The National Academies of
SCIENCES · ENGINEERING · MEDICINE

ORIGINS, WORLDS, AND LIFE

Robin Canup and Philip Christensen, Co-chairs

A Decadal Strategy for Planetary Science & Astrobiology
2023–2032

Cover by P. Byrne and J. Tuttle Keane

Purpose of a Decadal Survey

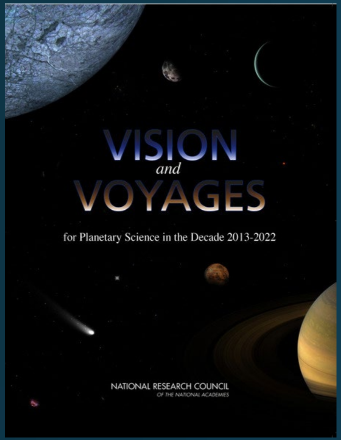
1. Assess the status of an entire scientific discipline
2. Identify key scientific questions to be addressed in the next decade
3. Prioritize the most important initiatives to address these questions
4. Provide Technical Risk and Cost Evaluation (TRACE) for recommended projects/missions
5. Conducted independently by the National Academies for sponsoring agencies

NASA's Planetary Science Division (PSD) and National Science Foundation (NSF)

Sponsoring agencies and Congress view surveys as the formal statement of priority by the US space science community, repeatedly state their intent to give highest priority to the missions identified in the survey

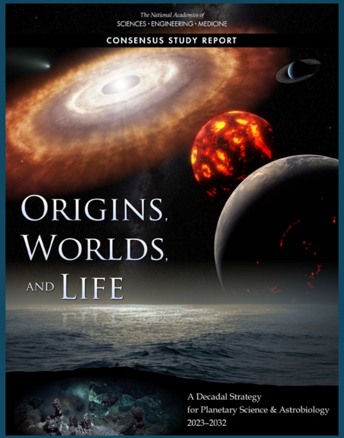
Process driven by the Statement of Task

Instructions to Committee from sponsors (NASA PSD and NSF)



Similarities to prior Decadal:

- Identification of top-level science questions and research activities
- Prioritization of large/medium space missions
- Optimized balance between target bodies, large/medium/small activities
- Infrastructure and technology needs
- Decision rules to accommodate budgetary changes and new discoveries



Key distinctions of this report:

- Consideration of the state of the profession and actions for enhancing diversity, equity, inclusion, and accessibility (DEIA)
- Report organized by significant, overarching scientific questions rather than by destinations
- Greater emphasis on astrobiology
- Inclusion of planetary defense
- Awareness of human exploration plans and identification of cooperation opportunities

Survey and Report Organization

SG + 6 Panels

Steering Group

Moon & Mercury

Venus

Mars

Small Bodies

Ocean Worlds & Dwarf Planets

Giant Planet Systems

Chapters 2-21: priority science questions and key topics, each drafted by a writing group comprised of SG and panel members

Tour of the Solar System: State of Knowledge

Priority Science Questions and Strategic Research

State of Profession

Research & Analysis

Planetary Defense

Human Exploration

Technology

Infrastructure

Highest-level recommendations and prioritizations in Chapter 22

Recommended Program: 2023-2032

- Table 1.2 provides detailed guide of location in report by topic
- About 75 recommendations in total, all within Chapters 16-22

Steering Group

Robin Canup, NAS, co-chair	Southwest Research Institute
Philip Christensen, co-chair	Arizona State University
Mahzarin Banaji, NAS	Harvard University
Steven Battel, NAE	Battel Engineering
Lars Borg	Lawrence Livermore National Laboratory
Athena Coustenis	Paris Observatory
James Crocker, NAE	Lockheed Martin Space Systems, Retired
Brett Denevi	Applied Physics Laboratory
Bethany Ehlmann	California Institute of Technology
Larry Esposito	University of Colorado
Orlando Figueroa	Orlando Leadership Enterprise LLC
John Grunsfeld	Endless Frontiers Associates LLC
Julie Huber	Woods Hole Oceanographic Institution
Krishan Khurana	University of California, Los Angeles
Barbara Sherwood Lollar, NAE	University of Toronto
William McKinnon	Washington University
Francis Nimmo, NAS	University of California, Santa Cruz
Carol Raymond	Jet Propulsion Laboratory
Amy Simon	NASA, Goddard Space Flight Center

NAS: National Academy of Sciences; NAE: National Academy of Engineering

- Leadership group with expertise spanning scientific, technical, policy and programmatic scope
- Formulated top-level prioritizations and recommendations

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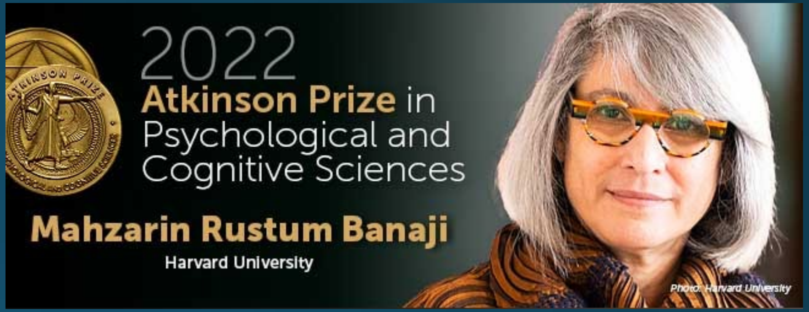
- Leadership group with expertise spanning scientific, technical, policy and programmatic scope
- Included a renown social scientist



For groundbreaking contributions to "establish and quantify the role that unconscious processes play in governing human social actions and judgments of others."

Panels (chairs and vice chairs listed first)

Moon and Mercury	Venus	Mars	Small Bodies	Ocean Worlds & Dwarf Planets	Giant Planet Systems
Tim Grove, NAS	Paul Byrne	Vicky Hamilton	Nancy Chabot	Alex Hayes	Jonathan Lunine, NAS
Brett Denevi	Larry Esposito	Bethany Ehlmann	Carol Raymond	Francis Nimmo, NAS	Amy Simon
James Day	Giada Arney	Will Brinckerhoff	Paul Abell	Morgan Cable	Frances Bagenal, NAS
Alex Evans	Amanda Brecht	Tracy Gregg	Bill Bottke	Alfonso Davila	Richard Dissly
Sarah Fagents	Thomas Cravens	Jasper Halekas	Megan Bruck Syal	Glen Fountain	Leigh Fletcher
Bill Farrell	Kandis Jessup	Jack Holt	Harold Connolly	Chris German	Tristan Guillot
Caleb Fassett	James Kasting, NAS	Joel Hurowitz	Tom Jones	Chris Glein	Matthew Hedman
Jennifer Heldmann	Scott King	Bruce Jakosky	Stefanie Milam	Candice Hansen	Ravit Helled
Toshi Hirabayashi	Bernard Marty	Michael Manga, NAS	Ed Rivera-Valentin	Emily Martin	Kathleen Mandt
James Keane	Thomas Navarro	Hap McSween, NAS	Dan Scheeres, NAE	Marc Neveu	Alyssa Rhoden
Francis McCubbin	Joseph O'Rourke	Claire Newman	Rhonda Stroud	Carol Paty	Paul Schenk
Miki Nakajima	Jennifer Rocca	Miguel San Martin, NAE	Myriam Telus	Lynnae Quick	Michael Wong
Mark Saunders	Alison Santos	Kirsten Siebach	Audrey Thirouin	Jason Soderblom	
Sonia Tikoo-Schantz	Jennifer Whitten	Amy Williams	Chad Trujillo	Krista Soderlund	
		Robin Wordsworth	Ben Weiss		

Each Panel vice chair was also a member of Steering Group

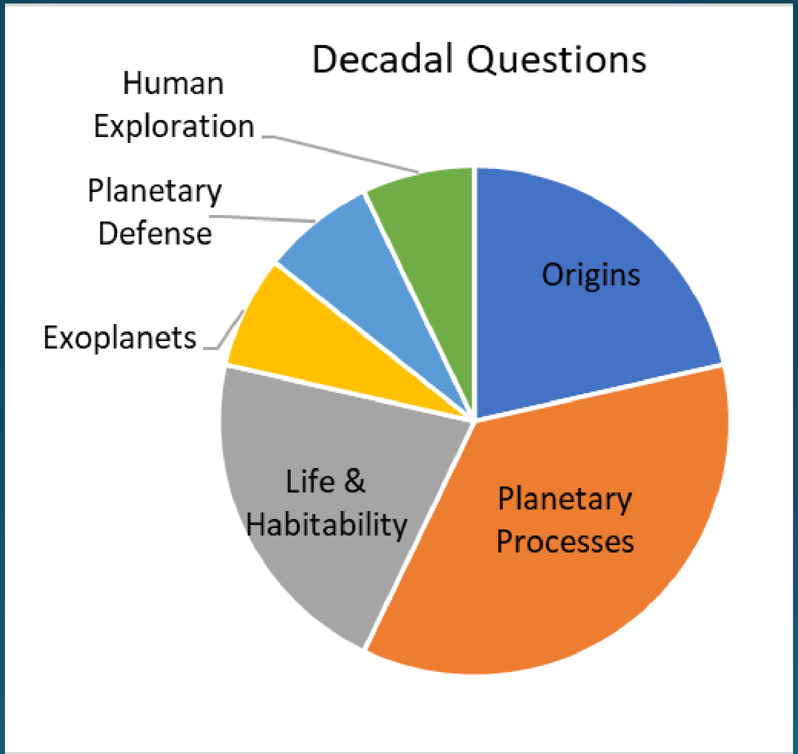
Decadal Process

- > 500 white papers received (summer 2020)
- 153 Panel and 23 steering group meetings (fall 2020 to fall 2021)
  - > 300 presentations by external speakers in open sessions
- Key Milestones:
  - Review of white papers and Planetary Mission Concept Study reports (Fall 2020)
  - Identification of priority science questions (Fall 2020)
  - Definition of 9 additional mission concepts & new study completion (Fall 2020 – Winter 2021)
  - Prioritization of mission concepts for TRACE (Spring 2021)
  - Prioritizations and high-level recommendations (Summer – Fall 2021)
  - Draft report to Academies and external review (November – December 2021)
  - Response to 23 external reviews and final report approval (January – March 2022)

Priority Science Question Development

"Report should … be organized according to the significant, overarching questions in planetary science, astrobiology, and planetary defense"

- First Steering Group (SG) task was to identity the most compelling, overarching questions
- Defined 12 Priority Science Questions across 3 themes + 2 related topics (Human Exploration and Planetary Defense)
- Plot shows distribution by topic



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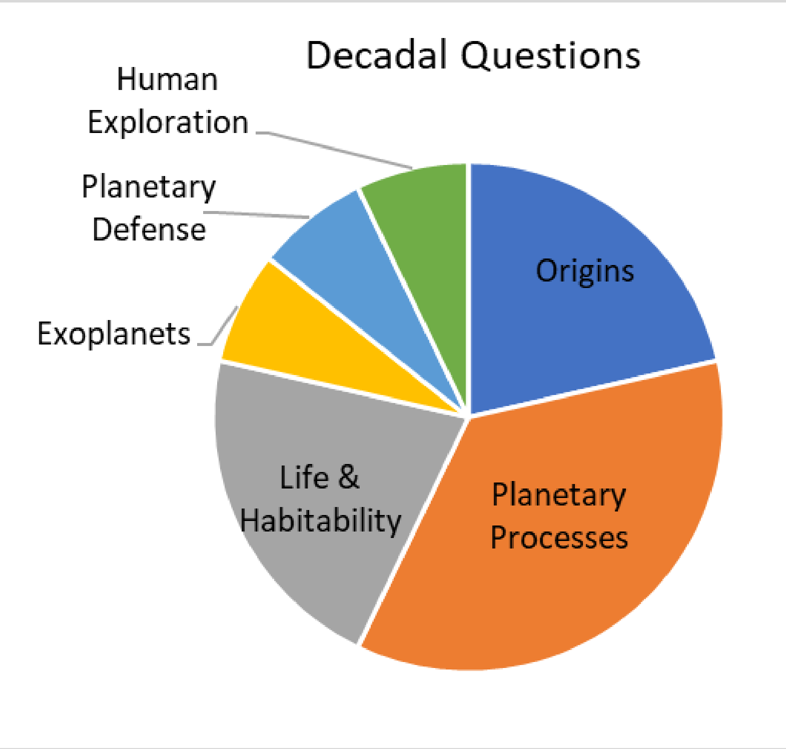
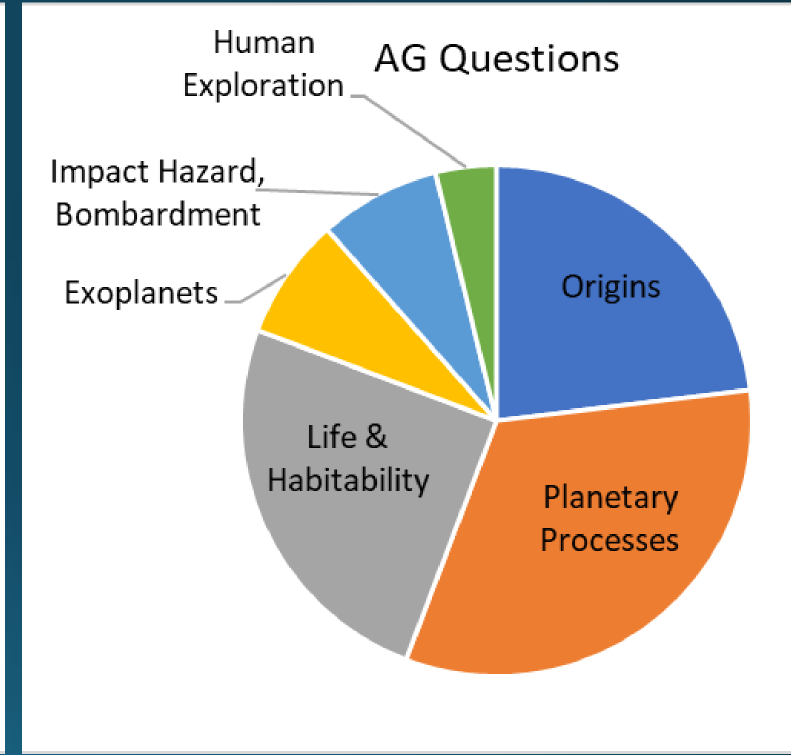
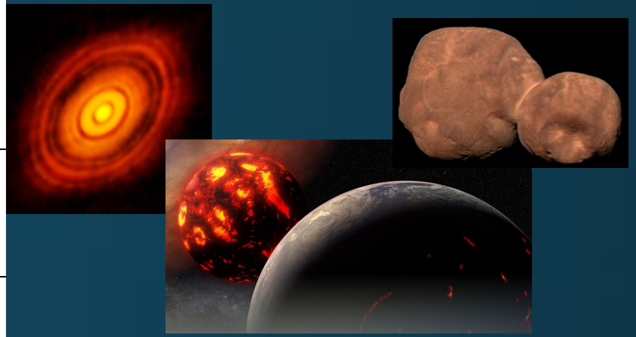
- Final check: compared Decadal distribution with that of big questions identified earlier by Assessment Groups* (AGs)

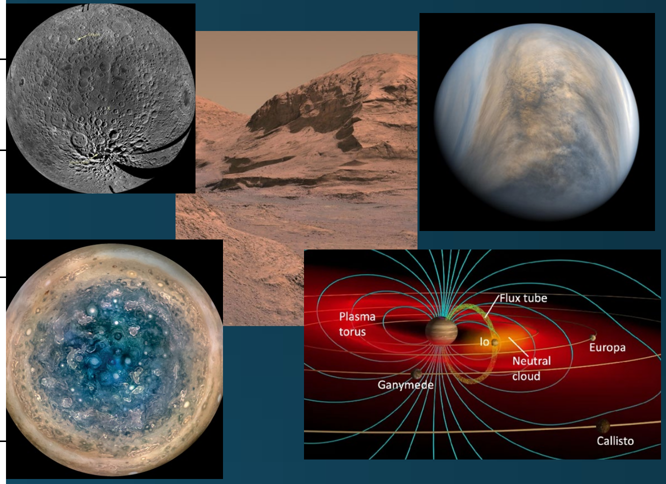


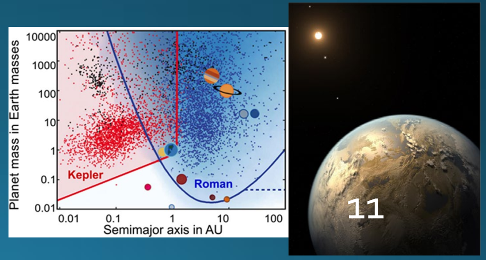


*LEAG, MAPSIT, MEPAG, OPAG, SBAG, MEXAG, & VEXAG identified "big questions" in response to request from Dr. Lori Glaze

Themes	Priority Science Question Topic and Scope
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 & 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 & 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?
All Themes	**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?







Science Question Chapter Format

Q2: Accretion in the Outer Solar System ← Priority Science Question Topic

Q2.1 How did the giant planets form? ← Most important sub-questions

Q2.1a. What is the formation mechanism of gas giant planets? What were the accretion rates of solids (planetesimals/pebbles) and gas during the formation process? How long did it take?
Q2.1b. How did Uranus and Neptune form and what prevented them from becoming gas giants?
Q2.1c. What were the primordial internal structures of giant planets?
……….

Strategic Research Q2.1: ← **Strategic research needed to address each main sub-question**

- **Determine the atmospheric composition of Saturn, Uranus, and Neptune** via in situ sampling of noble gas, elemental, and isotopic abundances, and remote sensing by spacecraft and ground/space-based telescopes.
- **Determine the bulk composition and internal structure of Uranus and Neptune** via gravity, magnetic field, and atmospheric profile measurements by spacecraft, as well as Doppler seismology.
- **Constrain physical properties and boundary conditions (i.e., tropospheric temperatures, shapes, rotation rates) for structure models of Uranus and Neptune** via gravity, magnetic field, and atmospheric profile measurements by spacecraft, remote sensing by spacecraft and ground/space-based telescopes.
- ………

Science Question Chapters: Key Takeaways

- Crucial role of sample return and in situ analyses
- Dearth of knowledge of the ice giant systems
- Importance of primordial processes to compositional reservoirs, planetary building blocks and primitive bodies, and early solar system dynamical evolution
- Interplay of internal and external processes that affect planetary bodies
- Varied evolutionary paths of the terrestrial planets
- Central question of how life on Earth emerged and evolved, and the compelling rationale to study habitable environments at Mars and icy ocean worlds
- Desire to make substantive progress this decade in understanding whether life existed (or exists) elsewhere in the solar system

State of Profession (SoP)

- SoP writing group: Mahzarin Banaji and Orlando Figueroa (co-leads)

  Giada Arney, Fran Bagenal, Larry Esposito, Francis McCubbin,
  Marc Neveu, Edgard Rivera-Valentin, Amy Williams

- 20 meetings with 17 guest presentations in open session

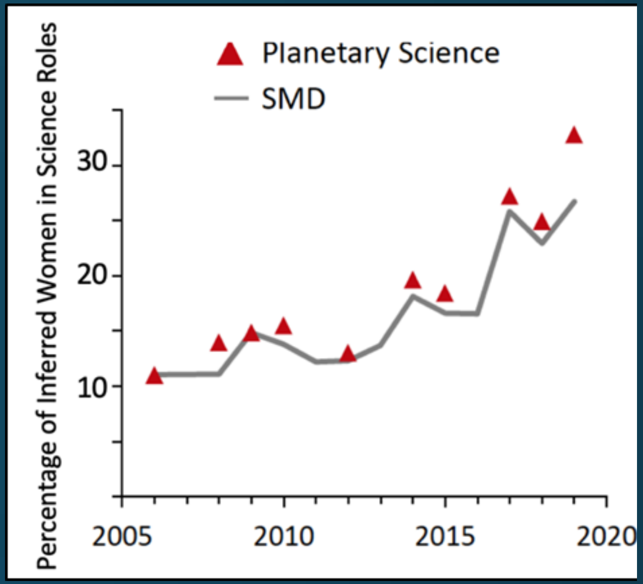
Core principles:

- Broad access and participation essential to maximizing excellence
- Substantial evidence shows that implicit biases affect judgements, even among those sincerely committed to equal opportunity and treatment
- Structures and processes designed to address implicit biases also address explicit biases
- Implementing objective measures of self-examination and evidence gathering supports DEIA improvement and builds community trust
- Strong system of equity and accountability needed to recruit, retain, and nurture the best talent

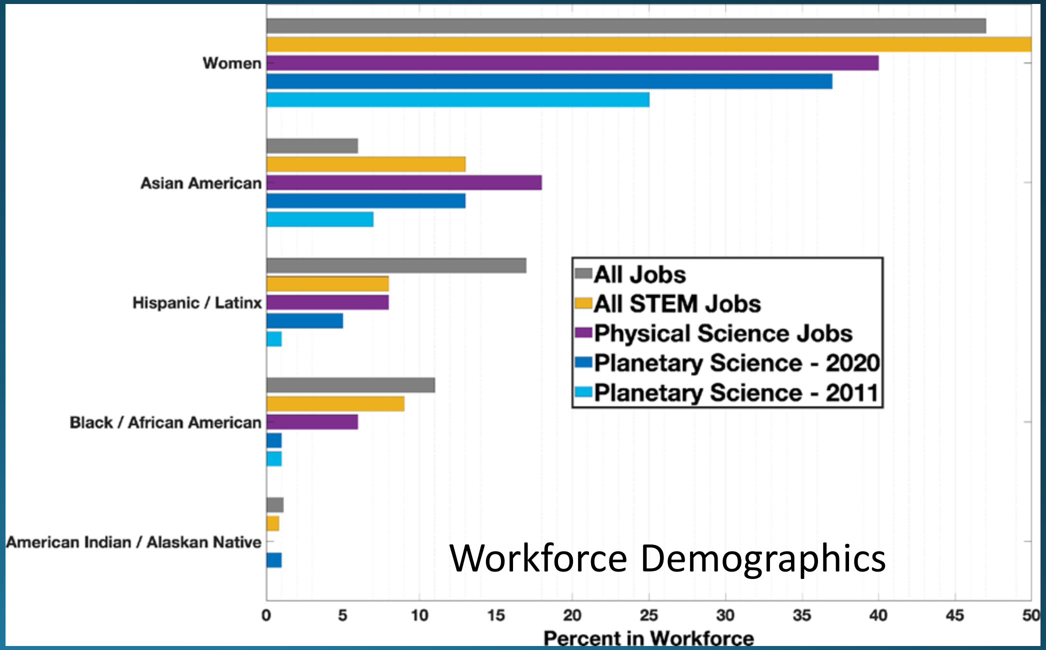
PI Launchpad 2019

SoP Findings

- Substantial progress made, especially with respect to entry and prominence of women in the profession
- Much work remains, particularly to address persistent, troubling issues of representation by race/ethnicity
- Implementation of Dual Anonymous Peer Review at STScI is a model for improving processes to mitigate bias
- Work-life balance issues are leading factor negatively impacting community, especially for women and LGBTQ+ individuals
- Mentoring and outreach to under represented communities (URCs) needed to enhance DEIA



Participation of women in mission teams by submission year



Workforce Demographics

SoP Recommendations

Four action themes:

1) Evidence gathering imperative

Without accurate and complete SoP data, it cannot be known if the best available talent is being utilized, nor how involvement may be undermined by adverse experiences.

NASA and NSF should prioritize obtaining currently lacking evidence about the SoP, including the size, identity, and demographics of the planetary science and astrobiology community, and workplace climate.

2) Education of individuals about the costs of bias and improvement of institutional procedures, practices, and policies

NASA PSD should adopt the view that bias can be both unintentional and pervasive. Report provides actionable steps to assist NASA in identifying where bias exists and in removing it from its processes.

SoP Recommendations

3) Broadening opportunities to advance the SoP

Engaging underrepresented communities (URCs) at secondary and college levels is essential to creating and sustaining a diverse community.

Four recommendations address 1) policies to increase interaction of scientists with society; 2) enhanced involvement of students and faculty from URCs in outreach, as well novel mechanisms to support education and outreach; 3) strengthening programs that mentor the next generation of mission leaders; and 4) reinstating predoctoral programs targeting URCs.

4) Creating an inclusive community free of hostility and harassment

Ensuring everyone is treated with respect is crucial for productive work environments and retaining talent.

NASA PSD should implement Codes of Conduct for funded field campaigns, conferences, and missions, including regular updates and policies for reporting incidents and enforcement. This process should include identification of a point of contact or ombudsperson to address issues.

Research & Analysis (R&A)

NASA's Planetary Science Directorate (PSD) goal: *"advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space"*

1) R&A is the intellectual foundation that ensures NASA's activities are designed and utilized to maximize the expansion of knowledge

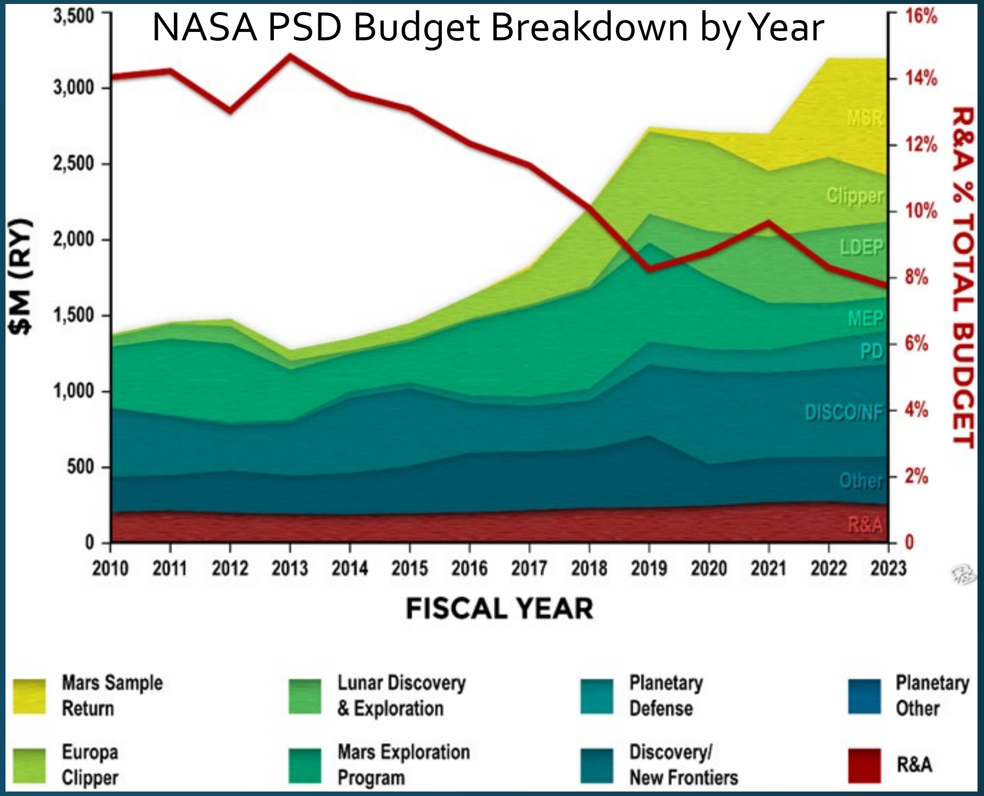
- Analysis of spacecraft data to optimize return on mission investments
- Development and testing of new hypotheses
- Identification of most important goals for future exploration, and development of needed instrumentation and new investigations

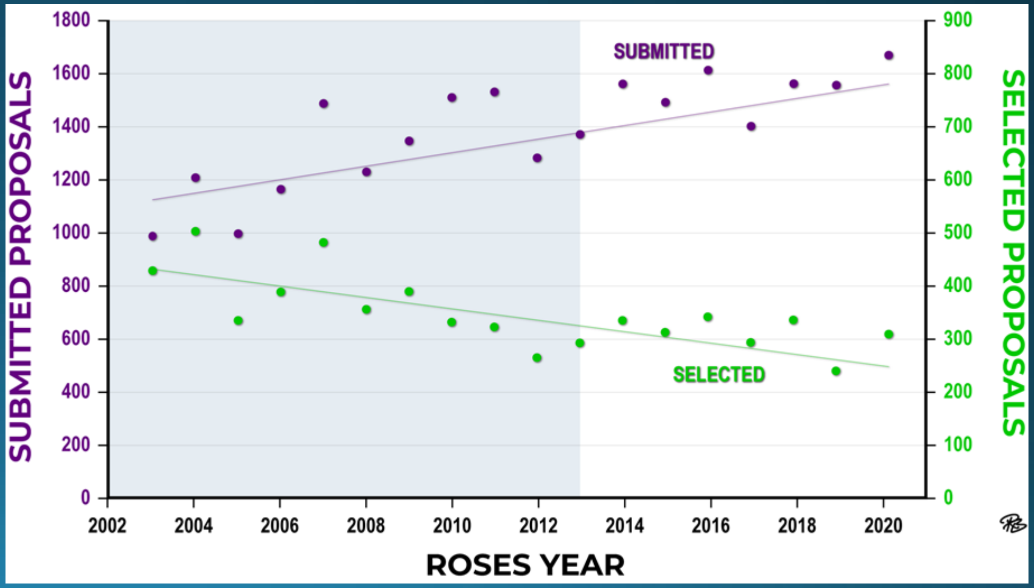
2) Of key importance are the openly competed R&A programs

- Broad access supports entry into field and DEIA
- Highly competitive process drives innovation and identification of most meritorious ideas
- Provides rapid response to scientific advances and evolving priorities

PSD Research & Analysis

- Intense, broad-based concern for health of R&A program
- Since 2010:
  - Doubling of PSD program, and associated growth in new missions, data volume, and needed analyses and new approaches
  - Flat R&A budget when inflation adjusted (red wedge)
- Fractional investment in R&A has decreased from near 15% in 2013 to ~ 8% currently
- Average selection rates ≤ 20% for past 5+ yr





PSD R&A Recommendations

Maintaining appropriate balance between mission and R&A funding is essential to success of PSD programs. The trend of decreasing fractional investment in R&A needs to be reversed.

Increase investment in R&A to achieve a minimum annual funding level of 10% of PSD annual budget by mid-decade, via a progressive ramp-up in funding allocated to the openly competed R&A programs. Progress in achieving this goal should be evaluated mid-decade.

Other recommendations address (see Chapter 17 for details):

- Adoption of a consistent definition of R&A, including category for openly competed programs (defined in report)
- Specific issues related to large R&A programs (ISFM, SSERVI, and ICAR)
- Processes required to 1) track products of R&A programs and proposal demographics, 2) assess R&A portfolio relative to Decadal and PSD goals, and 3) evaluate and improve proposal submission and review

National Science Foundation

Important support for planetary science and astrobiology through basic research, ground-based facilities and observations, and fieldwork/analog activities

Division of Astronomical Sciences; Office of Polar Programs; Divisions of Atmospheric and Geospace, Earth, and Ocean Sciences; Division of Physics

NASA and NSF would realize greater return on R&A investments by streamlining mechanisms to support science of benefit to both agencies

NASA and NSF should develop a plan to replace ground-based radar capabilities lost with Arecibo, which are crucial for planetary defense and Near Earth Object studies

NSF should continue (and if possible expand) support of existing and future observatories important for solar system studies (e.g., NOIRLab, ALMA, Rubin, TMT, GMT, ngVLA) and related PI-led and guest observer programs, and involve planetary astronomers in future observatory plans and development

Astrobiology

Central role in Decadal research strategy (3 of 12 priority science questions) and in many current and planned missions

Dynamic habitability and the co-evolution of planets and life are key concepts that require mechanisms to support interdisciplinary and cross-divisional collaboration

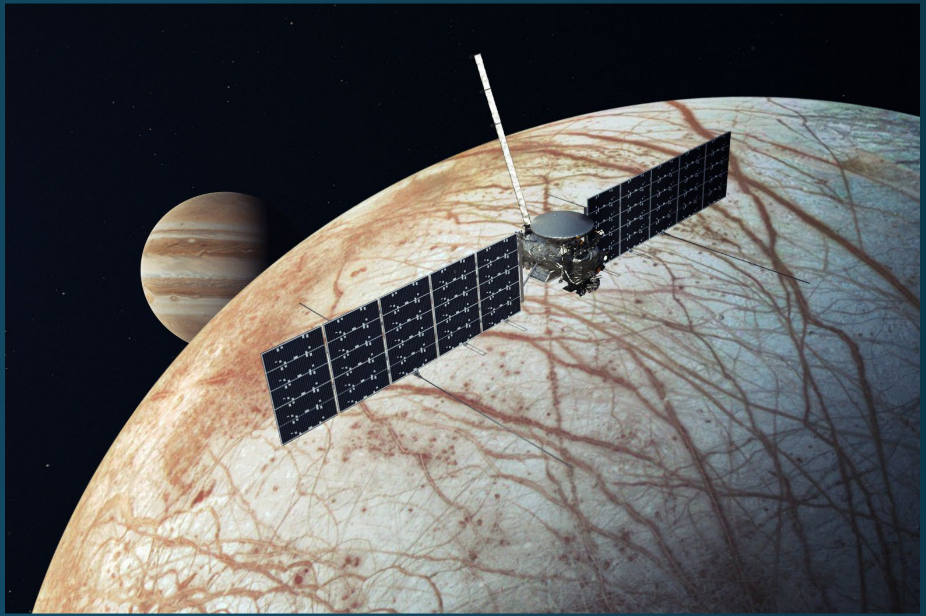
Dedicated focus on research related to subsurface life is warranted given advances in understanding the diversity of terrestrial life, and known subsurface fluids on Mars and icy ocean worlds

NASA should accelerate development and validation of mission-ready life detection technologies, and astrobiological expertise should be integrated in all stages – from inception to operations – of missions with astrobiology objectives

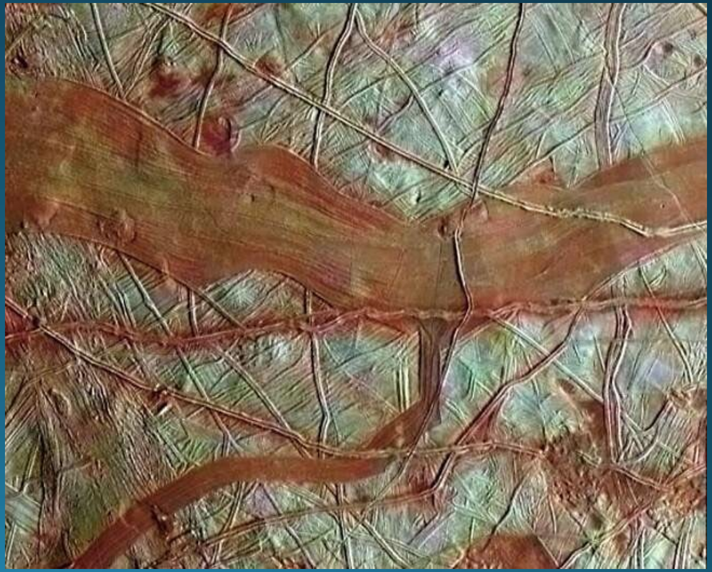
*From 2019 NASEM *Astrobiology Strategy for the Search for Life in the Universe*

Europa Clipper Recommendation

- Planned for launch in Oct. 2024
- Critical foundation for the exploration of ocean worlds
- Focused exploration of a key target of high astrobiological interest

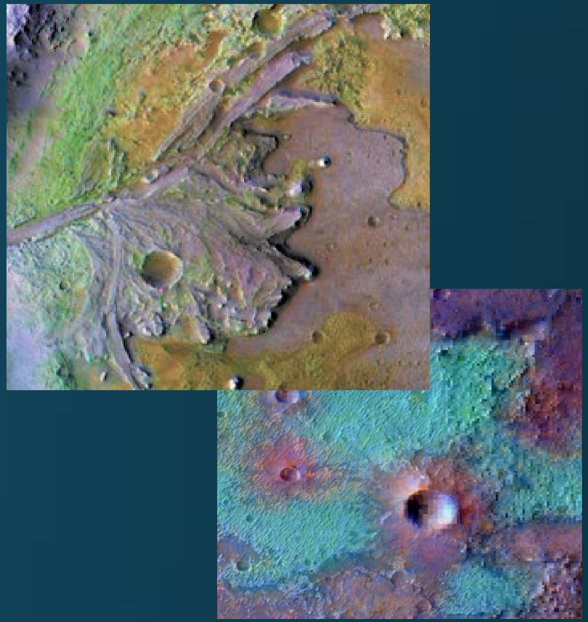


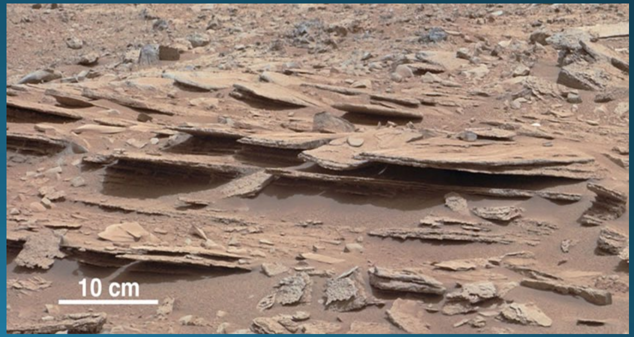
NASA should continue the development of the Europa Clipper mission



Mars sample return (MSR)

- **Why samples from Mars?**
  - Mars is unique in its extensive suite of ancient, well-preserved aqueous sedimentary rocks that record early solar system conditions
  - Rocks from these environments enable investigation of pre-biotic conditions and chemistry, as well as the search for evidence of life
  - Diverse, sophisticated lab instruments can precisely measure key isotopes, trace elements, and detailed petrologic structures
  - Martian meteorite collection has no rocks of fluvial, evaporative, or hydrothermal origin and most are young
- Return of martian samples a high scientific priority for over 25 years
  - *Vision and Voyages'* highest priority was a sample caching mission, now underway by the Perseverance rover
- In 2017 NASA announced a "focused and rapid" concept to return the samples to Earth including strong participation by European Space Agency (ESA)





MSR Recommendation

Mars Sample Return is of fundamental strategic importance to NASA, US leadership in planetary science, and international cooperation

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

Mars exploration: Programmatic balance

- Mars exploration has historically figured prominently in NASA's planetary program, with annual funding levels of ~25-35% of the PSD budget over the past three decades
- Program recommended in this report has a decade-long total for Mars exploration (MSR* + MEP) that is ~20% of the total PSD budget
- Even with an additional 20% growth in MSR's total cost, the decade funding for Mars would remain at or below previous percentage levels
- However, ≥ 20% cost growth would, without a budget augmentation, undermine the programmatic balance across the priority scientific questions, mission classes, and destinations

*Includes current estimate for MSR + US contribution to a Sample Receiving Facility

MSR Recommendation

- The cost of MSR should not be allowed to undermine the long-term programmatic balance of the planetary portfolio
- If the cost of MSR increases substantially (≥ 20%) beyond that adopted by the Committee ($5.3 billion), or goes above ~ 35% of the PSD budget in any given year, NASA should work with the Administration and Congress to secure a budget augmentation to ensure the success of this strategic mission

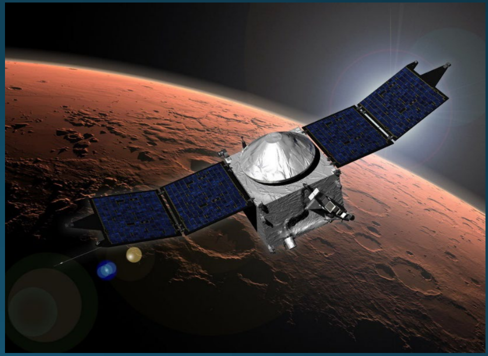
Mars Exploration Program (MEP)

The Mars Exploration Program is a scientific success story whose stability enables:

- Strategic science planning across decades
- The development of a multi-generational science community that defines the program goals
- Multi-mission coordination
- International collaboration

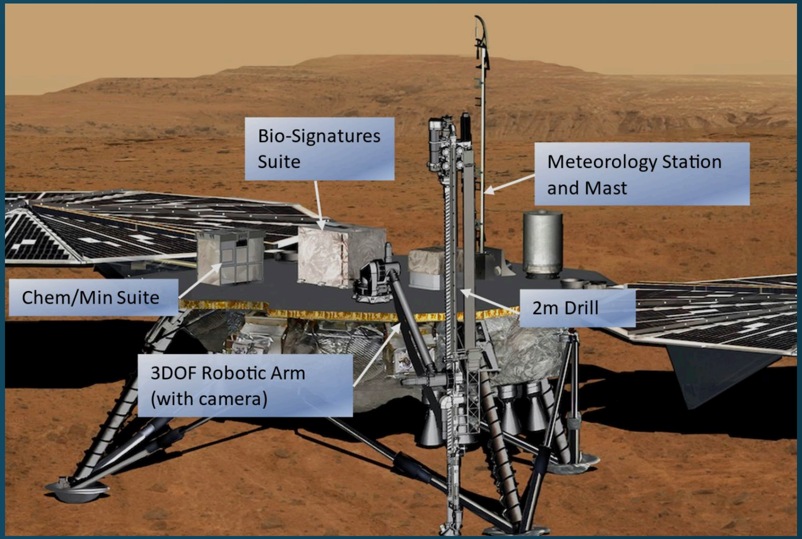
NASA should maintain the Mars Exploration Program which should:

- **Continue to be managed within the PSD**
- **Maintain its focus on the scientific exploration of Mars.**
- **Develop and execute a comprehensive architecture of missions, partnerships, and technology development**

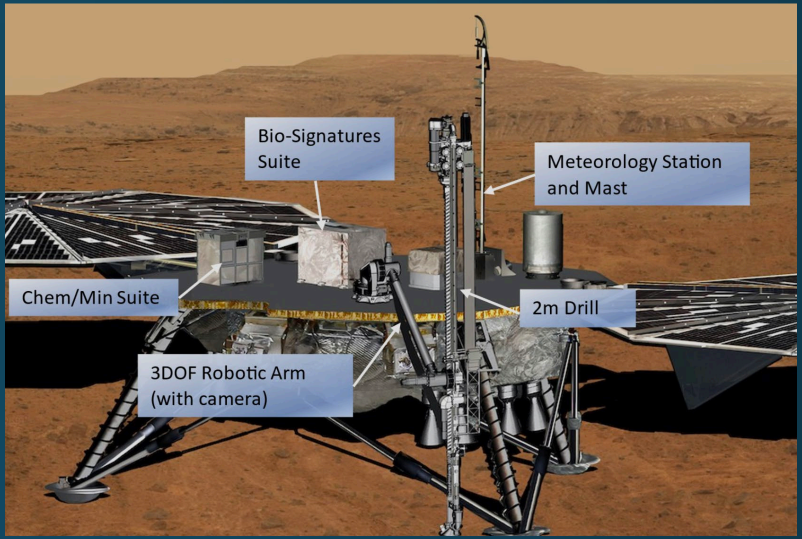


Mars Exploration Program

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



Mars Exploration Program



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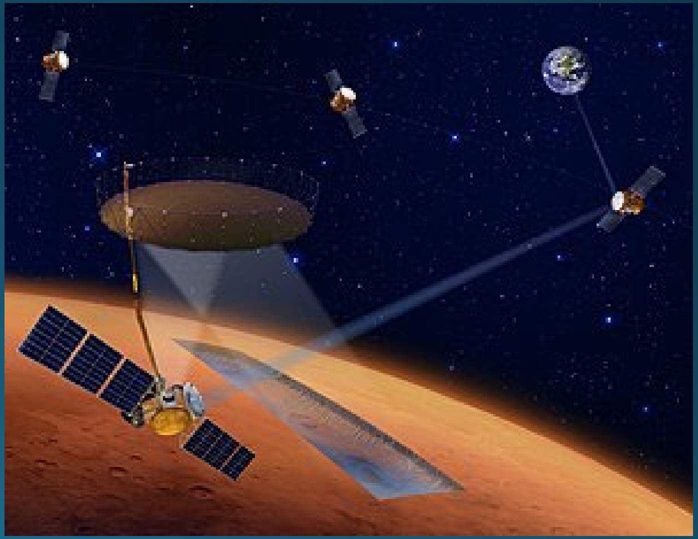
NASA should consider an ice mapping mission that prepares for ISRU by humans and addresses the priority climate science questions at Mars related to near-surface ice



- Soon after the report was completed the Administration proposed cancellation of the International Mars Ice Mapper
- This development underscores the importance of the MEP in developing the long-term strategy for Mars exploration

Human Exploration

- Human exploration is aspirational and inspirational, and NASA's Moon-to-Mars plans hold the promise of broad benefits to the nation and the world
- A robust science program provides the motivating rationale for sustained human exploration

The advancement of high priority lunar science objectives should be a key requirement of the Artemis human exploration program

- **PSD should execute a strategic program to accomplish planetary science objectives for the Moon, with an organizational structure that aligns responsibility, authority, and accountability**
- **SMD should have the responsibility and authority for integrating Artemis science requirements with human exploration capabilities**

Lunar Discovery and Exploration Program (LDEP)

- Commercial Lunar Payload Services (CLPS) program goal is to enable reliable and affordable access to the lunar surface by helping to establish a viable commercial lunar sector

- Promising and innovative approach that will benefit PSD and lunar science

NASA should continue to support commercial innovation in lunar exploration. Following demonstrated success in reaching the lunar surface:

- **NASA should develop a plan to maximize science return from CLPS by, for example, allowing investigators to propose instrument suites coupled to specific landing sites**
- **NASA should evaluate the future prospects for commercial delivery systems within other mission programs and consider extending approaches and lessons learned from CLPS to other destinations**

LDEP strategic mission: Endurance-A

The committee prioritizes the Endurance-A lunar rover mission to address the highest priority lunar science, revolutionizing our understanding of the Moon and the history of the early solar system recorded in the most ancient lunar impact basin. The mission would:

- Utilize CLPS for delivery to the lunar surface
- Collect ~100 kg of samples in a ~10^3 km traverse across diverse terrains in the South Pole Aiken basin
- Deliver the samples for return to Earth by astronauts

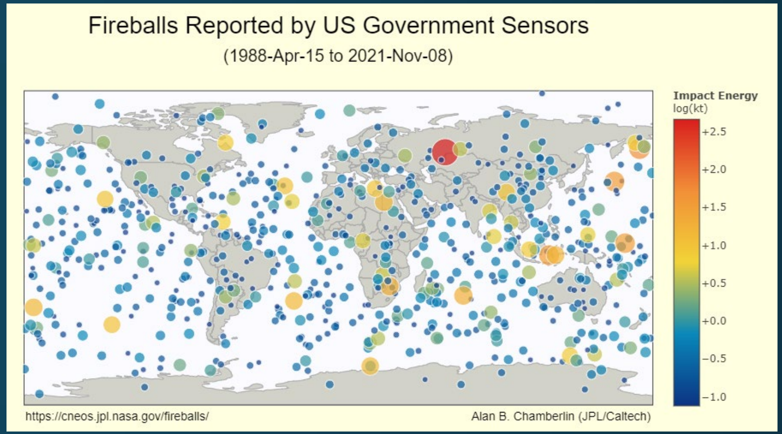
Coordination with Artemis provides outstanding opportunity to expand the partnership between NASA's human and scientific efforts at the Moon

- The result would be flagship-level science at a fraction of the cost to PSD

Endurance-A should be implemented as a strategic medium-class mission as LDEP's highest priority

The importance of Planetary Defense

- NASA's Planetary Defense Program coordinates and supports activities to detect and track all Near-Earth Objects (NEOs) and assess their threat
- PSD provides expertise on small body science, spaceflight technology, and missions
- NEO deflection demonstrations, like DART, provide technology building blocks necessary to develop approaches for deflecting or disrupting a threatening NEO

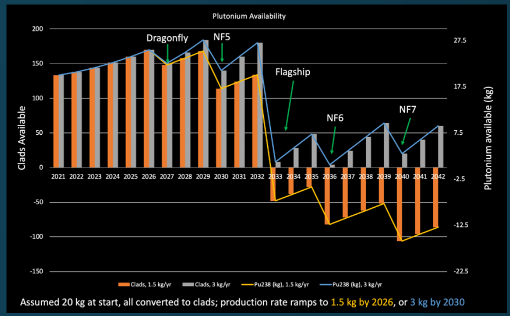


NASA should fully support the development and timely launch of NEO Surveyor to achieve the highest priority planetary defense NEO survey goals

The highest priority planetary defense demonstration mission to follow DART and NEO Surveyor should be a rapid-response, flyby reconnaissance mission targeted to a challenging NEO (~ 50-to-100 m in diameter object)

- **This mission should assess flyby characterization methods to better prepare for a short-warning-time NEO threat**

Infrastructure Recommendations



Plutonium

- NASA should evaluate plutonium-238 production capacity against the recommended mission portfolio and other NASA and national needs, and increase it as necessary
- NASA should continue to invest in maturing higher efficiency radioisotope power system technology to best manage its supply of plutonium-238 fuel

Launch vehicles

- NASA should develop a strategy to focus and accelerate development of high energy launch capability, or its equivalent, and in-space propulsion to enable robust exploration of all parts of the solar system

Uplink/Downlink

- NASA should expand uplink and downlink capacities as necessary to meet the navigation and communication requirements of the missions recommended by this decadal survey

Technology Development

Technology is the foundation of scientific exploration and significant investment is needed to ensure that priority missions recommended by this survey can be accomplished

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

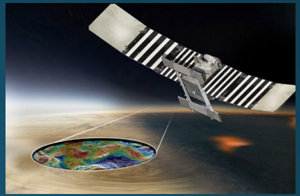
NASA should create a PSD Technology Program Plan that provides the details on program goals, how the program operates, who is involved, and how the science community and supporting organizations can play a role

STMD should ensure that its level of investment in SMD mission technologies is balanced at approximately 30% of its overall budget with the PSD portion at no less than 10%

Discovery Program





- Enormously successful program of PI-led missions
  - Cost cap, no science constraints → innovation to maximize science return per dollar
  - Modest costs, rapid development → high mission cadence

- *Vision & Voyages* recommended cost cap of $500M in FY15 dollars, excluding launch vehicle

- 2014 and 2018 Discovery calls had a cost cap of ≈ $500 M for Phases A-D (development), with Phase E (operations) and launch vehicle excluded from the cap

- Estimated life cycle costs (LCC) of four missions selected in 2014, 2018 calls are about a factor of two larger than the Phase A-D cost cap

Committee strongly supports recent Discovery missions, and finds their estimated LCC costs are commensurate with their expected scientific return

- However, large difference between cost cap and true LCC undermines budgetary planning, creating potential mismatch between expectations for mission cost/cadence and budget realities

Discovery Program Recommendations

- Single cost cap for Phases A-F
  - Allows each team to allocate costs between development and operations to best suit their mission
  - Straightforward to assess (and optimize) science return per dollar, in keeping with core philosophy of Discovery program
  - Supportive of budgetary planning needed to maintain high cadence
  - Launch vehicle costs should be excluded; outside of proposer’s control and (largely) predictable by NASA

- Substantial increase in cost cap
  - Needed to address priority science identified in the Decadal
  - Important to retain ability for innovative Discovery concepts to reach outer and innermost solar system

The Discovery Phase A through F cost cap should be $800 million in FY25 dollars, exclusive of launch vehicle, and periodically adjusted throughout the decade to account for inflation

SIMPLEx

- Very small missions managed within Discovery program that can be flexibly accommodated as budgets and ride-share opportunities allow
- Higher risk tolerance → infusion of new technologies and launch strategies
- Recent cost cap was $55M
- Modest dollar increase in cap warranted for continued high science value

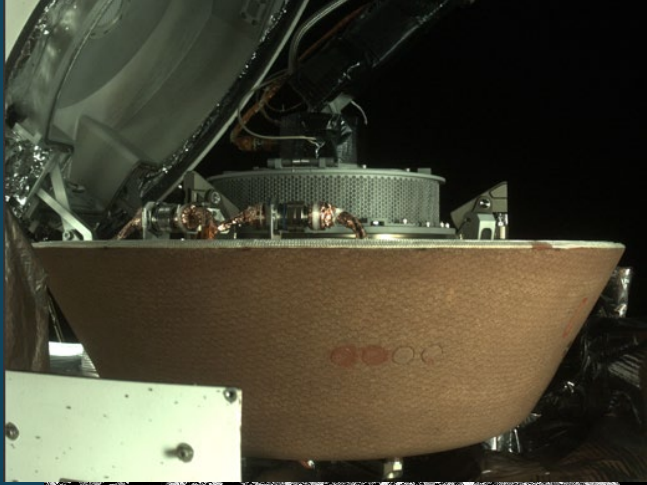
SIMPLEx cost cap should be increased to ~ $80M

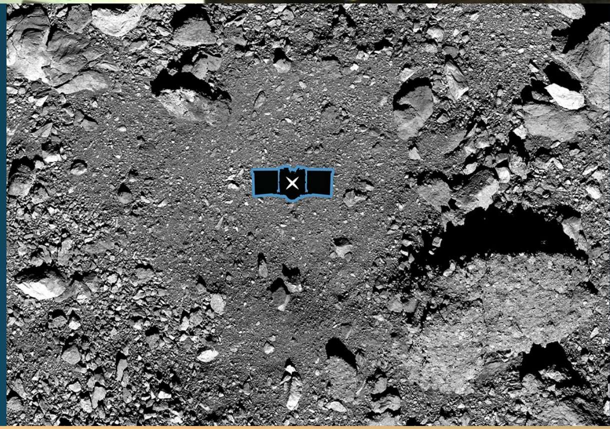
New Frontiers (NF) Program

- PI-led medium class missions that address specified mission themes
- Committee asked to consider whether NF should continue to specify science or be open in future calls

NF should continue to specify mission themes as determined by Decadal Survey

- Extensive time/resources go into proposals, and a NF mission can be a significant fraction of PSD budget
- NF missions should be strategically directed to highest priority science
- Decadal Surveys well-suited for determining what that science should be: broad community representation, extended time for balanced assessment





New Frontiers (NF) Program

Cost structure:

- NF-4 had $850M (FY15) cost cap, excluding Phase E and LV
- Aspirational Dragonfly mission LCC estimated at more than twice cost cap

Committee strongly endorses Dragonfly, and finds that its estimated LCC costs are commensurate with its expected scientific return

- Committee carefully deliberated on future NF cost structure, considering:
  - Crucial importance of accessing outer and innermost solar system
  - Prioritizing truly breakthrough science at NF, requiring more complex mission design/instrumentation, at possible expense of mission cadence
  - Realistic cost estimates for highly-ranked NF concepts (similar to Dragonfly LCC)

New Frontiers Program Recommendations

- Phase E costs should be included in the cost cap
- Substantial increase in cap needed
- **AND:** To enable access to all targets in the solar system, as well as long trajectories associated with sample return, cap should include an allocation based on the length of the quiet cruise phase

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

New Frontiers Mission Themes

- Committee retained NF-5 mission themes as originally specified by NASA
- Committee considered 13 (potentially) medium class missions it prioritized for TRACE + 6 other missions that underwent independent cost and technical evaluation as part of *Vision & Voyages*
- Prioritized 8 mission themes for NF-6 + 1 additional theme for NF-7 based on:

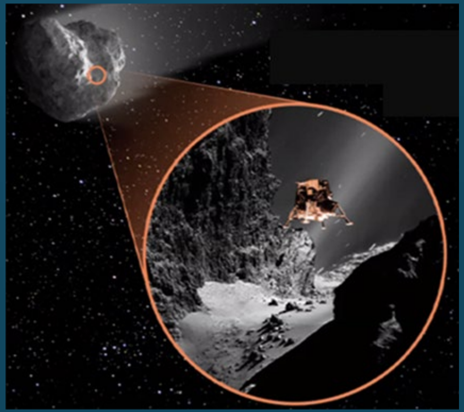
1) Ability to address priority science questions and produce breakthrough science
2) Programmatic balance across difference science questions and destination class
3) Cost and technical readiness

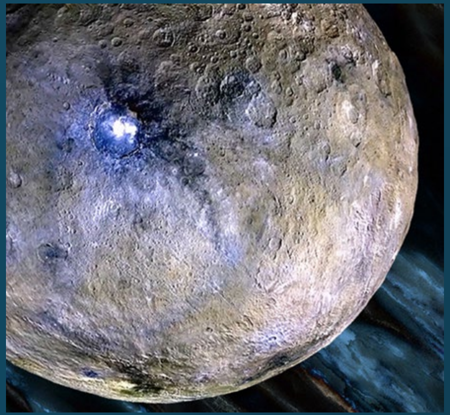
NF-6 Mission themes (alphabetical):

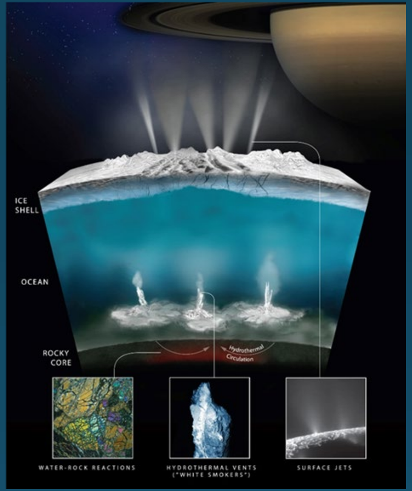
- Centaur Orbiter and Lander
- Ceres sample return
- Comet surface sample return
- Enceladus multiple flyby
- Lunar Geophysical Network
- Saturn probe
- Titan orbiter
- Venus In Situ Explorer

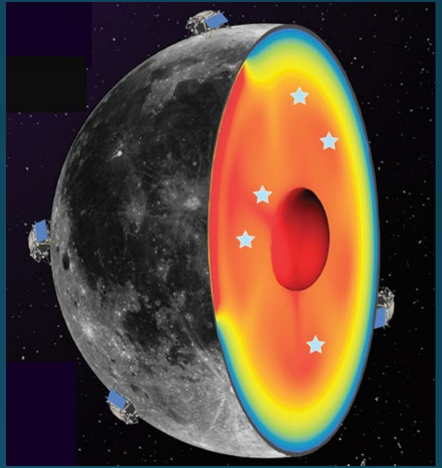
NF-7: All non-selected from NF-6 plus

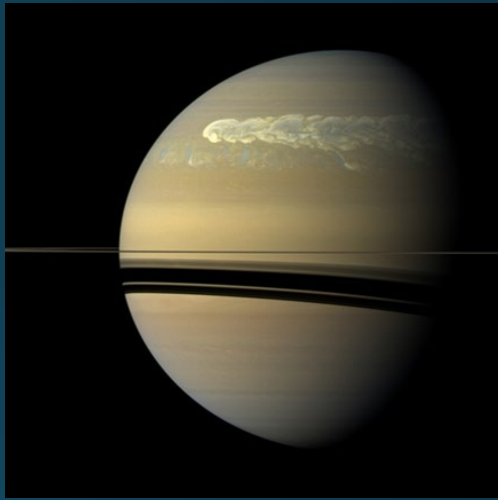
- Triton Ocean World Surveyor

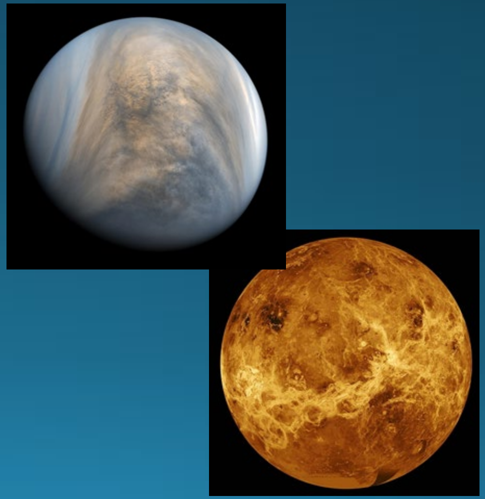


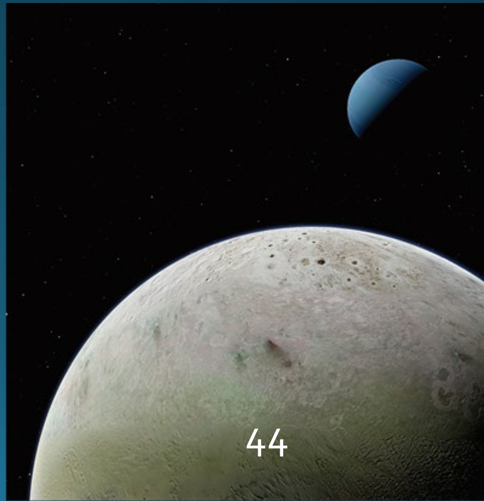












Large (“Flagship”) missions

Committee prioritized 6 candidate large missions for TRACE:

- Enceladus Orbilander
- Europa Lander
- Mercury Lander*
- Neptune-Triton Odyssey
- Uranus Orbiter and Probe
- Venus Flagship

*Originally proposed as a NF mission, but TRACE indicated it was a large mission. Due to its compelling science, Committee considered it as a candidate flagship.

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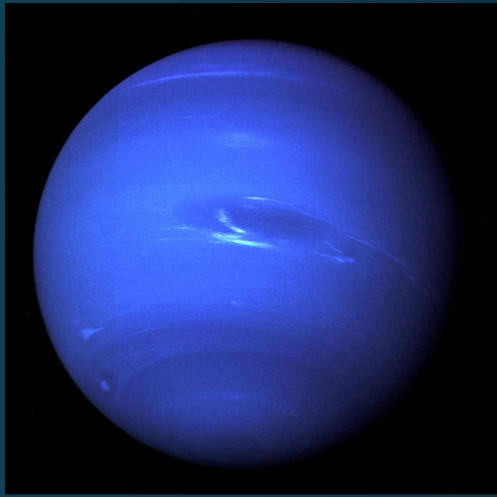
→ Ice giant mission judged to be the top priority, primarily for ability to produce transformative, breakthrough science for only class of planets never studied with a dedicated orbital tour

- Another consideration: a system-oriented, multi-target mission is programmatically complementary to flagships underway that focus on single bodies (Europa Clipper & MSR)

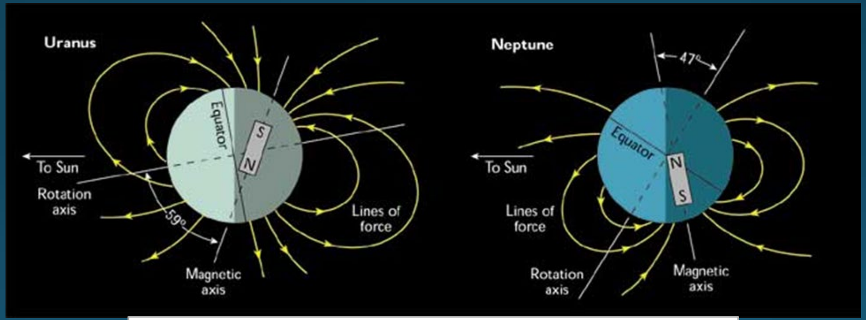
Both Uranus & Neptune are scientifically compelling

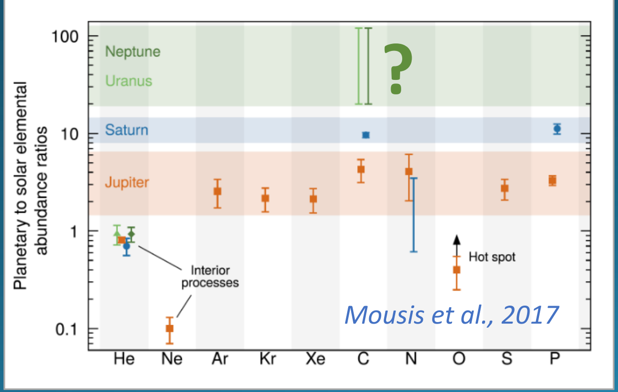
- Offset, tilted magnetic field
- Regular satellite system
- Possible ocean worlds (Ariel, Titania)
- Ring system
- Extreme seasons and storms
- Low internal heat

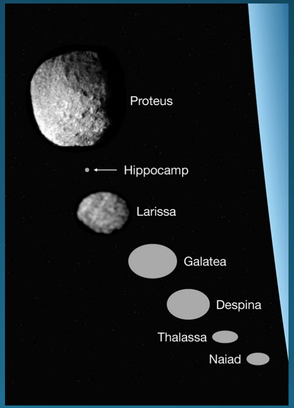
- Offset, tilted magnetic field
- Captured satellite (KBO)
- Triton has atmosphere, plumes and may be ocean world
- Clumpy ringlets
- Giant storms
- High internal heat



Both critical to understanding ice giant systems and solar system origins







Technical readiness differs substantially

Uranus Orbiter and Probe

- End-to-end viable mission concept on currently available launch vehicle
- Flexible launch dates starting in 2031 through 2038+
- No new technologies required
- Low-Medium risk (only large mission TRACEd to receive this)

Neptune Odyssey

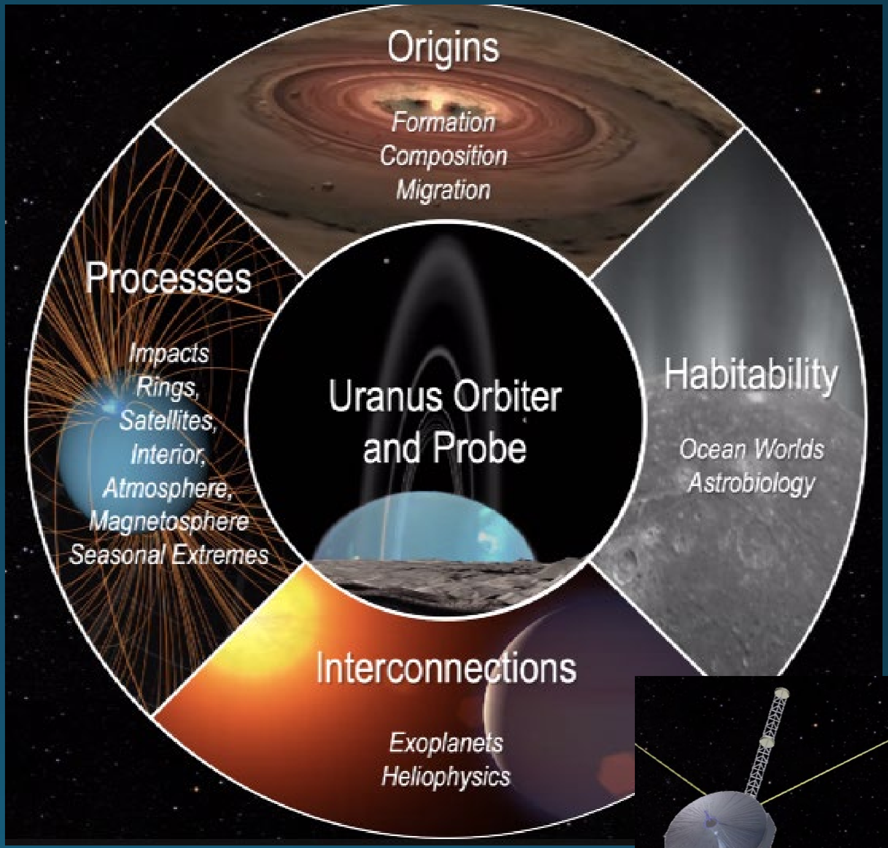
- Lacks demonstrated trajectory and launch date within the decade on currently available launch vehicle
- Uncertainties in power requirements and possible need for solar electric propulsion if neither SLS nor Jupiter gravity assist are available
- Accommodation on current launch vehicles unclear (faring size)

Highest priority new flagship: Uranus Orbiter and Probe

- In situ probe & multi-year orbital tour: atmosphere, interiors, magnetosphere, rings, and satellites
- First dedicated study of class of planets that may be most common in the universe
- Technically ready to start now
- Launch on Falcon Heavy Expendable

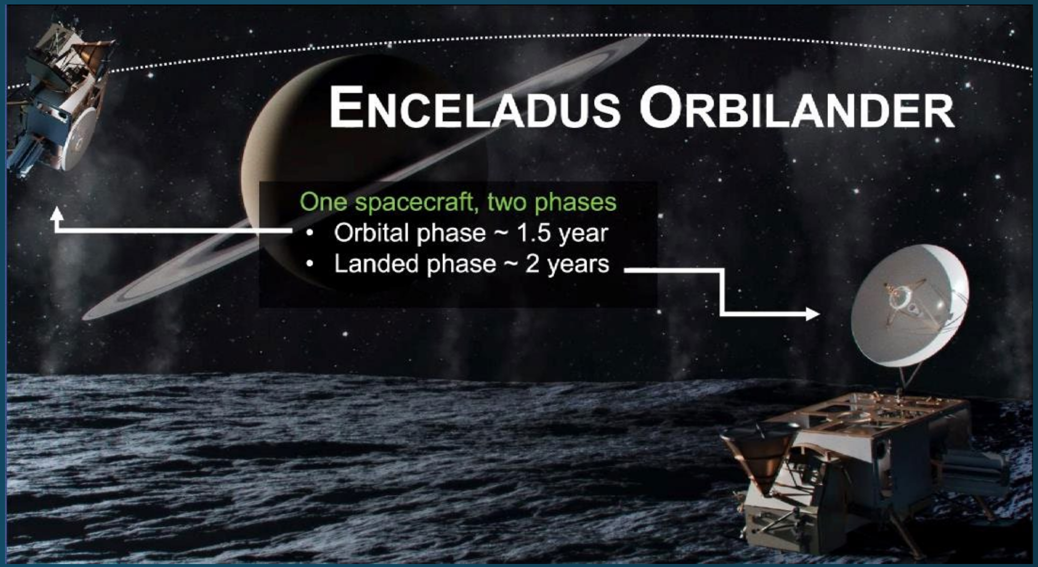
  → **Optimal launch in 2031-2032 with Jupiter gravity assist to shorten cruise to 12 to 13 yrs**

  - Flexible launch opportunities through 2038 with increased ~ 15 yr cruise and inner solar system gravity assists
- Strong international interest & potential for partnership (e.g., 2021 report of ESA's Voyage 2050 Senior Committee)

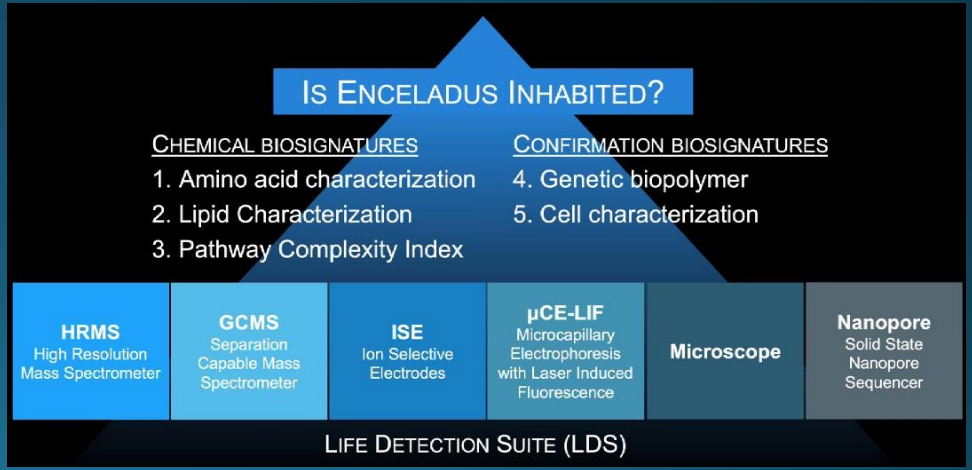


Second priority new flagship: Enceladus Orbilander

- Is Enceladus' inhabited?
- Enceladus is optimal locale to sample extant subsurface ocean through study of freshly ejected plume material
  - Search plume materials for evidence of life via multiple complementary approaches + geochemical/geophysical context for life detection
- Launch in 2037+, land early 2050s during favorable south pole illumination



- Study of habitability & life detection at Enceladus is such a high priority that it is included in both NF and Flagship class missions to provide alternative approaches to pursue this critical science



Budget planning assumptions

- Level Program
  - Assumes PSD’s FY23 budget with 2% per year inflation through the decade
  - Prioritized funding for the major program elements to create a balanced portfolio that fits within the Level Program budget
- Recommended Program: Aspirational and Inspirational
  - Created a program that fully addresses the report recommendations
  - Results in a budget that is < 20% higher over the decade

Recommended Program for the coming Decade

- Continues support for missions in operation and development
- Continues the Mars Sample Return campaign as currently planned

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- Initiates five new Discovery missions at recommended cost cap
- Initiates one NF 5 and two NF 6 selections at recommended cost cap
- Provides robust plutonium production to meet the needs of the decade

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- Restores MEP to pre-MSR funding level with late decade start of Mars Life Explorer
- Maintains support for Planetary Defense, with NEO Surveyor and a new NEO characterization mission

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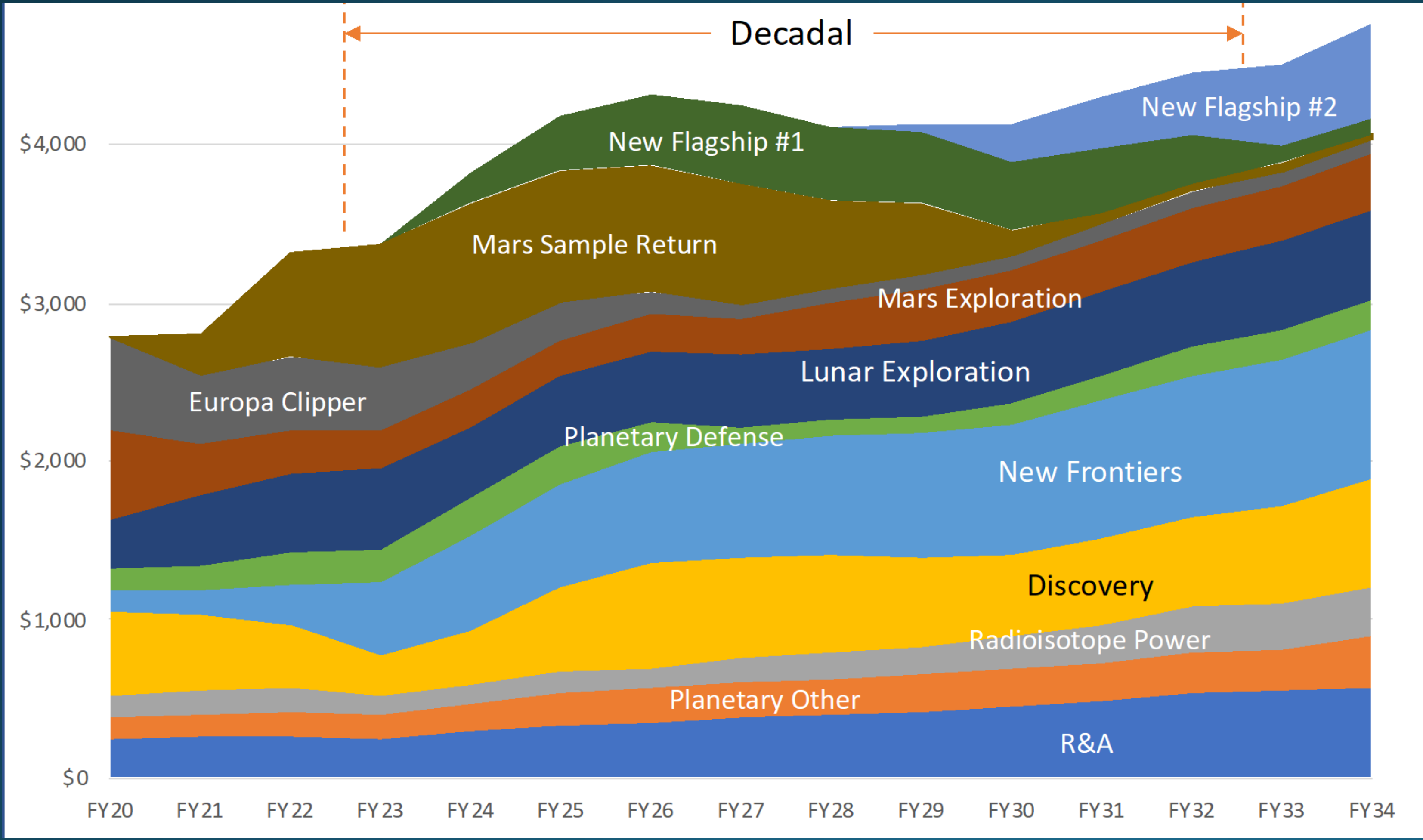
- Maintains support for Planetary Defense, with NEO Surveyor and a new NEO characterization mission
- Initiates the Enceladus Orbilander in FY29

The Recommended Program profile



Program element	***Recommended Program* ($M)**
R&A	3,870
Europa Clipper	1,700
Mars Sample Return	5,300
Discovery	5,250
New Frontiers	7,300
Mars Exploration	2,850
Lunar Exploration	4,760
Planetary Defense	1,700
Radioisotope power	1,750
Planetary Other	2,150
New Flagship #1	3,450
New Flagship #2	1,040
Total	**41,120**

Level Program

- Continues support for missions in operation and development
- Continues the Mars Sample Return campaign as currently planned
- Initiates five new Discovery missions at recommended cost cap
- Continues support the Lunar (LDEP) Program with mid-decade start of Endurance-A
- Maintains support for Planetary Defense, with NEO Surveyor and a new NEO characterization mission
- Sustains plutonium production
- Smaller increase in R&A ($730 million over the decade)
- Start of Uranus Orbiter and Probe Flagship delayed to FY28
- No new start for Orbilander this decade
- Initiates NF 5 but NF 6 selection late in decade or not included
- Gradually restores MEP to pre-MSR funding and no new start for Mars Life Explorer

Program element	***Recommended Program* ($M)**	***Level Program* ($M)**
R&A	3,870	3,350
Europa Clipper	1,700	1,700
Mars Sample Return	5,300	5,300
Discovery	5,250	5,250
New Frontiers	7,300	5,100
Mars Exploration	2,850	2,650
Lunar Exploration	4,760	4,760
Planetary Defense	1,700	1,700
Radioisotope power	1,750	1,750
Planetary Other	2,150	2,150
New Flagship #1	3,450	1,280
New Flagship #2	1,040	-
Total	**41,120**	**34,990**

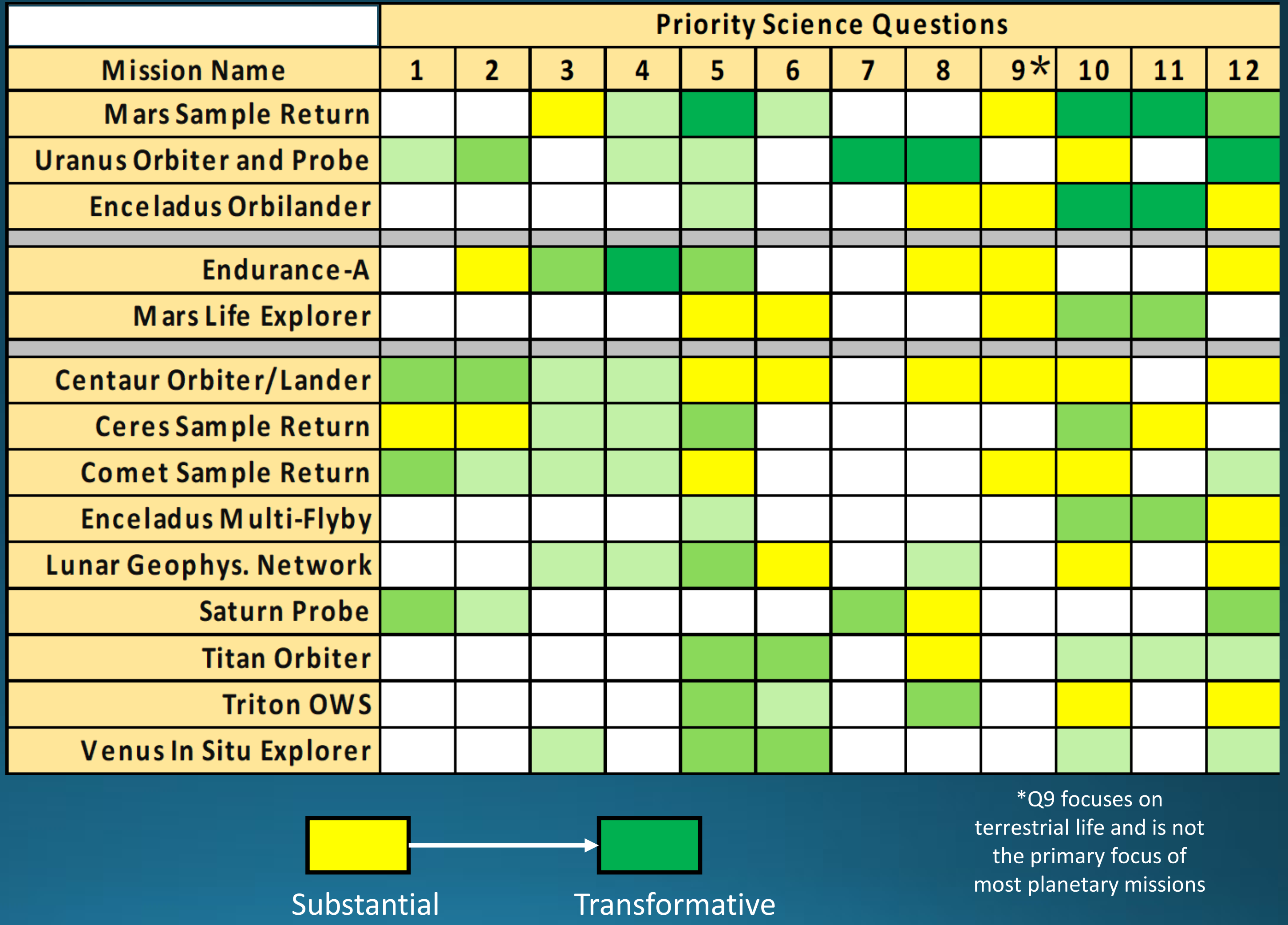
If less funding than the Level Program is available ....

NASA should implement decision rules in the following order:

1) Delay the start of the Uranus Orbiter/Probe flagship mission
2) Reduce the number of new Discovery missions from five to four
3) Reduce the funding level for Planetary Defense by removing the new-start flyby characterization mission
4) Reduce the cadence of New Frontiers in the coming decade
5) Reduce the funding for LDEP with a late-decade start of Endurance-A
6) Reduce the funding for MEP below the Level program
7) Reduce the number of new Discovery missions to three
8) Reduce R&A funding

Assessment of the prioritized mission portfolio

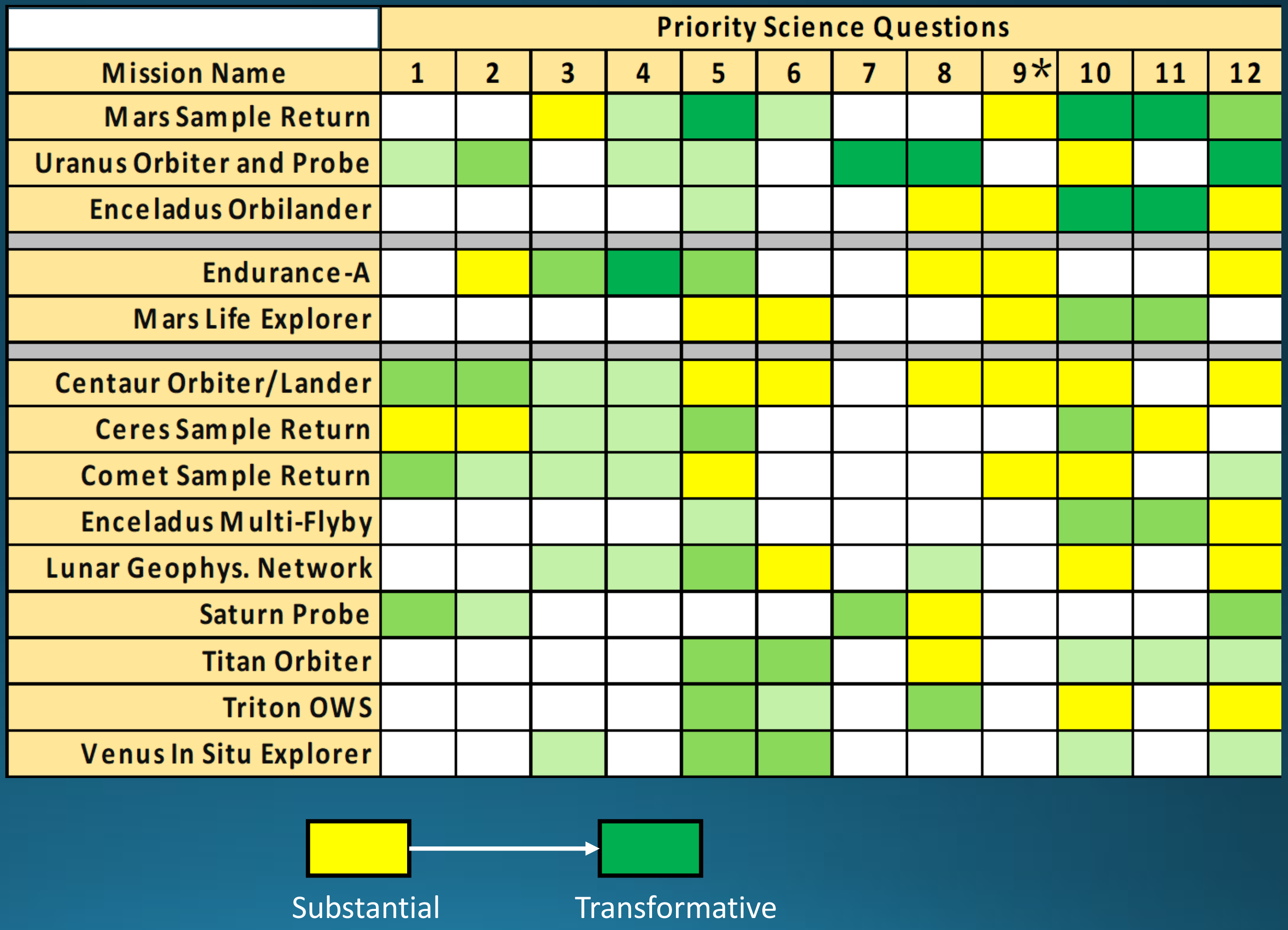
- Prioritized missions were selected based on science, programmatic balance, technical readiness, and cost
- Portfolio was then evaluated against the priority science questions
- The suite of missions does an excellent job of addressing the full breadth of these questions at a diverse set of destinations
- We emphasize that this matrix is not intended to prioritize between missions



*Q9 focuses on terrestrial life and is not the primary focus of most planetary missions

Traceability of recommended missions to science objectives

Themes	Priority Science Question Topic
A) Origins	**Q1. Evolution of the protoplanetary disk** **Q2. Accretion in the outer solar system** **Q3. Origin of Earth and inner solar system bodies**
B) Worlds & Processes	**Q4. Impacts and dynamics** **Q5. Solid body interiors and surfaces** **Q6. Solid body atmospheres, exospheres, magnetospheres, and climate evolution** **Q7. Giant planet structure and evolution** **Q8. Circumplanetary systems**
C) Life & Habitability	**Q9. Insights from Terrestrial Life** **Q10. Dynamic Habitability** **Q11. Search for life elsewhere**
All Themes	**Q12. Exoplanets**



Thank You

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Amanda Brecht
William Brinckerhoff
Megan Bruck Syal
Paul Byrne
Morgan Cable
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Thomas Cravens
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Krista Soderlund
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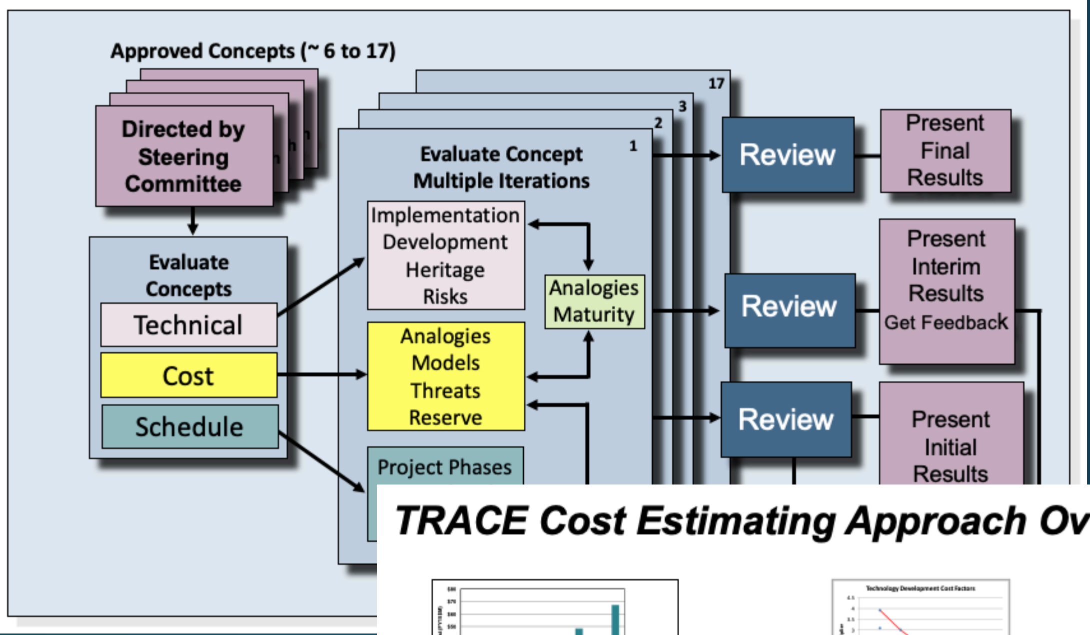
Myriam Telus
Audrey Thirouin
Sonia Tikoo-Schantz
Chad Trujillo
Benjamin Weiss
Jennifer Whitten
Amy Williams
Michael Wong
Robin Wordsworth

Backup

Technical Risk And Cost Evaluation (TRACE) process

- All prioritized missions were required to have an independent cost and technical risk evaluation
- Aerospace Corporation was selected to perform TRACE through competitive process
- Cost and risk evaluations were an element of the Committee's overall assessment of each mission concept



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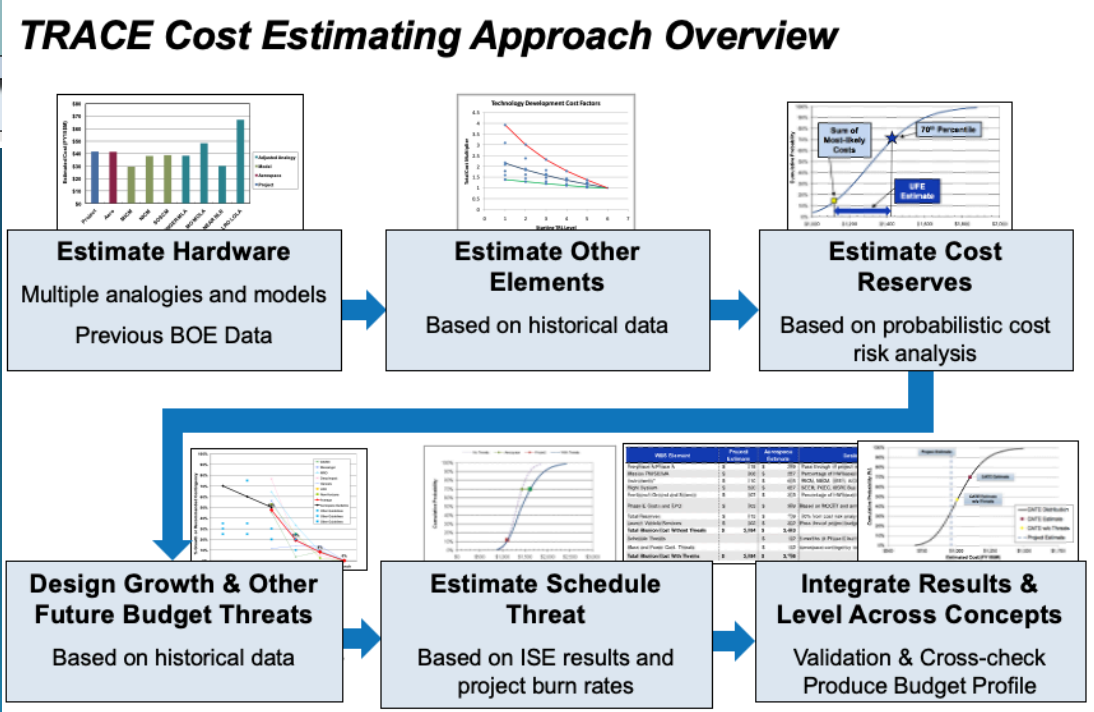


Practices to enhance DEIA & interactions during Survey

- Diversity across many axes in committee membership

27% early-career, 41% female, 16% underrepresented groups
Institution: 50% Academic, 28% Other (JPL, Non-academic), 15% Government, 7% Private

- Implicit bias seminar at beginning of SG work
- Remote meetings allowed for attendance without travel and across time zones
- Accommodation of diverse schedule demands & reduction of meeting-to-break time
- Combination of anonymous straw polls and discussion to ensure all views heard
- Key SG decisions made after (not during) group meetings, to provide time to reflect and minimize effects of being rushed or pressured associated with increased bias
- Discussion and deliberation continued until all key SG decisions had super-majority support
- Writing group chapter drafts sent to full Committee; virtual "Summit" for each to provide feedback
- All white papers read by multiple Committee members; numerous white paper leads presented to Committee and PMCS PIs presented directly to the SG
- Emphasis on what was best for PS&AB overall—rather than on competition between interest groups. "How to optimize the progression of planetary science as a whole while honoring the varied needs & stages of advance in each sub-discipline?"

Sample Receiving Facility

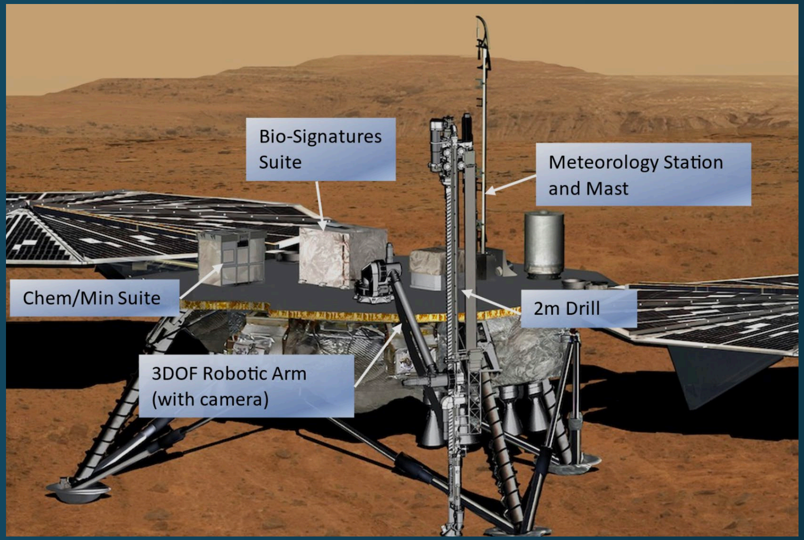
- Processing and analysis of samples returned from Mars will occur in three stages:
  - Initial receiving and characterization to verify they are safe to leave the facility
  - Distribution to the science community for detailed analysis
  - Long-term curation
- Biohazard requirements are challenging – the SRF implementation needs to begin immediately
- The SRF only requires the tools to verify sample safety - not the full range of instrumentation available at other labs
- An end-to-end plan for the samples is needed, with early engagement of the sample science community, government stakeholders, and the public

NASA, in partnership with ESA and community stakeholders, should develop the plan for the end-to-end processing of samples returned from Mars. This plan should:

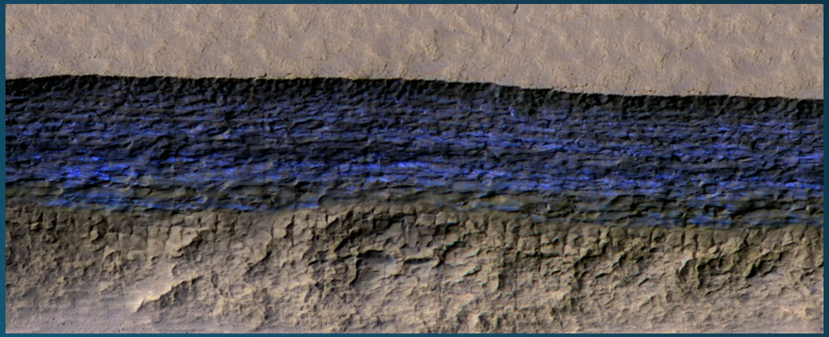
- **Provide for the definition, design, and construction of the SRF and ensure that it is ready to receive the samples by 2031**
- **Include provisions for expeditiously distributing the samples to the scientific community for analysis <u>and</u> to a long-term curation facility**

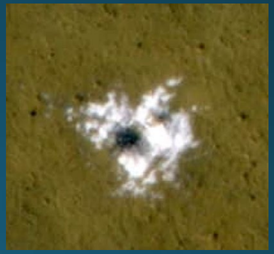
Mars Life Explorer

Search for modern biosignatures—including organics, gases, and isotopes—that could indicate biological activity within geologically recent materials. Characterize the habitability of the ices. Evaluate thermophysical properties to assess role of liquid water in ice formation or modification.



- Organics (e.g. amino acids, fatty acids), and non-equilibrium gases to evaluate their possible biological origin
- Evolved gases, small organic and inorganic cations and anions, silicate, oxide, and salt phases, and major and minor element chemistry with respect to required elements to support life energy sources, and possible toxic elements
- Temperature profiles of borehole to determine sub-surface thermophysical properties
- Atmospheric temperature, pressure, water vapor flux, and wind to determine processes that preserve/modify/destroy modern ice deposits

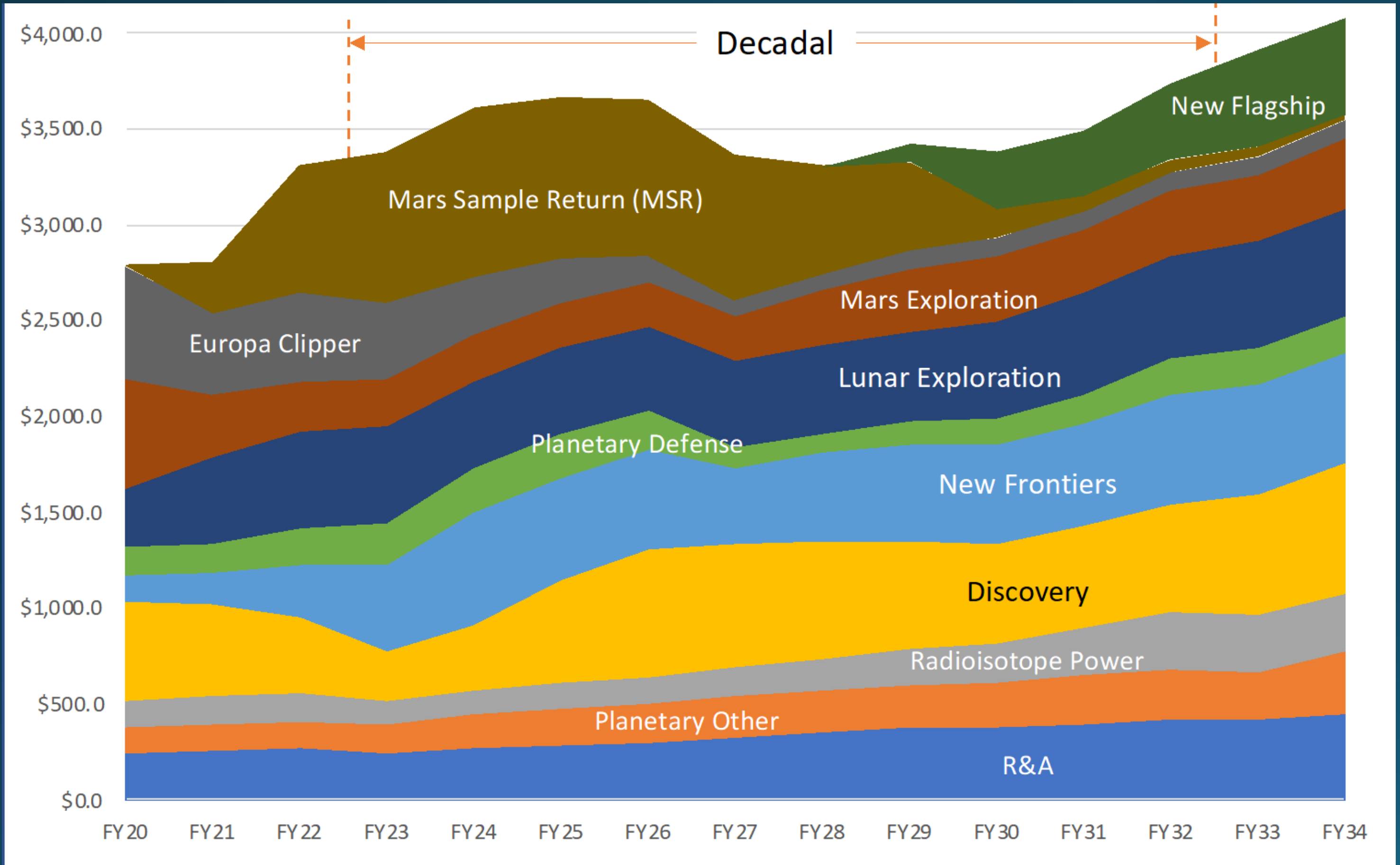




The need for coordinated exploration strategies

NASA should develop scientific exploration strategies, as it has for Mars, in areas of broad scientific importance, e.g. Venus and ocean worlds, that have an increasing number of U.S. missions and international collaboration opportunities

The Level Program profile



Program element	***Recommended Program*** **($M)**	***Level Program*** **($M)**
R&A	3,870	3,350
Europa Clipper	1,700	1,700
Mars Sample Return	5,300	5,300
Discovery	5,250	5,250
New Frontiers	7,300	5,100
Mars Exploration	2,850	2,650
Lunar Exploration	4,760	4,760
Planetary Defense	1,700	1,700
Radioisotope power	1,750	1,750
Planetary Other	2,150	2,150
New Flagship #1	3,450	1,280
New Flagship #2	1,040	-
Total	**41,120**	**34,990**

New Frontiers Mission Themes

Centaur Orbiter and Lander (CORAL)

Investigate physical + chemical properties of a Centaur from orbit and in situ, exploring one of a population of dynamically evolved but compositionally primitive small icy bodies from the Kuiper Belt that currently reside between Jupiter and Neptune. Constraint the nature of ice-rich planetesimals and compositional reservoirs in the protoplanetary disk.

NF-6 Mission themes (alphabetical):

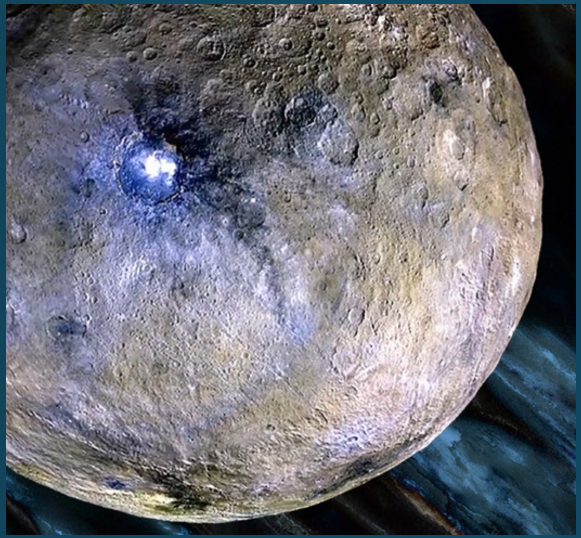
- Centaur Orbiter and Lander
- Ceres sample return
- Comet surface sample return
- Enceladus multiple flyby
- Lunar Geophysical Network
- Saturn probe
- Titan orbiter
- Venus In Situ Explorer

NF-7: All non-selected from NF-6 plus

- Triton Ocean World Surveyor

New Frontiers Mission Themes

Ceres Sample Return



Quantify accretional conditions and habitability of a dwarf planet and the most ice-rich body in the inner solar system through orbital, in situ, and sample return investigations. Samples to include young carbonate salt deposits (e.g., from Occator crater) and some of Ceres' typical dark materials.

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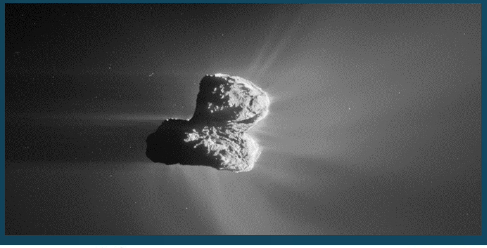
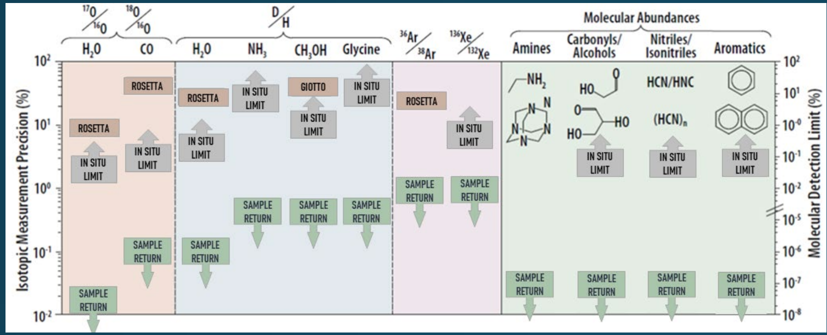
New Frontiers Mission Themes

Comet Surface Sample Return





Map comet nucleus and return sample to Earth for detailed analyses to understand comet formation and activity, primordial mixing in solar nebula, and role of comets in delivery of water and organics to Earth. Will include volatile characterization and sample processing to preserve organics and prevent aqueous alteration.

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NF-7: All non-selected from NF-6 plus

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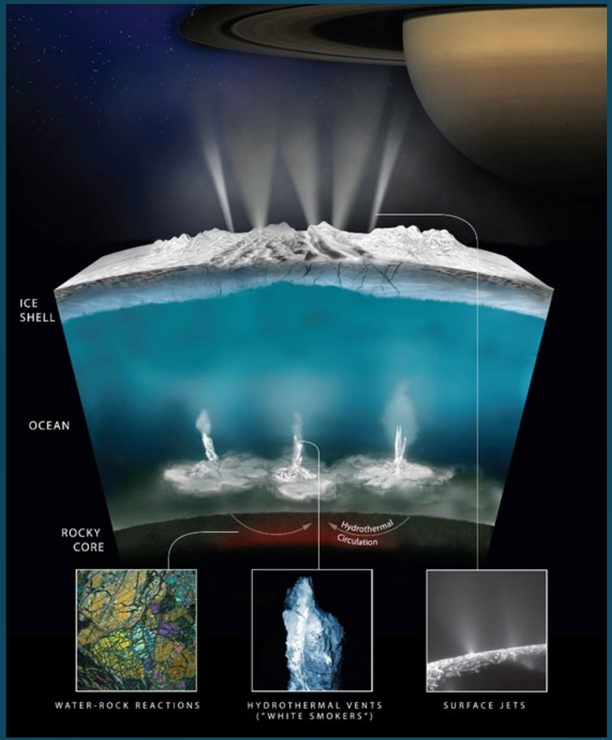
New Frontiers Mission Themes

Enceladus Multiple Flyby



Characterize habitability and look for evidence of life via analysis of fresh plume material sampled at low velocity (< 4 km/s) to preserve large organic molecules and with sample volume > 1 μl.

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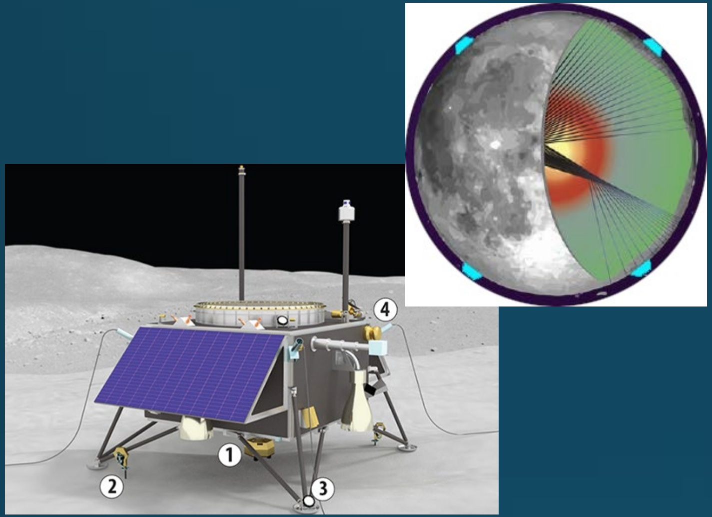
New Frontiers Mission Themes

Lunar Geophysical Network



Examine Moon with a global, long-lived (≥ 6 yr) network of geophysical instruments on surface to constrain geological processes, bulk composition, distribution of heat-producing elements, and Moon's interior state and thermal evolution.

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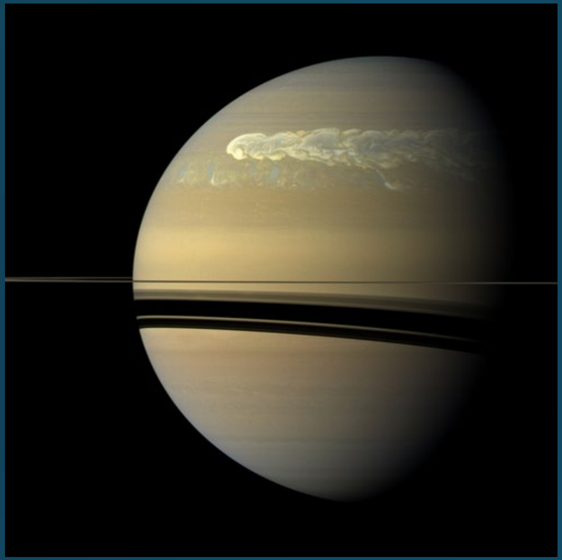
New Frontiers Mission Themes

Saturn Probe



Obtain in situ measurements of Saturn’s atmosphere from an entry probe to understand conditions in the protosolar nebula, constrain giant planet formation mechanisms including when and where Saturn formed, and study what governs the diversity of giant planet climates, circulations, and meteorology.

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NF-7: All non-selected from NF-6 plus

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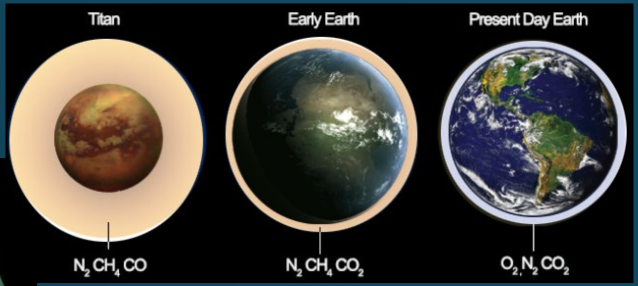
New Frontiers Mission Themes

Titan Orbiter



Characterize Titan's internal structure (including its ice shell and subsurface ocean), dense N_2 atmosphere, and methane hydrological cycle and seas to assess its potential habitability and prebiotic chemistry relevant to the early Earth. Global-scale studies are complementary to several 100s of km to be explored by Dragonfly.

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- Titan orbiter
- Venus In Situ Explorer

NF-7: All non-selected from NF-6 plus

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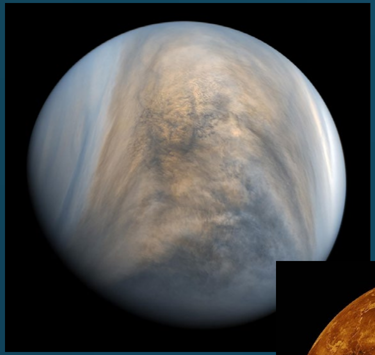
New Frontiers Mission Themes

Venus In Situ Explorer



Investigate processes and properties that cannot be characterized from orbit or from a single descent profile – e.g., global, complex atmospheric cycles, surface-atmosphere interactions, and surface properties – to provide breakthrough understanding on the origin and evolution of terrestrial planets.

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- Saturn probe
- Titan orbiter
- Venus In Situ Explorer

NF-7: All non-selected from NF-6 plus

- Triton Ocean World Surveyor

New Frontiers Mission Themes

Triton Ocean World Surveyor

Utilize a Neptune-orbiter to complete numerous flybys of Triton, a captured Kuiper Belt Object that has a geologically young surface and active geysers, and is a potential ocean world. Characterize internal structure, geology and composition, moon-magnetospheric interactions, and atmospheric properties and variability.

NF-6 Mission themes (alphabetical):

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- Lunar Geophysical Network
- Saturn probe
- Titan orbiter
- Venus In Situ Explorer

NF-7: All non-selected from NF-6 plus

- Triton Ocean World Surveyor