THE PLANETARY SCIENCE AND ASTROBIOLOGY DECADAL SURVEY

Statement of

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The National Academies of Sciences, Engineering, and Medicine

before the

Subcommittee on Space and Aeronautics
Committee on Science, Space, and Technology
U.S. House of Representatives

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Good morning Chairman Beyer, Ranking Member Babin, and members of the Subcommittee. My name is Robin Canup, and I am Assistant Vice President of the Planetary Science Directorate at Southwest Research Institute. I served as co-chair of the National Academies of Sciences, Engineering, and Medicine's Decadal Survey in Planetary Science and Astrobiology. We are deeply appreciative of the opportunity to speak to you about our Decadal Report, "Origins, Worlds, and Life".

A Prior Decade of Unprecedented Success and Continued US Leadership in Space Exploration

Ten years ago, Dr. Steven Squyres came here and argued for an ambitious program of planetary exploration. Thanks to the generosity of Congress, that program became a reality and has ushered in the past decade of unprecedented success. Collection of samples at Mars for return to Earth and Europa Clipper, the top priority large (Flagship) missions from the prior decadal survey, are now underway, and will revolutionize our understanding of the early habitable martian environment, and of the habitability of an icy ocean world. These have been accompanied by a vibrant program of small and medium missions, as well as new partnerships between NASA and the private sector that are increasing access to space and its affordability.

Against this backdrop of incredible accomplishments, and with awareness of efforts being undertaken by other space agencies around the world, we put forth an aspirational plan for the next decade to ensure groundbreaking scientific advances and our nation's continued leadership in solar system exploration.

Priority Science Questions: The Motivating Rationale for Planetary Science and Astrobiology

We began our task by defining the most important scientific questions that motivate our endeavors, which fall within three scientific themes.

The first theme, "Origins", addresses how the primordial disk of gas and solids that orbited our young Sun evolved to yield the outer giant planet systems and Kuiper belt objects, and the inner asteroids and terrestrial planets, including the Earth-Moon system.

The second theme, "Worlds and Processes", considers ongoing gravitational interactions and bombardment; the interiors and surfaces of solid planets as well as their atmospheres and climates; the properties of gas-dominated Jupiter and Saturn and the ice giants Uranus and Neptune; and the many diverse systems of moons and rings.

The third theme, "Life and Habitability", addresses how life on Earth emerged and evolved; the existence of habitable environments across our solar system; and the central question of whether life formed elsewhere and how to detect evidence of it.

Related to all three themes is the study of planets orbiting other stars, which can help us better understand whether Earthlike planets are common or rare in the universe.

Insuring the Vitality and Success of NASA's Most Valuable Resource: Its People

Answering such fundamental questions requires a highly-skilled and creative workforce. Broad access and participation, as well as equitable processes, are needed to recruit, retain, and nurture the best talent to work in our field. Our report makes numerous recommendations to enhance diversity, equity, inclusion and accessibility in our profession, including actions to minimize the effects of bias in processes, enhance outreach to underrepresented communities, and to foster respectful work environments.

Research and Analysis: The Foundation for the Advancement of Knowledge

Basic Research & Analysis provides the intellectual foundation to ensure NASA's activities are optimized to advance scientific knowledge. The openly-competed R&A programs support broad access into our profession, and their highly competitive nature drives innovation. While NASA's planetary program has grown substantially in the past decade, the per-year fractional investment in R&A activities has decreased, from nearly 15% in 2013 to less than 8% currently. *It is essential to the continued success of the nation's planetary and astrobiology program that this trend be reversed, and that a minimum of 10% of the annual program be invested in R&A activities*.

Importance and Priority of Mars Sample Return

The committee reaffirms the scientific and strategic importance of Mars Sample Return (MSR), and recommends that it be completed as soon as is practically possible as the highest priority of NASA's robotic exploration efforts. We provide specific guidance to ensure that the level of investment in MSR remains consistent with long-term programmatic balance across NASA's planetary portfolio.

The Pivotal Role of Science in Human Exploration

One of the most exciting recommendations in our report involves increased cooperation between NASA's science and human exploration endeavors. The Artemis program calls for landing humans on the Moon within the 2020s, with increasingly sustained operations on the lunar surface. *The committee strongly supports the visionary Artemis program, and argues that it is imperative that it be accompanied by a similarly visionary scientific program.* To not do so would be a missed opportunity for NASA and the nation that would undermine the tremendous potential value of the Artemis program.

The Endurance-A Mission: A ground-breaking robotic-human partnership to achieve transformative science at the Moon

To this end, the committee prioritizes a transformative robotic-human partnership: the Endurance-A lunar rover mission. This rover would complete a 1000-km traverse across the South Pole Aiken basin on the Moon's far side, collecting 100 kg of samples to address the highest priority science objectives. Endurance-A would then deliver these samples to a location on the lunar surface for return to Earth by Artemis astronauts.

The Endurance-A mission would revolutionize our understanding of the Moon and the history of the early solar system that is recorded in its most ancient impact basin. Its sample set would provide a lasting legacy for future generations. We recognize the challenges of integrating science into human exploration plans, but find that overcoming such challenges is strongly justified by the tremendous value of human-robotic partnerships to the agency and nation. We make numerous recommendations to assist NASA in this endeavor.

Thank you for the invitation to testify. I will be happy to answer any questions the Subcommittee might have.

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

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

STATE OF PROFESSION

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

The committee's eight SoP recommendations address:

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

TABLE S.1 The Twelve Priority Science Question Topics

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

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

MISSION CLASSES, BALANCE, AND ONGOING ACTIVITIES

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

Currently operating PSD spacecraft include the ongoing Mars orbiter missions, Curiosity and Perseverance Mars rovers; the Lunar Reconnaissance Orbiter; the InSight and Lucy Discovery missions; and the New Horizons, Juno, and OSIRIS-REx New Frontiers (NF) missions. Missions in development include four small SIMPLEx missions, the Psyche, DAVINCI, and VERITAS Discovery missions, the Dragonfly NF mission, and the Europa Clipper large strategic mission. NASA also contributes to international missions (e.g., ESA's BepiColombo, JUICE, and EnVision and JAXA's MMX). The committee strongly supports (1) continuation of these missions and contributions in their current operational or development phases and (2) the Senior Review process for evaluating the merit of additional extended mission phases.

MARS SAMPLE RETURN

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

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

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

MARS EXPLORATION PROGRAM

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

Recommendation: NASA should maintain the Mars Exploration Program, managed within the PSD, that is focused on the scientific exploration of Mars. The program should develop and execute a comprehensive architecture of missions, partnerships, and technology development to enable continued scientific discovery at Mars.

Recommendation: Subsequent to the peak-spending phase of Mars Sample Return, the next priority medium-class mission for the Mars Exploration Program should be Mars Life Explorer.

LUNAR DISCOVERY AND EXPLORATION PROGRAM

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

[1] All dollar amounts are real-year dollars unless otherwise indicated.
[2] The full Mars Life Explorer mission study report is available at https://tinyurl.com/2p88fx4f.

priority science. A structured, science-led approach to setting goals and measurement objectives for the Moon is needed for LDEP and to provide scientific requirements for Artemis.

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

Recommendation: The advancement of high-priority lunar science objectives, as defined by 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. Design and implementation of an integrated plan responsive to both NASA's human exploration and science directorates, with separately appropriated funding lines, presents management challenges; however, overcoming these is strongly justified by the value of human-scientific and human-robotic partnerships to the agency and the nation.

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

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

RESEARCH AND ANALYSIS

Robotic solar system exploration is driven by the desire to increase knowledge. Strong, steady investment in research and analysis (R&A) is needed to ensure (1) maximal return from mission data; (2) that data drives improved understanding and novel, testable hypotheses; (3) that advances feed into future mission development; and (4) training a diverse workforce. The fraction of PSD's budget devoted to R&A has decreased from 14 percent in 2010 to a projected 7.7 percent by FY23. It is essential to the nation's planetary science efforts that this trend be reversed. The openly competed R&A programs drive innovation, provide rapid response to new discoveries, identify the most meritorious ideas, and attract new and increasingly diverse investigators.

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

PLANETARY DEFENSE

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

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

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

DISCOVERY PROGRAM

The Discovery program supports relatively frequent missions that address any science achievable within a specified cost cap, with a central goal to maximize innovative science per total mission cost. The program has made fundamental contributions to planetary exploration and the committee strongly supports its continuation. The committee assessed the cost cap and structure needed to (1) address decadal-level science[3] questions, (2) more clearly anticipate mission life-cycle cost, and (3) maximize science return per dollar.

Recommendation: The Discovery Phase A through F cost cap should be $800 million in fiscal year 2025 dollars, exclusive of the launch vehicle, and periodically adjusted throughout the decade to account for inflation. This cap will enable the Discovery Program to continue to support missions that address high-priority science objectives, including those that can reach the outer solar system.

NEW FRONTIERS PROGRAM

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

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

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

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

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

Recommendation: The New Frontiers (NF) Phase A-F cost cap, exclusive of quiet cruise phase and launch vehicle costs, should be increased to $1.65 billion in fiscal year 2025 dollars. A quiet cruise allocation of $30 million per year should be added to this cap, with quiet cruise to include normal cruise instrument checkout and simple flyby measurements, outbound and inbound trajectories for sample return missions, and long transit times between objects for multiple-target missions.

NEW FRONTIERS MISSIONS

The committee considered a broad range of medium-class missions, and from these prioritized the following eight mission themes (in no specific order) for the New Frontiers 6 (NF-6) call:

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

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

- Triton Ocean World Surveyor

Theme descriptions are provided in the Report.

NEW LARGE MISSIONS

The committee prioritizes the Uranus Orbiter and Probe (UOP) as the highest-priority new Flagship mission for initiation in the decade 2023-2032. UOP will deliver an in situ atmospheric probe and conduct a multi-year orbital tour that will transform our knowledge of ice giants in general and the Uranian system in particular. Uranus is one of the most intriguing bodies in the solar system. Its low internal energy, active atmospheric dynamics, and complex magnetic field all present major puzzles. A primordial giant impact may have produced the planet's extreme axial tilt and possibly its rings and satellites, although this is uncertain. Uranus's large ice-rock moons displayed surprising evidence of geological activity in limited Voyager 2 flyby data, and are potential ocean worlds. UOP science objectives address Uranus' (1) origin, interior, and atmosphere; (2) magnetosphere; and (3) satellites and rings. UOP will provide ground-truth relevant to the most abundant, similarly sized class of exoplanets. UOP can launch on an existing launch vehicle. Optimal launch opportunities in 2031 and 2032 utilize a Jupiter gravity assist to shorten cruise time; other opportunities from 2032 through 2038 (and beyond) utilize inner solar system gravity assists with an increased cruise time.

The second- highest priority new Flagship mission is the Enceladus Orbilander.[4] Enceladus is an ice-rock world with active plumes of gas and particles that originate from its subsurface ocean. Study of plume material allows direct study of the ocean's habitability, addressing a fundamental question: is there life beyond Earth and if not, why not? Orbilander will analyze fresh plume material from orbit and during a 2-year landed mission. Its main science objectives are: (1) to search for evidence of life; and (2) to obtain geochemical and geophysical context for life detection experiments. Commencing Orbilander late in the decade supports arrival at Enceladus in the early 2050s when optimal illumination of the south polar region begins. Should budgetary constraints not permit initiation of Orbilander, the committee includes the Enceladus Multiple Flyby (EMF) mission theme in NF. EMF provides an alternative pathway for progress this decade on the crucial question of ocean world habitability, albeit with greatly reduced sample volume, higher velocity of sample acquisition and associated degradation, and a smaller instrument component to support life-detection.

REPRESENTATIVE FLIGHT PROGRAMS

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

The two programs differ in their support for new initiatives. The *Recommended Program* is aspirational and inspirational: it enables robust development of diverse science and engineering communities, drives technology development, and maintains U.S. leadership in solar system exploration. It begins the UOP Flagship in FY 2024 to support a launch in the early 2030s that minimizes cruise length and complexity and initiates the Orbilander Flagship late in the decade to reveal the astrobiological conditions of an ocean world. It also restores the *Vision and Voyages* recommendation, endorsed by the committee, for two NF missions per decade, with NF-5 (which was to be the second NF mission from the prior decade) completed early in the decade, followed

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

by a mid-decade selection of two NF missions in NF-6. The Mars Life Explorer would be initiated late in the decade through the Mars Exploration Program.

TABLE S.2 Comparison of Representative Programs

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

MISSION TRACEABILITY TO SCIENCE GOALS

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

KEY ADDITIONAL RECOMMENDATIONS

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

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

Recommendation: NASA’s Planetary Science Division (PSD) should strive to consistently fund technology advancement at an average of 6 to 8 percent of the PSD budget.

TABLE S.3 Mission Portfolio Assessment Matrix

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

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


The National Academies of
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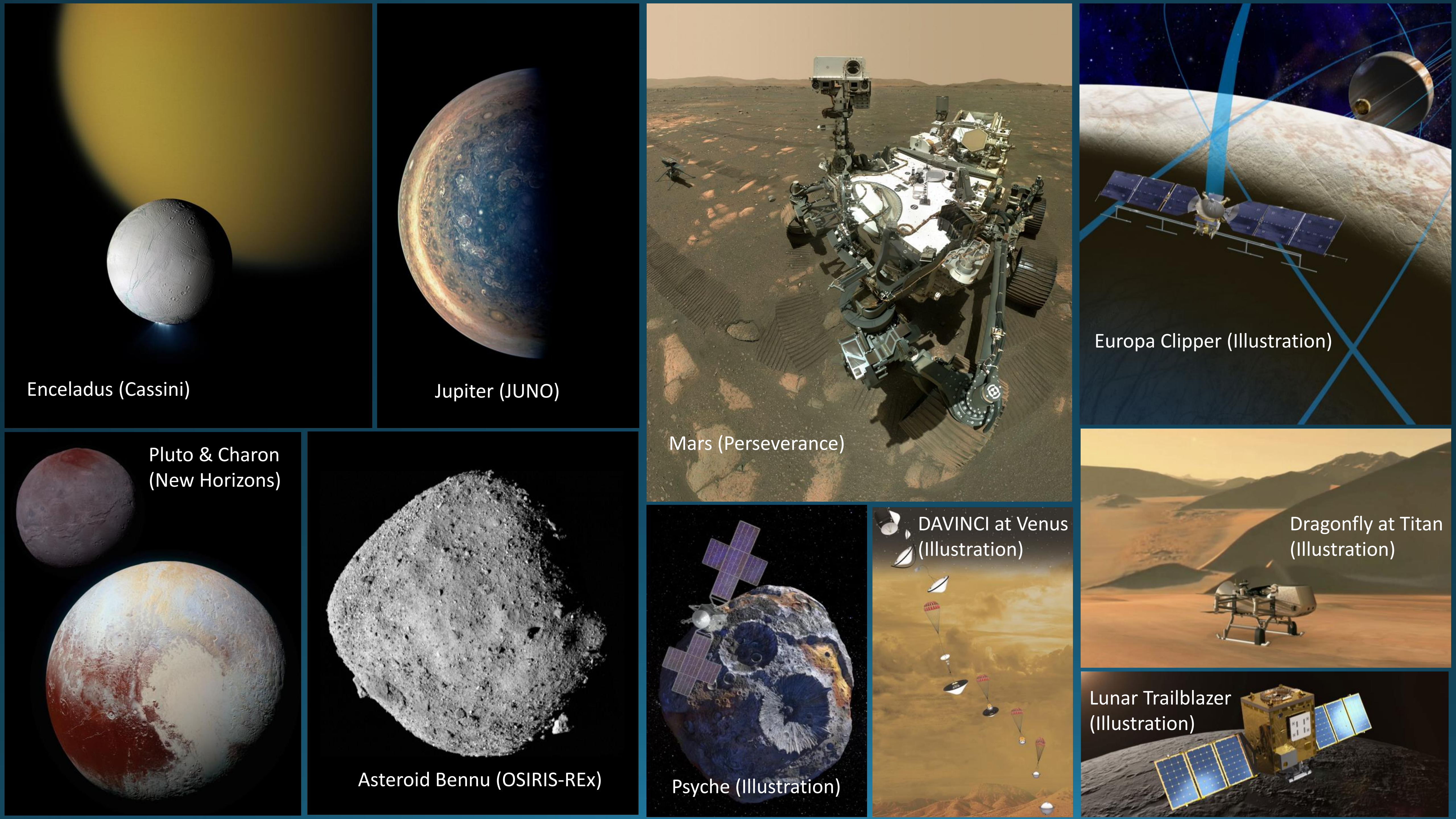
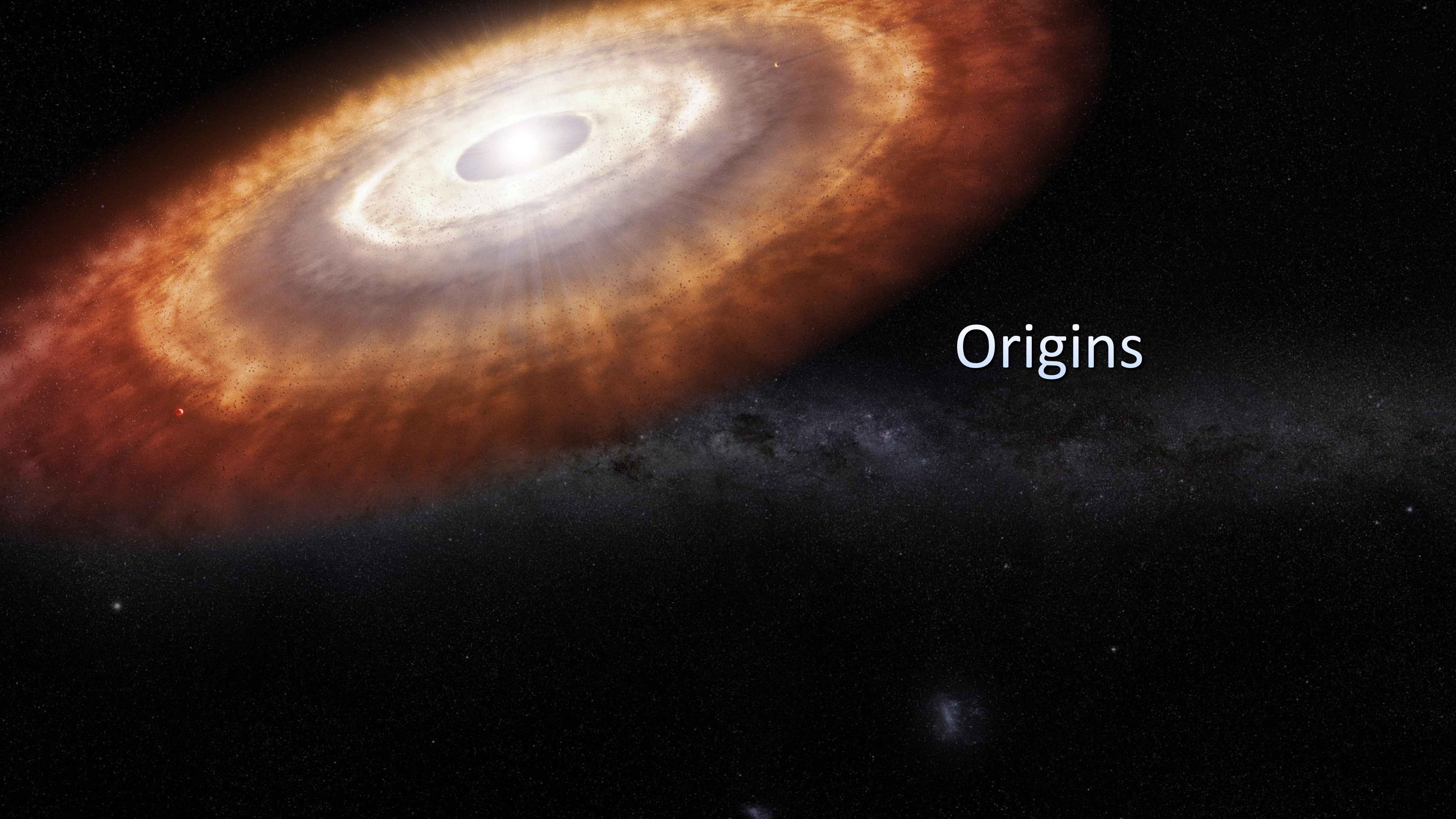
ORIGINS, WORLDS, AND LIFE
A Decadal Strategy for Planetary Science & Astrobiology
2023–2032


Enceladus (Cassini)
Jupiter (JUNO)
Mars (Perseverance)
Europa Clipper (Illustration)
Pluto & Charon
(New Horizons)
Asteroid Bennu (OSIRIS-REx)
Psyche (Illustration)
DAVINCI at Venus
(Illustration)
Dragonfly at Titan
(Illustration)
Lunar Trailblazer
(Illustration)

Origins



Worlds & Processes

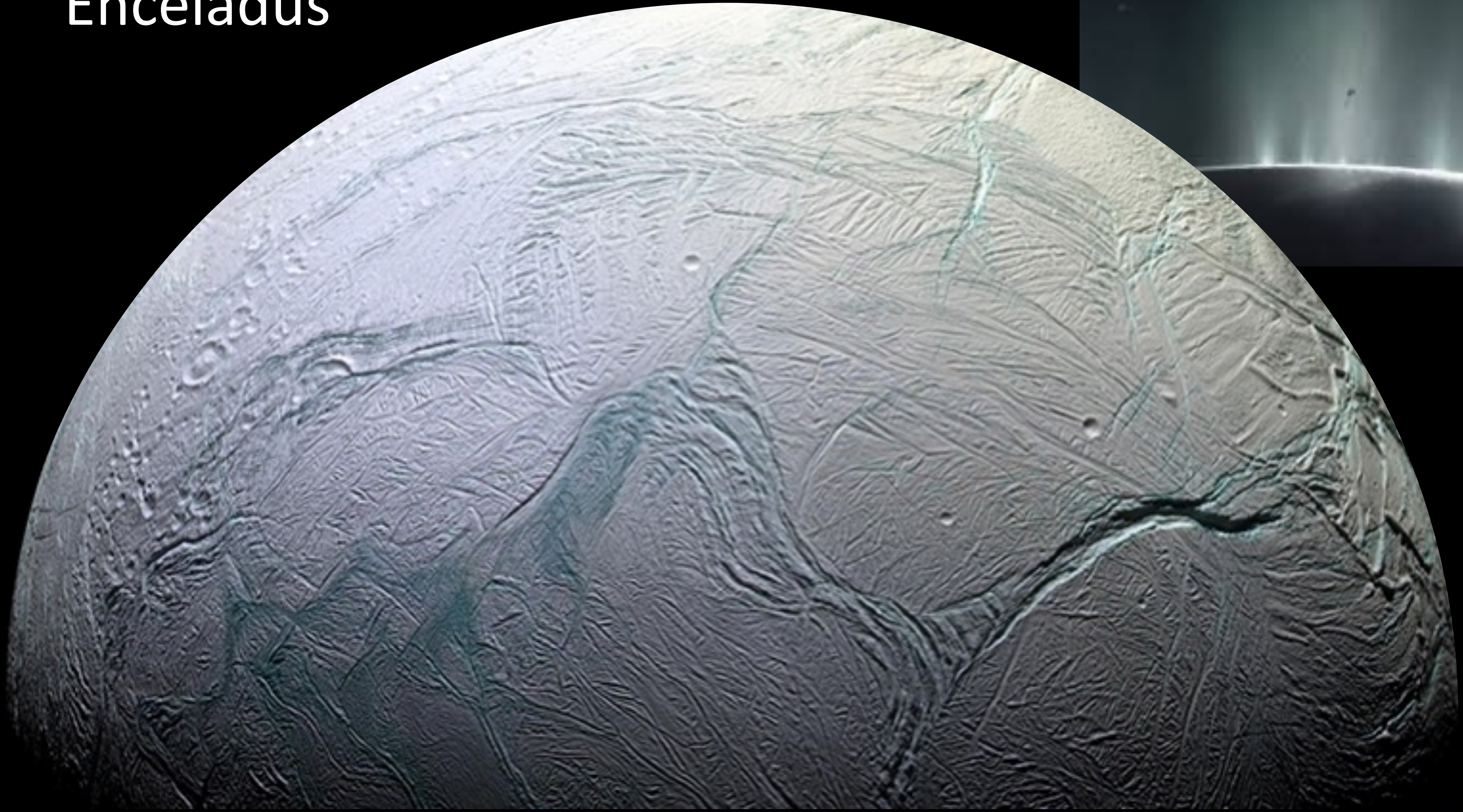

Life & Habitability


Endurance
National Aeronautics and
Space Administration
NASA

Uranus

Moons

Enceladus



Mission themes

- Centaur Orbiter and Lander
- Ceres sample return
- Comet surface sample return
- Enceladus multiple flyby
- Lunar Geophysical Network
- Saturn probe
- Titan orbiter
- Venus In Situ Explorer
- Triton Ocean World Surveyor

Double Asteroid
Redirect Mission


The National Academies of
SCIENCES · ENGINEERING · MEDICINE
ORIGINS, WORLDS, AND LIFE
A Decadal Strategy for Planetary Science & Astrobiology
2023–2032

ROBIN M. CANUP (NAS) is Assistant Vice President at Southwest Research Institute where she leads the Planetary Sciences Directorate in Boulder, Colorado. Dr. Canup is a theoretician that studies the formation and early evolution of planets and their moons. She has modeled many aspects of the formation of the Moon, including hydrodynamical simulations of lunar-forming giant impacts, the accumulation of the Moon, and its initial composition and orbital evolution. Dr. Canup has also developed models for an impact origin of the satellites of Pluto and Mars. Another major area of her work has addressed the origin of the systems of rings and satellites around the outer giant planets, including models of circumplanetary disk formation during late gas accretion, satellite accretion and migration, giant impacts and early dynamical evolution, and the compositional and interior properties of outer rings and moons.

She was the recipient of the 2003 Urey Prize of the Division of Planetary Sciences and the 2004 Macelwane Medal of the American Geophysical Union, and is a Fellow of the American Geophysical Union.

Dr. Canup was elected to the National Academy of Sciences in 2012, and the American Academy of Arts and Sciences in 2017. She earned her Ph.D. and M.S. in astrophysics and planetary sciences from the University of Colorado, Boulder.

Robin M. Canup
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Employment

Assistant Vice President	Southwest Research Institute	3/19—present
Associate Vice President	Southwest Research Institute	3/10 – 3/19
Institute and Chief Scientist	Southwest Research Institute	03/09 – 3/10
Executive Director	Southwest Research Institute	03/07—3/09
Director	Southwest Research Institute	04/05 – 3/07
Visiting Professor	Division of Geological and Planetary Sciences, California Institute of Technology	01/05 – 4/05
Assistant Director	Southwest Research Institute	09/99 – 4/05
Senior Research Scientist	Southwest Research Institute	03/98 – 09/99
Research Associate	LASP, University of Colorado	05/95 — 2/98

Education

Ph.D., M.S., Astrophysical, Planetary and Atmospheric Sciences	University of Colorado
B.S., Physics	Duke University

Honors and Awards

Stanton J. Peale Lecture, University of California Santa Barbara (2018)
American Academy of Arts and Sciences (2017)
Hertha Sponer Presidential Lecture, Duke University (2014)
National Academy of Sciences (2012)
Masursky Lecture, Lunar and Planetary Sciences Conference (2011)
Asteroid 17836 Canup
Brilliant 10, Popular Science magazine (2004)
Fellow of the American Geophysical Union (2004)
James B. Macelwane Medal of the American Geophysical Union (2004)
Harold C. Urey Prize of the Division of Planetary Sciences of the AAS (2003)

Selected Publications

Rufu, R., and Canup, R. M. 2022. *Coaccretion + Giant Impact Origin of the Uranus System: Tilting Impact*. **Astrophys J**., in press.

Salmon, J., and Canup, R. M. 2022. *Coaccretion + Giant Impact Origin of the Uranus System: Post-impact Evolution*. **Astrophys J**.

Canup, R.M., Righter, K., Dauphas, N., Pahlevan, K., Cuk, M., Lock, S. J., Stewart, S. T., Salmon, J., Rufu, R., Nakajima, M. and T. Magna. 2022 *Origin of the Moon.* To appear in **New Views of the Moon II**, Reviews in Mineralogy and Geochemistry.

Canup, R. M., Kratter, K. M., and Neveu, M. 2021. *On the Origin of the Pluto System.* In **The Pluto System after New Horizons**, Space Science Series, Univ. of Az. Press.

Rufu, R. and Canup, R. M. 2020. *Tidal evolution of the Evection Resonance/Quasi-resonance and the Angular Momentum of the Earth-Moon System.* **Journal Geophys. Res**., 125, e06312.

Ward, W. R., Canup, R. M. and Rufu, R. 2020. *Analytical model for the tidal evolution of the evection resonance and the timing of resonance escape.* **Journal Geophys. Res**., 125, e06266.

Marchi, S., Walker, R. J., and Canup, R. M. 2020. *A compositionally heterogeneous martian mantle due to late accretion*. **Science Advances**, 6.

Salmon, J. and Canup, R. M. 2019. *HydroSyMBA: A 1D Hydrocode Coupled with an N-body Symplectic Integrator*. **Astrophys. J**., 881, 13pp.

Marchi, S., Canup, R. M., and Walker, R. J. 2018. *Heterogeneous delivery of silicate and metal to the Earth by large planetesimals*. **Nature Geoscience**, 11, 77-81.

Canup, R. M. and Salmon, J. 2018. *Origin of Phobos and Deimos by the impact of a Vesta-to-Ceres sized body with Mars*. **Science Advances** 4.

Charnoz, S., Canup, R. M., Crida, A., and Dones, L. 2018. *The origin of planetary ring systems.* In **Planetary Ring Systems. Properties, Structure, and Evolution**, Edited by M.S. Tiscareno and C.D. Murray. ISBN: 9781316286791. Cambridge University Press, pp. 517-538

Rufu, R. and R. M. Canup, 2017. *Triton's evolution with a primordial Neptunian satellite system*. **Astron. J**. 154, No. 208, 8 pp.

Salmon, J., and R. M. Canup, 2017. *Accretion of Saturn's mid-sized moons from a massive primordial ice ring*. **Astrophys. J**., 836, 19 pp.

Canup, R. M., Visscher, C., Salmon, J., and B. Fegley, Jr., 2015. *Lunar volatile depletion due to incomplete accretion within an impact-generated disk.* **Nature Geoscience** 8, 918-921.

Peale, S. and R. M. Canup, 2015. *The Origin of the Natural Satellites.* In **Treatise on Geophysics**, 2nd edition, Vol 10., Gerald Schubert (editor-in-chief) Oxford: Elsevier; pp. 559-604.

Canup, R. M., 2015. *The Moon's tilt for gold.* **Nature** 527, 455-456.

Canup, R. M., 2015. *An incredible likeness of being*. **Nature** 520, 169-170.

Canup, R. M., 2014. *Lunar-forming impacts: Processes and alternatives*. **Phil. Trans. Roy. Society A.**, 372: 20130175, 1-14.

Salmon, J. and R. M. Canup, 2014. *Lunar accretion from non-canonical disks*. **Phil. Trans. Roy. Society A**., 372: 20130256, 1-14.

Canup, R. M., 2013. *Lunar conspiracies*. **Nature** 504, 27-30.

Canup, R. M., 2013. *Modification of the rock content of the inner Saturnian satellites by an outer Solar System LHB.* **44th LPSC**, 2298.

Ward, W. R. and R. M. Canup, 2013. *The evection resonance and the angular momentum of the Earth-Moon system*. **44th LPSC**, 3029.

Canup, R. M., A. C. Barr, and D. Crawford, 2013. *High-resolution simulations of Moon-forming impacts with SPH and CTH.* **Icarus** 222, 200-219.

Canup, R. M., 2012. *Forming a Moon with an Earth-like composition via a giant impact*. **Science**, 338, 1052-1055.

Salmon, J. and R. M. Canup, 2012. *Lunar accretion from a Roche interior disk*. **Astron. J.**, 760, 1-18.

Canup, R. M., 2011. *Conditions in an infall-supplied protoplanetary disk.* **42nd LPSC**, 1245.

Canup, R. M., 2011. *On a giant impact origin of Charon, Nix and Hydra*. **Astron. J.,** 141, 35-44.

Canup, R. M., 2010. *Origin of Saturn's rings and inner moons via mass removal from a lost Titan-sized satellite*. **Nature**, **468**, 943-946.

Ward, W. R. and R. M. Canup, 2010. *Circumplanetary disk formation*. **Astron. J., 140**, 1168-1193.

Barr, A. C., R. I. Citron, and R. M. Canup, 2010. *Origin of a partially differentiated Titan*. **Icarus**, 209, 858-862.

Barr, A. C. and R. M. Canup, 2010. *Origin of the Ganymede/Callisto dichotomy by impacts during the late heavy bombardment*. **Nature Geoscience**, 3 164-167.

Canup, R. M. and W. R. Ward, 2009. *Origin of Europa and the Galilean satellites*. In **Europa**, Univ. Az. Press, Eds., R. Pappalardo, W. McKinnon and K. Khurana, pp. 59-84.

Canup, R. M., 2008. *Accretion of the Earth*. **Phil. Trans. R. Soc. A.**, 366, 4061-4075.

Barr, A. C. and R. M. Canup, 2008. *Constraints on gas giant satellite formation from the interior states of partially differentiated satellites*. **Icarus**, 198, 163-177.

Canup, R. M., 2008. *Lunar forming collisions with pre-impact rotation.* **Icarus**, 196, 518-538.

Canup, R. M. and W. R. Ward, 2006. *A common mass scaling for satellite systems of gaseous planets.* **Nature**, 441 834-839.

Ward, W. R. and R. M. Canup, 2006. *The Obliquity of Jupiter*. **Astrophy. J. Let**, 640, L91-94.

Canup, R. M. and E. Pierazzo 2006. *Retention of water during planet-scale collisions*. **37th LPSC**, 2146.

Ward, W. R. and R. M. Canup, 2006. *Tidal interactions between a planet and a circumplanetary disk*. **37th LPSC**, 2169.

Canup, R. M., 2005. *A Giant Impact Origin of Pluto-Charon*. **Science**, 307, 546-550.

Canup, R. M., 2004. *Formation of the Moon*. **Ann. Revs. Astron. Astrophy**., 42, 441-475.

Canup, R. M., 2004. *Simulations of a late lunar forming impact*. **Icarus** 168, 433-456.

Canup, R. M., 2004. *Origin of terrestrial planets and the Earth-Moon system*. **Physics Today** 57, 56-62.

Canup, R. M. and W. R. Ward, 2002. *Formation of the Galilean satellites: Conditions of accretion.* **Astron. J**., 124, 3404-3423.

Canup, R. M. and E. Asphaug, 2001. *Origin of the Moon in a giant impact near the end of the Earth's formation*. **Nature,** 412, 708-712.

Canup, R. M., W. R. Ward, and A. G. W. Cameron, 2001. *A scaling relationship for satellite-forming impacts.* **Icarus**, 150, 288-296.

Ward, W. R. and R. M. Canup, 2000. *Origin of the Moon's orbital inclination through resonant disk interactions*. **Nature**, 403, 741-743.

Canup, R. M. and W. R. Ward, 2000. *A Hybrid Fluid/N-Body Model for Lunar Accretion*. **31st LPSC.**

Canup, R. M. and C. B. Agnor, 2000. *Accretion of the terrestrial planets and the Earth-Moon system*. In **Origin of the Earth and Moon** (R. M. Canup and K. Righter, Eds.), Univ. of Arizona Press, Tucson.

Kokubo, E., R. M. Canup and S. Ida, 2000. *Lunar accretion from an impact-generated disk.* In **Origin of the Earth and Moon** (R. M. Canup and K. Righter, Eds.), Univ. of Arizona Press, Tucson.

Agnor, C. B., R. M. Canup and H. F. Levison, 1999. *On the character and consequence of large impacts in the late stage of terrestrial accretion.* **Icarus** 142 219-237.

Canup, R. M., H. F. Levison and G. R. Stewart, 1999. *Stability of a terrestrial multiple moon system*. **Astron. J. 117** 603-620.

Ida, S., R. M. Canup and G. R. Stewart, 1997. *Lunar accretion from an impact-generated disk.* **Nature** 389, 353-357.

Canup, R. M. and L. W. Esposito, 1996. *Formation of the Moon from an impact-generated disk*. **Icarus** 119, 427-446.

Canup, R. M. and L. W. Esposito, 1995. *Accretion in the Roche zone: Co-existence of rings and ringmoons*. **Icarus** 113, 331-352.

Canup, R. M., J. E. Colwell and M. Horanyi, 1993. *Size distributions of satellite dust ejecta: Effects of radiation pressure and planetary oblateness*. **Icarus** 105, 363-369.

Selected Professional and Service Activities

Co-Chair, 2023-2032 Planetary Science and Astrobiology Decadal Survey (2020 – present)
NASA Planetary Advisory Council (2018-2020)
Editorial board, Annual Reviews in Earth and Planetary Science (2015- 2018)
J. Lawrence Smith Medal Committee, NAS (2015, 2018);
Class Membership Committee, Class I, NAS (2014, 2017-2019)
AGU Planetary Prize Committee (2010-2014)
AGU Hess Medal Prize Committee (2009 – 2010)
Planetary Science Subcommittee of the NASA Advisory Council (2006 – 2009)
DPS Prize Committee (2007 – 2009)
NSF Astronomy Division's Committee of Visitors (2008)
Editorial board member, *Icarus* (2003 - 2006)
Brouwer Award Committee, Division of Dynamical Astronomy, AAS (2003-2006)
Jupiter Icy Moons Orbiter Science Definition Team (2003-2004)
Committee Member (2001-2003), Division of Dynamical Astronomy
Lead Editor, 'Origin of the Earth and Moon', University of Arizona Space Science Series, 2000

Served as PI on NASA (Origins of Solar Systems, Planetary Geology & Geophysics, Outer Planets Research, Emerging Worlds, NFDAP) and NSF (Planetary Astronomy) grants

Post-doctoral advisor to Dr. R. Rufu (present), Dr. J. Salmon (2011-2016), and Dr. A. Barr (2006-2010).