Io Observer as a New Frontiers candidate, "because of its compelling science and because it was the only outer planet satellite mission studied for which cost estimates placed it plausibly within the New Frontiers cost cap." However, *V&V* restricted the NF-4 candidate mission list to only five concepts (a reduction from the eight that were solicited in the NF-3 AO), and Io Observer was not included on the NF-4 candidate list. *V&V* did recommend that Io Observer be added again as a candidate for the NF-5 opportunity.

Io is subject to intense tidal heating owing to its orbital resonance with Europa and Ganymede, making this world an unprecedented location to study tidal heating and its effects, including high heat flow, extreme volcanism, and active tectonics. These fundamental planetary processes are thought to have played a role in shaping the surfaces of young planets in our solar system, and their study at Io will lead to a better understanding of planetary evolution. Io's dynamic atmosphere and its interactions with the Jovian system will also provide important insight into fundamental planetary physics. Additionally, the moon serves as an analog to extremely heated exoplanets like tidally heated worlds or planets with extreme solar insolation and provides an opportunity to understand worlds beyond our solar system.

The science goals of the Io Observer mission as defined in *V&V* are as follows:

- Study tectonic processes;
- Investigate interrelated volcanic, atmospheric, plasma-torus, and magnetospheric mass and energy exchange processes;
- Constrain the state of Io's core via improved constraints on whether Io generates a magnetic field; and
- Investigate endogenic and exogenic processes controlling surface composition.

These science goals were responsive to priorities in *V&V*: "How did the giant planets and their satellite system accrete, and is there evidence that they migrated to new orbital positions?"—these can be considered analogous to Q2: "Accretion in the outer solar system" and Q8: "Circumplanetary systems" in *OWL.*

During the 2019 Discovery Program call, the Io Volcano Observer (IVO) Mission was selected as one of four finalists for a Phase-A Concept Study but was ultimately not selected for flight. The primary goal of this mission would be to understand how tidal heat is generated, is lost, and drives the evolution of Io. IVO would address this goal through a series of 10 flybys of Io carrying a payload that included a camera, thermal mapper, magnetometers, plasma instrument for magnetic sounding, gravity science investigation, and ion and neutral mass spectrometer (NASA 2021a). This approach is the same as the Io Observer study commissioned in *V&V,* with a significant difference that IVO would have been solar powered and feasible under a Discovery budget.

In the 2020 study *Options for the Fifth New Frontiers Announcement of Opportunity* (NASEM 2020), CAPS recommended that Io Observer remain on the next NF AO in the event that IVO was not selected for flight. The study noted that "Discovery proposals have been a useful step in maturing mission concepts. For example, the missions that became OSIRIS-REx and Juno were proposed to the Discovery program twice and three times, respectively, before being revised, reproposed, and selected as New Frontiers missions."

*OWL* reaffirmed the importance of the science that would be achieved by an Io Observer mission concept, and anticipated that Io Observer would have an opportunity to compete in the NF-5 selection. However, *OWL* did not include Io Observer in the NF-6 or NF-7 candidate mission list. The committee concluded that the selection of the IVO Discovery concept for a Phase A study demonstrated that fundamental Io science could now be achieved at a lower cost cap, and therefore this theme was given lower priority than other NF-6 and NF-7 themes that clearly demanded medium-class mission cost caps.

The *Options for the Fifth New Frontiers Announcement of Opportunity* report details many of the new scientific findings related to Io since *V&V*. This new information comes from Earth-based studies and continued analysis of data sets collected by the Voyager, Galileo, New Horizons, and Juno missions.

In December 2023 and then again in February 2024, the Juno spacecraft flew within ~1,500 km of Io, the closest approach of a spacecraft to the surface of the moon in more than 20 years. During the flyby, JunoCam collected color images of Io's high northern latitudes at higher resolution than previous Galileo and New Horizons coverage, enabling new investigations of Io surface geology and an opportunity to identify surface changes that occurred over the past 2–4 decades (Ravine et al. 2024). The unique geometries of the Juno flybys compared to the Galileo mission also presented an opportunity to refine Io's gravity field, and in particular, to improve constraints on the tidal potential Love number, k2, which is an important test of the presence of a shallow magma ocean beneath Io's surface (Keane and Bolton 2024). Juno also observed Io with its microwave radiometer (MWR) to partially map the satellite's surface and subsurface at six frequencies ranging from 600 MHz to 22 GHz, and analysis of these data is in progress (Zhang et al. 2024).

Despite the wealth of new data from Juno, the mission is limited in its ability to address many of the major gaps in our knowledge of Io due in part to its spin-stabilized orbit (which makes it difficult to point instruments at Io), resolution-limited data sets, and limitations of types of instruments carried in the Juno payload (Keane et al. 2022). Thus, we find no significant practical or programmatic challenges that would change the recommendation of the Io Observer mission theme.

## Titan Orbiter

*V&V* considered a flagship-class Titan Saturn System Mission, of which the Titan Orbiter was one component (NRC 2011). Science objectives of the full mission were to "Explore Titan as an Earth-like system," "Examine the organic chemistry of Titan's atmosphere," and "Explore Enceladus and Saturn's magnetosphere for clues to Titan's origin and evolution." The Titan Orbiter underwent CATE cost evaluation in *V&V*, receiving an estimate of $6.7 billion. The key challenges identified in *V&V* for the full Titan Saturn System Mission were uncertainty in instrument mass, low launch margin, and power requirements (see Box C.11 in *V&V*; NRC 2011).

A less costly dedicated Titan orbiter concept first emerged in the mid-2010s, following the success of the Cassini mission (NASA 2021b). In response to NASA's NF-4 call, a Titan orbiter "Oceanus" that included a sea probe was proposed. The sea probe element was de-scoped shortly before proposal submission. Oceanus was not selected for Phase A study in NF-4, and the selection ultimately went to the Dragonfly Titan mission instead.

In the CAPS 2020 report on New Frontiers 5 (NASEM 2020), it was stated that removing Titan Orbiter from the list of potential missions was appropriate based on programmatic considerations, given the selection of Dragonfly for New Frontiers 4. This theme was therefore not included in the NF-5 draft AO. This decision was revised in the *OWL* report, which stated that "Titan Orbiter provides important and complementary science to Dragonfly." *OWL* further noted that Cassini was not a dedicated Titan orbiter, and that the upper atmospheric composition of Titan remains unknown.

The *OWL* mission concept study report for the Titan Orbiter included the sea probe that was de-scoped in the NF-4 proposal, on the basis that the required technology had matured since the Oceanus concept was first proposed. The Titan Orbiter was sent for TRACE analysis as part of *OWL*, with the sea probe once again de-scoped. TRACE analysis assessed the technical risk rating as medium-low, with the megaflex arrays and hypervelocity aerosampling technologies identified as key challenges. The TRACE cost estimate was $2.17 billion. The stand-alone version of the Titan orbiter was included in the NF-6 list outlined in *OWL*.

Titan is the only moon in the outer solar system with a thick atmosphere, and the only body in the solar system besides Earth with an ongoing hydrological cycle, including precipitation cycles, lakes, and surface fluvial erosion. This cycle involves liquid hydrocarbons, rather than water, making it a fascinating case study for comparative planetology. The long-standing question of how the methane cycle remains closed on geological timescales is a particularly important motivation for further exploration that links to geophysical questions about Titan's interior. Titan's climate is affected by bulk atmospheric properties and seasonal variations, but also by its complex hydrocarbon cycle, allowing further analogies with how Earth's climate system operates. Despite significant advances, atmospheric chemistry and hydrocarbon haze formation in Titan's upper atmosphere remain poorly understood. This chemistry has similarities to prebiotic chemistry on the early Earth, making Titan an important target for astrobiology research. From *OWL*:

> Titan Orbiter globally characterizes Titan's dense $N_2$ atmosphere that harbors prebiotic molecules, its Earth-like methane hydrological cycle and seas, and its subsurface liquid water ocean, including how they evolve over time, in order to assess Titan's potential habitability. Cassini flybys revealed complex organic chemistry, methane–ethane lakes and seas, and meteorology on Titan; however, these processes could not be thoroughly studied owing to instrumentation and flyby coverage limitations. Titan Orbiter will investigate how the organic chemical factory on Titan works, both in the atmosphere and on the surface, providing important context for data from Dragonfly and complementary global measurements. (NASEM 2023, p. 590)

The science objectives for Titan Orbiter from *OWL* are as follows:

- Determine Titan's internal structure, the depth and thickness of the ice shell and subsurface ocean, and whether the former is convecting; and determine rates of interior–surface solid or gas interchange;
- Characterize Titan's global geology and its landscape-shaping processes;
- Characterize Titan's global methane hydrological and sedimentological system, including surface transport/flow rates and cloud distributions; and
- Quantify the production, transport, and fate of organic molecules in Titan's upper atmosphere and atmospheric and climate evolution in general.

The Titan Orbiter mission theme addresses 6 of the 12 priority science questions from *OWL* (see Box 1-1): Q5, Q6, Q8, Q10, Q11, and Q12. (Note that the assessment of science questions addressed in the mission study report differed, in part because that report also included a sea probe element.) Titan Orbiter was described in *OWL* as having the potential to provide breakthrough advances in Q5: "Solid body interiors and surfaces" and Q6: "Solid body atmospheres, exospheres, magnetospheres, and climate evolution."

Key breakthroughs that Titan Orbiter would enable in Q5 include a determination of the thickness and conductivity of the ice crust, an understanding of how material is transported across Titan's surface, and a determination of the relative importance of aeolian, fluvial, cryovolcanic, and other processes in surface alteration. Advances in Q6 include determination of the 3D distribution of Titan's aerosols and clouds, as well as detection of storms and rainfall events. In addition, the orbiter would allow advances in atmospheric chemistry, including the role of oxygen in atmospheric organics and the importance of ion neutral versus radical reaction pathways (NASA 2021b).

The science questions addressed by Titan Orbiter remain compelling and have not been significantly advanced since *OWL* was published. The results from new observations of Titan by JWST, as well as forthcoming observations, have not yet appeared in the peer-reviewed literature. Observations of Titan from JWST or Earth complement the science that Titan Orbiter would perform but are not a replacement for it.

## VENUS

### Venus In Situ Explorer

Venus In Situ Explorer (VISE) was recommended as an NF-class mission in three decadal surveys: *NFSS* (2003), *V&V* (2011), and *OWL* (2023). NASA removed VISE from the NF-5 Draft AO in 2022, citing programmatic balance (NASA n.d.-g). *OWL* included VISE in the NF-6 mission theme list, citing scientific importance (NASEM 2023).

Planetary scientists have prioritized VISE for its importance in understanding the evolution of terrestrial planets, writ large, and specifically why Venus and Earth are different. Venus also provides an opportunity to better understand Earth-sized exoplanets. *OWL* encapsulates this in Q3.4a: "Why are Earth and Venus so different?" Venus hosts a dynamic atmosphere and (likely) active surface, meaning that scientifically critical processes are complex, coupled, and occur across large spatial and temporal scales. Scientists will not fully understand these processes with data acquired only by orbiters or individual probes. An in situ platform that dwells in the atmosphere or reaches the surface requires an NF-class investment.

VISE was not subjected to the CATE process in *V&V* nor the TRACE process in *OWL* because "the survey committee concurred with Vision and Voyages' decision that the phase-A study—conducted when a concept responsive to VISE was in the step-two competition for the third New Frontiers launch opportunity—was equivalent to or better than a CATE" (NASEM 2023). As noted previously, *OWL* did not comment on the NF-5 mission candidates because doing so would have created conflicts of interest. *OWL* recommended VISE for the NF-6 opportunity.

As most recently defined, VISE must address at least two of three science objectives:

- Characterize past or present large-scale spatial and temporal (global, longitudinal, and/or diurnal) processes within Venus's atmosphere;
- Investigate past or present surface–atmosphere interactions at Venus; and
- Establish past or present physical and chemical properties of the Venus surface and/or interior.

These objectives would address at least five priority science questions from *OWL* (see Box 1-1): Q3: "Origin of Earth and inner solar system bodies"; Q5: "Solid body interiors and surfaces"; Q6: "Solid body atmospheres, exospheres, magnetospheres, and climate evolution"; Q10: "Dynamic habitability"; and Q12: "Exoplanets."

*OWL* defined the newest NF-6 science objectives for VISE after the selection of three new missions to Venus in 2021 by NASA and ESA: VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy; Smrekar et al. 2022); DAVINCI (Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging; Garvin et al. 2022); and EnVision (European Space Agency n.d.). *OWL* acknowledged that these missions do not meet the science objectives of VISE, stating, "Venus In Situ Explorer (VISE) investigates the processes and properties of Venus that cannot be characterized from orbit or from a single descent profile." For example, VERITAS and EnVision cannot directly measure atmospheric or surface chemistry, intrinsic magnetism, or seismic activity. DAVINCI will probe the atmosphere at one time and location on a planet with complex chemical gradients and dynamics in three dimensions and over time. No planned mission is designed to collect data at the surface, and the study of lunar, martian, and asteroidal samples attests to the value of direct geochemical and mineralogical analysis to understand the fundamental composition and evolution of planetary bodies. Ultimately, the VISE mission concept complements the newly selected missions. Because *OWL* recommended that VISE be included on the NF-6 mission list, when an NF-6 selection was expected within the current decade, the report recognized that the VISE science objectives were independent of EnVision, DAVINCI, and VERITAS and that VISE could be selected before those missions reach Venus.

Scientifically, recent work emphasizes that Venus is highly dynamic over the timescale of a spacecraft mission. Although data from the last NASA mission to Venus (Magellan) is now more than 30 years old, scientists continue to mine it for new insights. In 2023, new analyses revealed a large, volcanic vent that may have changed shape in the 8 months between two imaging passes, which would represent active volcanism (Herrick and Hensley 2023). Recent geophysical modeling makes the case for the formation of cratons on surface of Venus by mechanisms that may have operated on early Earth (Capitanio et al. 2024). The JAXA Akatsuki mission continues to operate as a meteorology-focused orbiter, returning spectacular images of the clouds in different wavelengths. The identity of the "unknown UV absorber" remains a mystery under active investigation (Jiang et al. 2024). The lack of knowledge about the physical and chemical processes in the clouds remains such that we cannot exclude the possibility of modern cloud life (Bains et al. 2024; Petkowski et al. 2024). During a Venus gravity assist, the Parker Solar Probe observed whistler waves, the origin of which has been debated for decades (George et al. 2023). The importance of Venus to the understanding of Earth-sized exoplanets only grows (Way et al. 2023). Investments in the Hot Operating Temperature Technology (HOTTech) program have shown promise and would critically enable a future VISE proposal.

Overall, ongoing scientific research and technological investments for this active and dynamic planet only bolsters the case for VISE's in situ measurements.

# 3
# Impact on New Frontiers 5 Mission Theme Considerations

The science objectives and overall goals of each New Frontiers (NF)-5 and NF-6 mission theme summarized in the Chapter 2 set the stage to evaluate the second item in the statement of task:

> Has scientific understanding or external factors, such as programmatic developments or technological advances, been sufficiently substantial since *OWL* to warrant reconsidering or removing any of these mission themes?

The following sections identify those mission themes that fall into this category, and those that do not, with specific emphasis on those aspects of the mission theme that have changed to warrant reconsideration. In those cases where no significant developments warrant reconsideration, the committee encompasses these mission themes into a single finding.

## LUNAR SCIENCE

As the nearest neighbor and Earth's only satellite, the Moon remains one of the most accessible bodies within the solar system to elucidate Earth's early planetary evolution as well as early solar system dynamics. The growing national and international focus on lunar missions, including the National Aeronautics and Space Administration's (NASA's) Artemis program, India's Chandrayaan-3 mission, and China's Chang'e-6 sample return mission, is evidence of the importance of lunar science to broad planetary exploration.

Lunar science and exploration directly address at least 3 of *OWL*'s 12 priority science questions, including Q3: "Origin of Earth and inner solar system bodies"; Q4: "Impacts and dynamics"; and Q5: "Solid body interiors and surfaces." Furthermore, lunar exploration for both scientific and resource utilization was highlighted in 2017 as part of Space Policy Directive-1 (White House 2017). In 2019, NASA instituted the Lunar Discovery and Exploration Program (LDEP), which is funded through PSD and managed between the Planetary Science Division (PSD) and the Exploration Science Strategy Integration Office (ESSIO). *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023; hereafter, *OWL*) explicitly recommended that NASA focus a lunar exploration program that prioritized lunar science objectives:

> 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. [These lunar science objectives include] Science Theme 1: Uncover the lunar record of solar system origin and early history; Science Theme 2: Understand the geologic processes that shaped the early Earth, and that are best preserved on the Moon; and Science Theme 3: Reveal inner solar system volatile origin and delivery processes. (NASEM 2023, pp. 571–572)

Within this framework set out by *OWL*, the committee considered the two lunar missions contained in the comprehensive NF-5 and NF-6 mission themes: Lunar South Pole–Aitken (SPA) Basin Sample Return and Lunar Geophysical Network (LGN).

The SPA Basin Sample Return mission theme has remained a planetary science exploration priority for the past three decadal surveys because it targets the chronology of lunar basin-forming impacts and early solar system impact dynamics, lower crust and upper mantle composition, as well as lunar differentiation. As such, this mission theme is directly responsive to Q3, Q4, Q5, as well as Q9 and Q10. *OWL* studied two mission concepts, Endurance-R and Endurance-A, and concluded that this high-priority science was more likely accomplished through an Endurance-A mission framework in which a single, medium-class mission concept would return ~100 kg of lunar samples through a robotic–human partnership. Given the high priority of lunar science and the 2019 establishment of the LDEP to coordinate lunar exploration, *OWL* recommended that an SPA sample return mission would be better suited within LDEP. The committee concluded that no new scientific discoveries or technological developments have negated these findings.

> Finding 1: Endurance-A, identified in *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023) as the highest-priority medium-class mission for the Lunar Discovery and Exploration Program (LDEP), addresses multiple decadal survey priority science questions. Because the Endurance-A mission scope encompasses the objectives outlined in the New Frontiers (NF)-5 draft announcement of opportunity (AO) Lunar South Pole–Aitken Basin Sample Return mission theme, the absence of this theme from the next NF AO is warranted.

The LGN mission theme has been identified in the past three planetary decadal surveys as high-priority science. The last LGN mission concept study was conducted in 2011, and the mission concept was last reviewed in full in *Vision and Voyages for Planetary Science in the Decade 2013–2022* (NRC 2011; hereafter, *V&V*). The 10-year mission proposes an array of four seismic stations, each with a seismometer, heat flow probe, retroreflector, and magnetotelluric sounder. Direct mission objectives include determining the size, structure, composition, and heterogeneity of the Moon's interior, its relation to surface characteristics, and the current seismo-tectonic and thermal state of the interior. Also informing understanding of the evolution of terrestrial planets, the LGN mission is directly responsive to priority decadal science question themes Q3, Q4, Q5, and Q8.

Although not included in the NF-4 solicited mission themes, *V&V* did recommend the inclusion of LGN in the next NF AO. The science proposed by the mission is still important, and there has not yet been a mission to address these particular lunar science questions despite advances by both GRAIL and LRO as discussed in Chapter 2.

This mission does present several challenges that preclude it from other existing mission lines such as Discovery or Commercial Lunar Payload Services (CLPS). A single station with a seismometer, heat flow probe, retroreflector, and magnetotelluric sounder is insufficient to fulfill the science objectives. Rather, four stations are required to achieve the stated science objectives, exceeding the Discovery mission cost cap.

Furthermore, the 4-seismometer array must be deployed together and survive for at least a full lunar tidal cycle of 6 years to achieve its primary science objective: determining the distribution and origin of lunar seismic activity. While LDEP's ongoing CLPS Program shows promise, delivering an array of seismometers, simultaneously or in quick succession, that can survive a full lunar tidal cycle is currently outside the CLPS capability scope. Work is under way to extend lifespans of CLPS landers and associated payloads (Lunar and Planetary Institute 2022); the Lunar Farside Seismic Suite is packaged as a self-sufficient payload with thermal control to enable survival through the lunar night, and it is designed to operate for at least 4.5 months. However, no discussion so far has proposed the 6-year lifespan required to achieve the decadal objectives addressed by LGN.

In sum, owing to the lower cost cap of Discovery and the inability of CLPS landers to survive long enough to accomplish the science goals of this mission theme, the committee finds that there are no programmatic avenues that can accomplish LGN other than the NF program. Furthermore, the mission still meets decadal survey–level science objectives. Therefore, the committee finds that there has not been a significant change in scientific understanding or programmatic developments to warrant the reconsideration of this mission theme for inclusion.

The committee continues to support NASA's focus on lunar science with the establishment of LDEP during the end of the past decade. However, priority lunar science, including LGN, must continue to be prioritized across NASA mission programs while LDEP and ESSIO capabilities are expanded.

> Finding 2: The science proposed by the Lunar Geophysical Network (LGN) addresses multiple decadal survey priority science questions. There are currently no programmatic avenues, including the NASA Lunar Discovery and Exploration Program (LDEP) and the Commercial Lunar Payload Services, that could accomplish LGN other than the New Frontiers (NF) program. Therefore, the inclusion of LGN as a theme in the next NF announcement of opportunity is warranted.

## SMALL BODIES

Three orbiter, lander, and sample return missions to small bodies were included in the *OWL* report NF-5 and NF-6 mission theme lists. Comet Surface Sample Return (CSSR) has been included in New Frontiers mission target lists since NF-2, and both Centaur Orbiter and Lander (CORAL) and Ceres Sample Return were added to the NF-6 list during the *OWL* process as part of a planetary mission concept study (PMCS). *OWL* concluded that each of the three small body mission themes was unique and addressed high-priority decadal science. Collectively, these mission themes address 11 of the 12 priority science question topics, with the most significant contributions to Q1: "Evolution of the protoplanetary disk"; Q2: "Accretion in the outer solar system"; Q3: "Origin of Earth and inner solar system bodies"; Q5: "Solid body interiors and surfaces"; and Q10: "Dynamic habitability."

CSSR has been a community and decadal priority since the early formulation of the New Frontiers program. The related Comet Astrobiology Exploration Sample Return (CAESAR) mission was one of two finalists in NF-4, evidence of both community prioritization and mission feasibility. Samples returned by a CSSR-themed mission would represent some of the most primitive materials of the early solar system and protosolar nebula. Ceres Sample Return targets the only dwarf planet within the asteroid belt. Ceres Sample Return would represent the first cryo-preserved sample and the first sample return from a candidate Ocean World, making this mission and the Enceladus Multiple Flyby (EMF) mission theme the only two that could result in breakthrough science addressing Q10: "Dynamic habitability."

Chemical and physical observations from Dawn (McCord et al. 2022) suggest that Ceres's internal structure and surface are the outcome of extended water–rock–organic compound interactions, which could be further explored by this orbiter/lander/sample return mission. Centaur Orbiter and Lander (CORAL) represents a second cometary target, but specifically targeting a Centaur provides an opportunity to investigate nebular volatiles in primordial, ice-rich planetesimals that originated in the primordial Kuiper belt. CORAL addresses 10 of the 12 priority science questions, with the most significant potential for questions Q1, Q2, and Q3.

All three small body mission targets would provide key reference measurements for ground- and space-based observations and expand applicability of these observations across the solar system. Furthermore, the current NF timeline could allow for upcoming observations from the Vera C. Rubin Observatory, NEO Surveyor, and James Webb Space Telescope (JWST) to improve target selection for these missions. Recent successes in small body sample return from Ryugu and Bennu can only improve sample return, curation, and analysis protocols from small bodies, and may provide mission cost savings. Results of the Autonomous Navigation Demonstration Relevance Assessment (ANDRAT) chartered study (NASA 2024) could also result in reduced operation mission costs. The committee concluded that these scientific, mission, and technological developments only support the continuation of small body mission research.

> Finding 3: Comet Surface Sample Return, Centaur Orbiter and Lander, and Ceres Sample Return address multiple decadal survey priority science questions. Inclusion of these missions in the next New Frontiers announcement of opportunity is warranted.

## OUTER SOLAR SYSTEM PLANETS AND MOONS

The saturnian moon Enceladus has been identified as high-priority science in both *V&V* (NRC 2011) and *OWL* (NASEM 2023). In *V&V,* Enceladus Orbiter was listed as the fourth-priority target for flagship missions, and the Ocean Worlds theme (with a focus on either Titan or Enceladus) was then included in the NF-4 AO by NASA. Following the selection of Dragonfly for NF-4, the NF-5 Draft AO included Ocean Worlds (Enceladus only). *OWL* subsequently completed the PMCS for an EMF mission theme. EMF addresses at least two of *OWL*'s 12 priority science questions, Q10: "Dynamic habitability" and Q11: "Search for life elsewhere," while also contributing to Q5: "Solid body interiors and surfaces" and Q12: "Exoplanets." The committee concluded that no additional scientific, technological, or programmatic changes impact the evaluation of EMF in *OWL*.

Saturn Probe was first added to the New Frontiers missions themes list for NF-4 in *V&V*, and has subsequently been included in the NF-5 draft AO as well as recommended for inclusion in NF-6 by *OWL*. *V&V* noted that this mission concept was the only one to address giant planet science questions within the cost cap of the NF program (NRC 2011). The Saturn Probe mission theme will explore the structure of Saturn's atmosphere, the abundance of noble gases, and the isotopic ratios of hydrogen, carbon, nitrogen and oxygen. It is responsive to Q1: "Evolution of the protoplanetary disk" and Q12: "Exoplanets." Importantly, Saturn Probe is the only recommended NF concept that addresses Q7: "Giant planet structure and evolution."

The only other mission concept in any mission program reviewed in *OWL* to address Q7 was the Uranus Orbiter and Probe (UOP), which was determined in *OWL* as the highest-priority flagship mission for the coming decade. *V&V* noted that "When a Saturn Probe mission is combined with a Uranus Orbiter and Probe mission, the understanding of planetary formation will be greatly advanced in the next decade" (NRC 2011), and *OWL* maintained Saturn Probe in the NF-5 and NF-6 mission themes. The committee concluded that selection of UOP for the next flagship, whose start is already delayed, did not pose a significant impact on programmatic balance.

> Finding 4: Enceladus Multiple Flyby and Saturn Probe address multiple decadal survey priority science questions. Inclusion of these missions in the next New Frontiers announcement of opportunity is warranted.

Io Observer was first evaluated in the 2003 decadal survey *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NRC 2003; hereafter, *NFSS*) and was included in NF-3 AO and the NF-5 draft AO. A mission concept study for Io Observer was part of the *V&V* review and included in the *V&V* NF-5 priority list. Io Observer was also reviewed in *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (NRC 2008) and maintained on the NF-5 list in *OWL*. Each review maintained the importance of addressing the science objectives of the Io Observer mission concept.

The Io Volcano Observer (IVO) mission was a finalist for Phase-A Concept Study in the 2019 Discovery Program but was ultimately not selected for flight. The 2020 Committee on Astrobiology and Planetary Sciences (CAPS) report reiterated the importance of the science objectives of Io Observer and asserted that the mission theme should be maintained on the NF-5 mission theme list if IVO was not selected. The Io Observer mission concept was not included in *OWL*'s priority science question matrix but would cover major themes including Q5: "Solid body interiors and surfaces"; Q6: "Solid body atmospheres, exospheres, magnetospheres, and climate evolution"; and Q8: "Circumplanetary systems." The committee reaffirms the importance of Io as a unique body for understanding active volcanic, tectonic, and plasma processes, and for providing a potential analogue to certain exoplanets and young terrestrial planets. Furthermore, while Juno observations of Io are contributing to Io science, the Juno instrument package cannot address all 7 of the science objectives outlined for Io Observer in *V&V*.

> Finding 5: The broad objectives of Io Observer continue to address multiple decadal survey priority science questions. Recent advances in Io science, including those from the Juno flybys, do not warrant reconsideration or removal of Io Observer from the next New Frontiers (NF) announcement of opportunity (AO). Therefore, inclusion of Io Observer in the next NF AO is warranted.

The concept of a Titan Orbiter was included as part of the Flagship-class Titan Saturn System Mission in *V&V* (NRC 2011). While the science objectives were deemed important, the cost estimate was well outside the NF cost cap and, therefore, not included in *V&V*'s recommended NF mission themes. However, Titan was added to the NF-4 AO by NASA as part of the Ocean Worlds—Titan or Enceladus theme, and the Titan Orbiter Oceanus was proposed but not selected in NF-4.

With science targets that include the exploration of Titan's dense atmosphere, potential for atmospheric prebiotic chemistry, a unique methane hydrological cycle, and subsurface ocean, the Titan Orbiter mission theme directly addresses *OWL*'s Q5: "Solid body interiors and surfaces" and Q6: "Solid body atmospheres, exospheres, magnetospheres, and climate evolution." Titan Orbiter is also responsive to Q8, Q10, Q11, and Q12. In evaluating Titan Orbiter within the NF program, *OWL* cited the previous CAPS report (NASEM 2020), which suggested that the mission theme remain in the NF-6 concept list but be removed from the NF-5 theme owing to the selection of Dragonfly in NF-4. The *OWL* steering committee concluded that Titan Orbiter provides important and complementary science to Dragonfly and prioritized it for the NF-6 list. *OWL* assumed that Titan would not be included in the next NF AO while making this prioritization. The committee affirms that there is no new significant science or technological changes that counter the conclusions in *OWL*.

> Finding 6: Titan Orbiter addresses several decadal survey priority science questions that are distinct from the Dragonfly mission to Titan selected in the New Frontiers (NF)-4. However, to maintain programmatic balance, the absence of Titan Orbiter from the next NF announcement of opportunity is warranted. Titan Orbiter remains a high priority for future NF mission opportunities as recommended by *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023).

## VENUS

The Venus in Situ Explorer (VISE) mission has been recommended as a New Frontiers mission in each of the three planetary decadal surveys. VISE proposals reached Phase-A in NF-3 and received development funding in NF-4. VISE was included in the NF-5 list of *V&V*. As stated earlier, *OWL* did not comment on the NF-5 mission candidates. Therefore, *OWL* prioritized VISE for NF-6 and NF-7 but did not directly address VISE with respect to NF-5.

VISE was included in the "Second Community Announcement: Advance Notice Regarding New Frontiers 5 (NF-5) Announcement of Opportunity" (NASA n.d.-g) but was removed from the "Fifth Community Announcement: Advance Notice Regarding Forthcoming Release of the New Frontiers 5 (NF-5) Announcement of Opportunity (AO)" (NASA 2022) by the PSD after the selections of DAVINCI and VERITAS in Discovery and the ESA EnVision mission (which includes a NASA-supported radar). NASA decided to remove VISE from the draft NF-5 AO for reasons of programmatic balance. Since then, budgetary turbulence has delayed the launches of VERITAS and DAVINCI, but they (and EnVision) have not changed their scientific objectives. A private company (Rocket Lab) continues to plan to launch a small, low-cost probe to Venus, focused on astrobiology. Other national space agencies have discussed new Venus missions but have not revealed any finalized plans.

When NASA removed VISE from the NF-5 draft AO in early 2023, after the then-recent selections of DAVINCI, VERITAS, and EnVision, programmatic balance was the most significant driver for omission. As per this committee's charge, when considering the scientific, technical, and programmatic changes in the past 2 years since VISE was removed from the 2023 NF-5 draft AO, the science remains compelling and the programmatic landscape is unchanged. The committee asserts that it would be challenging for NASA to demonstrate programmatic balance of principal investigator (PI)-led missions if three Venus missions are selected in a row.

> Finding 7: Venus In Situ Explorer (VISE) addresses several decadal survey priority science questions that are distinct from those addressed by recently selected missions (DAVINCI, VERITAS, and EnVision) to Venus. However, to maintain programmatic balance, the absence of VISE from the next New Frontiers (NF) announcement of opportunity is warranted. VISE remains a high priority for future NF mission opportunities as recommended by *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023).

# 4
# Upcoming New Frontiers 5 Announcement of Opportunity

The New Frontiers (NF) program is meant to support medium-sized, principal investigator (PI)-led missions that bridge flagship missions and the Discovery program at a launch cadence of 60 months. Three NF missions have been flown: New Horizons launched in 2006, Juno launched in 2011, and OSIRIS-REx launched in 2016, maintaining the optimal cadence. Dragonfly, the NF-4 selection, is expected to launch no earlier than 2028. The delay of the Dragonfly launch will create at least a 12-year gap in NF launches. With the delay of the NF-5 announcement of opportunity (AO) to no earlier than 2026, the next NF mission would likely launch no earlier than 2033, within the next decadal. NF-5 is currently the only confirmed AO that will happen in this decade, and even that could be at risk in the current fiscal environment. It is therefore critical that the next AO include missions that directly address the priority science questions identified therein. This goal can be accomplished with a list of targets that includes missions on both the NF-5 draft AO and NF-6 lists recommended in *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023; hereafter, *OWL*).

*OWL* gave careful consideration to the number of NF-6 and NF-7 mission themes to be prioritized:

> As emphasized by Vision and Voyages, "Because preparation and evaluation of New Frontiers proposals places a substantial burden on the community and NASA, it is important to restrict each New Frontiers solicitation to a manageable number of candidate missions." Indeed, with only three major design centers (APL, JPL, GSFC) that can manage NF missions and proposals, a restricted list is needed so they can appropriately allocate resources. On the other hand, after the NF-5 selection, six mission themes from the prior decade will remain unselected. Adding themes based on concepts studied in this survey, which is desirable to ensure that the NF list continues to address the currently highest priority science, then requires increasing the number of mission themes and/or removing some of the prior themes. In consideration of this balance, the committee decided to recommend eight NF themes per call. (NASEM 2023, p. 587)

The recommendation of seven missions is in keeping with the original number of NF-5 missions, the number of NF-4 AO (six mission themes), the NF-5 draft AO (seven mission themes), and the sentiment expressed in *OWL* to find a balance between breadth of science questions and manageable number of concepts the community can pursue. NF mission proposals require enormous resources at the three participating entities and associated contractors, and limiting mission themes prevents the scenario in which the management resources of the proposing centers are not the deciding factor on which mission themes are proposed. In light of the current declining budget and NASA mission portfolio, this balance is consistent with 7 recommended targets. Furthermore, CAPS has previously recommended that NF themes be reconsidered for or removed from an AO based on programmatic balance. For example, the Committee on Astrobiology and Planetary Sciences previously recommended that NASA reconsider the inclusion of Ocean Worlds (Titan) in the NF theme because of programmatic balance, where programmatic balance includes not only the mission themes within any one AO, but also considers the entire NASA Planetary Science Division (PSD) fleet.

Finding 8: Given that NASA anticipates that the New Frontiers (NF)-5 announcement of opportunity will be announced no earlier than 2026, it is important to assemble a mission list for this upcoming call that can address the broadest range of priority science questions identified in *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023).

Finding 9: Based on the findings of the committee, the next New Frontiers announcement of opportunity would be most effective if it includes the following themes, listed alphabetically:

- Centaur Orbiter and Lander
- Ceres Sample Return
- Comet Surface Sample Return
- Enceladus Multiple Flyby
- Io Observer
- Lunar Geophysical Network
- Saturn Probe

The committee recognizes that the current cadence of NF AOs is far outside both the original intent of the NF program and the recommendations included in each planetary science decadal surveys of two per decade. In fact, the committee itself has twice made interim findings to accommodate the delayed cadence of the NF-5 AO. This departure from the original and recommended cadence has several implications.

First, the cadence is no longer synchronized with the decadal surveys that conduct extensive reviews of the priority mission themes and put forward a recommended program. Each decadal review strives to strike a balance between scientific priorities, programmatic balance, and cost estimates (as compared to AO cost caps); however, a delayed and increasingly unpredictable mission cadence undermines the recommended program as outlined by each decadal survey. Without a regular cadence, the NF mission theme list will continue to expand without accomplishing previously prioritized missions. These factors all undermine the fulfillment of the recommended balanced program of the decadal surveys. As NASA considers how to best accommodate an ever-growing list of high science priority missions within its proposal structure, it is critical to incorporate mechanisms that allow for development of mission concept studies for emerging targets of opportunity.

Finding 10: New Frontiers (NF) mission cadence is critical to programmatic balance. Without a predictable cadence aligned with the decadal surveys, the NF mission theme list will continue to expand without accomplishing previously prioritized missions, jeopardizing decadal survey priorities.

Second, an extension of the program cadence also has significant budgetary implications. Cost estimates for mission themes put forward by the decadal surveys are often outdated by the time the AO is released, owing to both inflationary pressure and increased costs because of supply chain issues since the mission costs were estimated. The extended length of time since the selection of NF-4, together with recent financial and budgetary landscape, creates a disconnect between the estimated costs of NF-5 and NF-6 targets recommended in *OWL* and the NF-5 cost cap proposed in the 2023 draft NF-5 AO. This is also complicated by the uncertainty for the present-day costs of the missions advanced from the NF-4 AO list, whose costs were not assessed through the technical risk and cost evaluation process in the *OWL* report.

Finding 11: Due to factors such as inflationary pressure and supply chain challenges, the draft New Frontiers (NF)-5 announcement of opportunity cost cap is likely insufficient for many of the mission themes considered here and therefore merits reconsideration by NASA.

Ultimately, delays in cadence cause budgetary pressures that subsequently cause further delays, producing an unsustainable cycle in the NF program. Owing to these factors, timely release of the NF-5 AO to return to the two per decade cadence of medium-class missions recommended by the decadal surveys is vital. However, the committee also recognizes that increases to the cost caps in the current budget climate could have adverse effects on mission cadence.

The committee recognizes that NASA and the administration alone cannot fix the cadence of NF missions, and it is beyond the remit of this report to recommend potential solutions. However, the committee, along with other consensus studies (NASEM 2024) continue to highlight and be concerned by this difficult problem.

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# Appendixes

# A
# Statement of Task

## COMMITTEE STATEMENT OF TASK

The National Academies of Sciences, Engineering, and Medicine will appoint the Committee on Astrobiology and Planetary Sciences (CAPS) to operate as an ad hoc committee. The overarching purpose of the committee is to support scientific progress in astrobiology and planetary science and assist the federal government in integrating and planning programs in these fields by providing advice on the implementation of decadal survey recommendations. The CAPS provides an independent, authoritative forum for identifying and discussing issues in astrobiology and planetary science between the research community, the federal government, and the interested public.

The CAPS will issue reports that will provide guidance to federal agencies that support astrobiology and planetary science research. The CAPS scope spans space-based and supporting ground-based planetary research within our own planetary system, including, for example, geosciences, atmospheres, particles and fields of planets, moons, and small bodies, as well as astrobiology, planetary astronomy, and planetary protection. The CAPS's scope also includes appropriate cross-disciplinary areas and consideration of budget and programmatic aspects of the implementation of the decadal survey.

The committee will build on the current decadal survey of the field, "Vision and Voyages for Planetary Science in the Decade 2013-2022" (VVPS) and monitor the progress of its recommended priorities for the most important scientific and technical activities in that report and recommendations in the mid-decadal review report due to be issued in 2017.

The committee will carry out its charge by undertaking the following tasks:

1. At each of its in-person meetings, as appropriate, the committee may prepare concise assessments of progress on the implementation of the decadal survey's recommended scientific and technical activities. The assessments will be based on evidence gathered by the committee at its in-person and virtual meetings. The committee's assessment reports may include findings and conclusions on key strategies being pursued by the agencies and the status of agency actions that relate to the state of implementation. The reports may also highlight scientific discoveries and engineering and technical advances relevant to progress on the science objectives identified in VVPS and in addition will focus on one or more of the following types of issues:

    - The scientific impact of a change in the technical and engineering design, cost estimate, schedule, or programmatic sequencing of one or more of the survey-recommended activities;
    - The impact of a scientific advance on the technical and engineering design, schedule, or programmatic sequencing of one or more survey-recommended activities;
    - The scientific impact of a course of action at a decision point described in the survey report and recommended therein as being suitable for consultation with an independent decadal survey implementation committee; and

- The scientific impact of implementing recommendations from the mid-decadal review and other relevant National Academies' reports.

2. At an in-person meeting, the committee may prepare a concise report with advice on the preparation for future decadal and mid-decadal studies. These reports will be based on evidence gathered by the committee at its in-person and virtual meetings. Future decadal and mid-decadal studies will be carried out by an ad hoc committee appointed by the National Academies under a separate task.
3. For advisory activities assessed to require a more in-depth review than is possible through the normal operation of the CAPS, the committee will assist the National Academies in formulating the task and committee membership for such studies, which will be designed as separate tasks.

## REPORT STATEMENT OF TASK

The National Academies of Sciences, Engineering, and Medicine will address the following questions:

- Has scientific understanding or external factors, such as programmatic developments or technological advances, significantly changed since the New Frontiers 5 (NF-5) mission themes or New Frontiers 6 (NF-6) mission themes were evaluated by most recent planetary science and astrobiology decadal survey, Origins, Worlds, and Life (*OWL*)?
- Has scientific understanding or external factors, such as programmatic developments or technological advances, been sufficiently substantial since OWL to warrant reconsidering or removing any of these mission themes?
- Given that NASA anticipates the next New Frontiers Announcement of Opportunity (AO) will be released no earlier than 2026, should NASA use the mission themes provided in the draft NF-5 AO (released 1 September 2023),[1] the NF-6 mission themes as provided in *OWL*, or a hybrid of the these?

[1] It is noted here that the draft NF-5 AO cited above in the statement of task was released on September 1, 2022. The committee corrects this editorial error here and uses the actual release date in the remainder of the report.

# B
# Acronyms and Abbreviations

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| ANDRAT | Autonomous Navigation Relevance Assessment |
| AO | announcement of opportunity |
| APL | Johns Hopkins University Applied Physics Laboratory |
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| CAESAR | Comet Astrobiology Exploration Sample Return |
| CAPS | Committee on Astrobiology and Planetary Sciences |
| CATE | cost and technical evaluation |
| CLPS | Commercial Lunar Payload Services |
| CORAL | Centaur Orbiter and Lander |
| CSSR | Comet Surface Sample Return |
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| DAVINCI | Deep Atmosphere Venus Investigation of Noble Gasses, Chemistry, and Imaging |
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| EMF | Enceladus Multiple Flyby |
| ESA | European Space Agency |
| ESSIO | Exploration Science Strategy and Integration Office (NASA) |
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| FSS | Farside Sessions Suite |
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| GRAIL | Gravity Recovery and Interior Laboratory mission |
| GSFC | Goddard Space Flight Center (NASA) |
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| HotTech | Hot Operating Temperature Technology |
| | |
| ILSA | Instrument for Lunar Science Activity |
| IVO | Io Volcanic Observer |
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| JPL | Jet Propulsion Laboratory (California Institute of Technology) |
| JWST | James Webb Space Telescope |
| | |
| LDEP | Lunar Discovery and Exploration Program (NASA) |
| LGN | Lunar Geophysical Network |
| LRO | Lunar Reconnaissance Orbiter |
| LSST | Large Synoptic Sky Telescope |
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| MWR | microwave radiometer |
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| NF | New Frontiers (mission) |
| *NFSS* | *New Frontiers in the Solar System: An Integrated Exploration Strategy* (2003) |

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|---|---|
| *NOSSE* | *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (2008) |
| ONF5 | *Options for the Fifth New Frontiers Announcement of Opportunity* (2020) |
| OSIRIS-REx | Origins, Spectral Interpretation, Resource Identification, and Security—Regolith Explorer Mission (NF-3) |
| *OWL* | *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology* (2023) |
| PI | principal investigator |
| PMCS | planetary mission concept study |
| PSD | Planetary Science Division (NASA Science Mission Directorate) |
| RTG | radioisotope thermoelectric generator |
| SMD | Science Mission Directorate |
| SPA | South Pole–Aiken |
| SSB | Space Studies Board |
| TRACE | technical risk and cost evaluation |
| UOP | Uranus Orbiter and Probe |
| *V&V* | *Vision and Voyages for Planetary Science in the Decade 2013–2022* (2011) |
| VERITAS | Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy |
| VISE | Venus In Situ Explorer |

# C
# Committee and Staff Biographical Information

MARTHA S. GILMORE, *Co-Chair*, is the Joshua Boger University Professor of the Sciences and Mathematics, a professor in the Department of Earth and Environmental Sciences and is currently the dean of the Division of Natural Sciences and Mathematics at Wesleyan University. Dr. Gilmore is a geologist who specializes in the study of the evolution of planetary surfaces using geomorphic mapping and visible to near-infrared spectroscopy on Venus, Mars, and Earth. She also studies the growth and weathering of minerals under simulated Venus and Mars conditions in her laboratory and the National Aeronautics and Space Administration (NASA) Glenn Extreme Environments Rig. Dr. Gilmore is a science team member on the DAVINCI and VERITAS missions to Venus and was co-principal investigator of the Venus Flagship Planetary Decadal Mission Concept Study. Dr. Gilmore is a fellow of the Geological Society of America and a recipient of that body's Randolph W. "Bill" and Cecile T. Bromery Award. She also received the Claudia J. Alexander Prize from the Division for Planetary Sciences of the American Astronomical Society. She delivered the 30th Masursky lecture at the Lunar and Planetary Science Conference. Dr. Gilmore received a PhD in geological sciences from Brown University. She has formerly served the National Academies as a member of the Committee on Planetary and Lunar Exploration (COMPLEX) and as a member of the Inner Planets Panel of the *Vision and Voyages* planetary decadal survey.

KARYN L. ROGERS, *Co-Chair*, is an associate professor in Earth and Environmental Sciences at Rensselaer Polytechnic Institute (RPI) and directs the Rensselaer Astrobiology Research and Education Center. Dr. Rogers's research interests focus largely on habitability in extreme environments and uses both terrestrial analog environments and novel laboratory experimental systems to explore the synthesis of prebiotic molecules on the early Earth, as well as the environmental limits of life. Before joining the faculty of RPI, Dr. Rogers was a research scientist at the Carnegie Institution of Washington, an assistant professor at the University of Missouri, and a Deep Ocean Exploration Institute postdoctoral scholar at Woods Hole Oceanographic Institution. Dr. Rogers is a co-lead of the Prebiotic Chemistry and Early Earth Environments consortium and was recently a resident Global Visitors Fellow at the Earth and Planets Laboratory at the Carnegie Institution for Science. Additionally, at RPI Dr. Rogers serves on the Faculty Senate and is appointed in the Institute for Data Exploration and Applications. Dr. Rogers, whose PhD in Earth and planetary sciences is from Washington University in St. Louis, was a member of the National Academies' Committee on Astrobiology Science Strategy for the Search for Life in the Universe.

WILLIAM F. BOTTKE is the executive director of the Science Directorate of the Solar System Science and Exploration Division at the Southwest Research Institute (SwRI). Dr. Bottke was a member of NASA's OSIRIS-REx mission and is a science team member of NASA's Lucy, Psyche, and NEO Surveyor missions. Dr. Bottke's research is broadly focused on the formation and bombardment history of planetesimals, planets, and satellites; the origin and evolution of small body populations throughout the solar system; and the evolution of near-Earth objects from their source regions in various asteroid and cometary populations to their observed orbits. Dr. Bottke is the director of the Center for Lunar Origin and Evolution of NASA's Solar System Exploration Research Virtual Institute. He was the first recipient of the Paolo Farinella Prize. Dr. Bottke delivered the 2015 Shoemaker Lecture for the American Geophysical Union (AGU) and the 2017 Kavli Lecture at the 229th American Astronomical Society meeting. Dr. Bottke has also been named a fellow of both the Meteoritical Society and AGU. He earned a PhD in planetary science from the University of Arizona. Dr. Bottke was a member of the National Academies' Committee on Planetary Science and Astrobiology Decadal 2023–2032: Panel on Small Solar System Bodies.

CAROLYN A. CROW is an assistant professor in the Department of Geological Sciences at the University of Colorado Boulder. Prior to moving to Boulder, Dr. Crow was a postdoctoral researcher at Lawrence Livermore National Laboratory. Dr. Crow's research focuses on understanding the evolution of planetary crusts through geochemical analyses of samples, with particular focus on the timing and process of impact cratering. Dr. Crow has worked with samples ranging from lunar rocks returned by Apollo astronauts, martian and lunar meteorites, and samples from terrestrial impact structures. Dr. Crow earned a PhD in geochemistry from the University of California, Los Angeles, as a NASA Earth and Space Sciences Fellow.

ORLANDO FIGUEROA is the president of Orlando Leadership Enterprise, LLC, which focuses on providing expert advice in space mission systems and technology, organization and enterprise/program management, strategic planning, and team and leadership development. Mr. Figueroa retired from NASA after serving as the director of applied engineering and technology at the Goddard Space Flight Center (GSFC), the deputy center director of science and technology at GSFC, and the NASA deputy associate administrator for Science Mission Directorate. Mr. Figueroa was named the 2005 Service to America Federal Employee of the Year and was awarded the 2008 Smithsonian Institution Latino Center Legacy Award, the 2010 NASA Distinguished Service Medal, the 2016 National Space Society Pioneer Award, and the Senior Executive Service President Rank Award. He earned a BS in mechanical engineering from the University of Puerto Rico, Mayaguez. Mr. Figueroa served on the National Academies' Committee on Planetary Science and Astrobiology Decadal Survey 2023–2032 and the Committee on Increasing Diversity and Inclusion in the Leadership of Competed Space Missions.

ABIGAIL A. FRAEMAN is a research scientist at the Jet Propulsion Laboratory, a visiting associate at the California Institute of Technology, a deputy project scientist for the Mars Science Laboratory, a former deputy project scientist for the Mars Exploration Rover mission, and a former co-investigator for the Compact Reconnaissance Imaging Spectrometer for Mars. Dr. Fraeman's research focuses on the history and evolution of Mars, Phobos, and Deimos, and reflectance spectroscopy from the macro- to micro-scale. Dr. Fraeman holds multiple NASA Group Achievement Awards, the NASA Early Career Award, and the NASA Early Career Public Achievement Medal. She earned a PhD in Earth and planetary sciences from the Washington University in St. Louis as a National Science Foundation (NSF) Graduate Research Fellow. Dr. Fraeman was a member of the National Academies' Committee on Planetary Protection Requirements for Sample-Return Missions from Martian Moons.

TIMOTHY L. GROVE is the Robert R. Shrock Professor of Earth and Planetary Sciences at the Massachusetts Institute of Technology (MIT). Dr. Grove's research is focused on the processes that have led to chemical evolution of the Earth and other planets, including the Moon, Mars, Mercury, and meteorite parent bodies, a topic he studies by combining field, petrologic, and geochemical studies of igneous rocks with high-pressure and high-temperature experimental petrology. Dr. Grove is recognized for important contributions to understanding magma generation on Earth, other planets, and early formed planetesimals. Before being appointed to the faculty at MIT, he served in teaching and research roles at Harvard University; the State University of New York, Stony Brook; and the California Institute of Technology and as a visiting scientist at the University of Cape Town, a research scientist at the University of Zimbabwe (Harare), a visiting professor at ETH Zürich, and a guest professor at the University of Lausanne. Dr. Grove is a recipient of the Harry H. Hess Medal from AGU and the V.M.

Goldschmidt Award from the Geochemical Society, is a member of the National Academy of Sciences, and has been named a fellow of the Geochemical Society, AGU, and the Mineralogical Society of America. His PhD in geology was awarded by Harvard University. Dr. Grove served as the chair of the National Academies' Panel on Mercury and the Moon for the Planetary Sciences and Astrobiology Decadal Survey 2023–2032 and as an ex officio member of the U.S. National Committee for the International Union of Geodesy and Geophysics.

BRANDON C. JOHNSON is a professor at Purdue University in the Department of Earth, Atmospheric, and Planetary Sciences, whose research focuses mainly on impact cratering and impact processes in the evolution of planets, moons, and asteroids. This research extends to the study of the geophysics of planets and the various processes that modify planetary surfaces, in addition to the early solar system and meteorites, the breakup of comets, and the understanding of the lunar gravity field. Before joining the faculty at Purdue University, Dr. Johnson was a postdoctoral associate at MIT and an assistant professor of Earth, environmental, and planetary sciences at Brown University. Dr. Johnson is the recipient of the Ronald Greeley Early Career Award in Planetary Science from AGU, the Lark-Horovitz Award for outstanding research in physics from Purdue University, and the Nininger Meteorite Award from the Center for Meteorite Studies at Arizona State University. Dr. Johnson earned a PhD in physics from Purdue University.

MELISSA A. MCGRATH is a senior scientist at the SETI Institute. Previously, Dr. McGrath served as the chief scientist at NASA's Marshall Space Flight Center. Her research expertise includes planetary and satellite atmospheres and magnetospheres, particularly imaging and spectroscopic studies of Jupiter's Galilean satellites. Dr. McGrath is currently a co-investigator on the Ultraviolet Spectrometer instrument on the European Space Agency JUICE mission to Ganymede, as well as a co-investigator on two instruments for NASA's Europa Clipper mission. Dr. McGrath served as the chair of the American Astronomical Society's Division for Planetary Sciences; served as the president of the International Astronomical Union's Commission 16 (Physical Studies of Planets and Satellites); and is a scientific editor for the American Astronomical Society journals *The Astrophysical Journal*, *The Astronomical Journal*, *The Astrophysical Journal Letters*, and *The Astrophysical Journal Supplement*. Dr. McGrath has been awarded the NASA Exceptional Service Medal, the NASA Superior Accomplishment Award, and the NASA Ames Honor Award in Lunar Science. She earned a PhD in astronomy from the University of Virginia.

JOSEPH G. O'ROURKE is an assistant professor at the School of Earth and Space Exploration (SESE) and an affiliated faculty member of the Interplanetary Initiative at Arizona State University (ASU). Dr. O'Rourke's research focuses on the interior dynamics in planetary bodies made of metal, rock, and ice; on the application of solar system discoveries to exoplanet characterization; and on the mission and instrument development for spacecraft exploration. He was formerly an SESE Exploration Postdoctoral Fellow at ASU and a postdoctoral scholar in planetary science at the California Institute of Technology. Dr. O'Rourke has received the Antarctica Service Medal and was a finalist of the Hertz Foundation Fellowship. He earned a PhD in planetary science as an NSF Graduate Research Fellow. Dr. O'Rourke served as a member of the National Academies' Planetary Science and Astrobiology Decadal Survey 2023–2032: Panel on Venus.

EDGARD G. RIVERA-VALENTÍN is a senior planetary scientist at the Johns Hopkins University Applied Physics Laboratory. Dr. Rivera-Valentín's research focuses on applications for planetary protection policies and planetary defense strategies. He studies surface processes with implications for planetary habitability and uses ground- and space-based radar observations to characterize asteroids and planetary surfaces. Dr. Rivera-Valentín was a planetary scientist at the Lunar and Planetary Institute and a planetary radar astronomer at the Arecibo Observatory in Puerto Rico, following a postdoctoral research appointment at Brown University. Dr. Rivera-Valentín was named a NASA Early Career Fellow by the

NASA Planetary Science Division in 2016, and the asteroid 2010 ER87 is now officially designated as 389478 Rivera-Valentín. He earned a PhD in space and planetary sciences from the University of Arkansas and was recognized as a Doctoral Academy Fellow. Dr. Rivera-Valentín serves as the science editor of the American Astronomical Society's *Planetary Science Journal* and has served on the National Academies' Planetary Science and Astrobiology Decadal 2023–2032: Panel on Small Solar System Bodies.

ORENTHAL J. TUCKER is the associate lab chief of the Planetary Magnetospheres Lab (Code 695) in the Sciences and Exploration Directorate at GSFC. Dr. Tucker's research interests include understanding how dynamics at the molecular level affects planets and planetary materials, which includes developing and carrying out molecular-level simulations to model gas flows on planetary bodies and describing radiation effect in solids. At GSFC, Dr. Tucker has been a co-investigator on the Solar System Exploration Research Virtual Institute's Dynamic Response of the Environments at Asteroids, the Moon, and moons of Mars and Lunar Environment and Dynamics for Exploration Research science teams investigating dynamics of the lunar exosphere, and he is a co-lead of the Exosphere Ionospheres Magnetospheres Modeling theme at GSFC. Previously, Dr. Tucker was a research scientist at the University of Virginia and the University of Michigan and served as a member of the Cassini Plasma Spectrometer science team developing and using numerical models to examine dynamics of the atmospheres of Titan, Enceladus, and Saturn's rings. He is a recipient of NASA's Susan Mahan Niebur and Robert H. Goddard Science awards and the University of Virginia's Robert A. Bland Award. Dr. Tucker was a participant in the CAS-NAS Third Forum for New Leaders in Space Science in 2015 and earned a PhD in engineering physics from the University of Virginia.

ROBIN D. WORDSWORTH is the Gordon McKay Professor of Environmental Science and Engineering and a professor of Earth and planetary sciences at Harvard University. Dr. Wordsworth's research interests include planetary climate and climate evolution, astrobiology and planetary habitability, and atmospheric physics and chemistry. Dr. Wordsworth leads the Planetary Climate and Atmospheric Evolution Research Group at Harvard University, which focuses on understanding the evolution of solar system and exoplanet atmospheres and climates. Past work of the Wordsworth group has included studies of Mars' early climate during warm and wet episodes, snowball and hothouse climates in Earth's distant past, the link between ultraviolet radiation and life, and the detectability of water and life on exoplanets. Wordsworth is a recipient of an NSF CAREER award. Dr. Wordsworth earned a doctorate in physics from the University of Oxford and served as a member on the National Academies' Planetary Science and Astrobiology Decadal Survey 2023–2032: Panel on Mars.

## STAFF

DANIEL NAGASAWA, *Study Director*, joined the Space Studies Board (SSB) in July 2019 and is a program officer. Before joining the SSB, he was a graduate research assistant specializing in stellar astrophysics, measuring the abundance of elements in the atmospheres of very old, metal-poor stars. Dr. Nagasawa began his research career as an undergraduate research assistant for the Cryogenic Dark Matter Search. When he began graduate school, he transitioned to designing and evaluating astronomical instrumentation, specifically ground-based spectrographs. He went on to specialize in high-resolution stellar spectroscopy and applied these techniques on stars in ultra-faint dwarf satellite galaxies of the Milky Way to study the chemical history of the Galaxy as part of the Dark Energy Survey (DES). He also developed skills in education and public outreach by teaching an observational astronomy course and writing for an outreach initiative for DES. Dr. Nagasawa earned his PhD in astronomy and MS in physics at Texas A&M University and his BS in physics with a concentration in astrophysics from Stanford University.

MEGAN CHAMBERLAIN joined the SSB and the Aeronautics and Space Engineering Board (ASEB) as a senior program assistant in September 2019. Ms. Chamberlain began her career at the National Academies in 2007 working for the Transportation Research Board in the Cooperative Research Program. She has assisted with meeting facilitation and administrative support of hundreds of research projects over the course of her career. Chamberlain attended the University of the District of Columbia and majored in psychology.

COLLEEN N. HARTMAN joined the National Academies in 2018 as the director for both the SSB and the ASEB. After beginning her government career as a presidential management intern under Ronald Reagan, Dr. Hartman worked on Capitol Hill for House Science and Technology Committee Chair Don Fuqua, as a senior engineer building spacecraft at NASA GSFC, and as a senior policy analyst at the White House. She has served as the planetary division director, deputy associate administrator, and acting associate administrator at NASA's Science Mission Directorate, as the deputy assistant administrator at the National Oceanic and Atmospheric Administration, and as the deputy center director and director of science and exploration at GSFC. Dr. Hartman has built and launched scientific balloon payloads, overseen the development of hardware for a variety of Earth-observing spacecraft, and served as the NASA program manager for dozens of missions, the most successful of which was the Cosmic Background Explorer (COBE). Data from the COBE spacecraft gained two NASA-sponsored scientists the Nobel Prize in physics in 2006. She also played a pivotal role in developing innovative approaches to powering space probes destined for the solar system's farthest reaches. While at NASA Headquarters, she spearheaded the selection process for the New Horizons probe to Pluto. She helped gain administration and congressional approval for an entirely new class of funded missions that are competitively selected, called "New Frontiers," to explore the planets, asteroids, and comets in the Solar System. She has several master's degrees and a PhD in physics. Dr. Hartman has received numerous awards, including two prestigious Presidential Rank Awards.