The National Academies of
SCIENCES · ENGINEERING · MEDICINE

Origins, Worlds, and Life

Presentation to the PAC, June 23, 2022

Robin Canup and Philip Christensen, Co-chairs

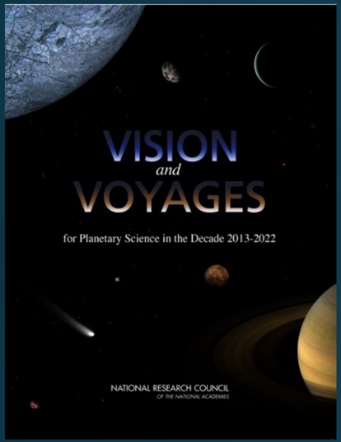
David H. Smith, Study Director

A Decadal Strategy for Planetary Science & Astrobiology 2023–2032

Cover by P. Byrne and J. Tuttle Keane

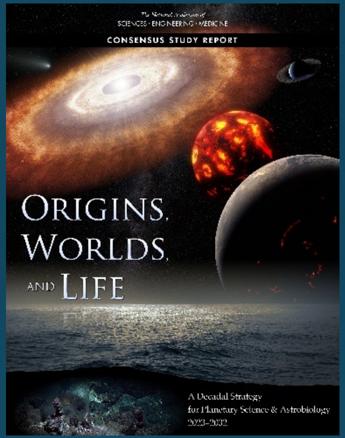
Process driven by the Statement of Task

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 and Panels
(panel chairs and vice chairs listed first)

Steering Group
Robin Canup, NAS, co-chair
Phil Christensen, co-chair
Mahzarin Banaji, NAS
Steve Battel, NAE
Lars Borg
Athena Coustenis
James Crocker, NAE
Brett Denevi
Bethany Ehlmann
Larry Esposito
Orlando Figueroa
John Grunsfeld
Julie Huber
Krishan Khurana
Bill McKinnon
Francis Nimmo, NAS
Carol Raymond
Barbara Sherwood Lollar, NAS, NAE
Amy Simon

Moon and Mercury
Tim Grove, NAS
Brett Denevi
James Day
Alex Evans
Sarah Fagents
Bill Farrell
Caleb Fassett
Jennifer Heldmann
Toshi Hirabayashi
James Keane
Francis McCubbin
Miki Nakajima
Mark Saunders
Sonia Tikoo-Schantz

Venus
Paul Byrne
Larry Esposito
Giada Arney
Amanda Brecht
Thomas Cravens
Kandis Jessup
James Kasting, NAS
Scott King
Bernard Marty
Thomas Navarro
Joseph O'Rourke
Jennifer Rocca
Alison Santos
Jennifer Whitten

Mars
Vicky Hamilton
Bethany Ehlmann
Will Brinckerhoff
Tracy Gregg
Jasper Halekas
Jack Holt
Joel Hurowitz
Bruce Jakosky
Michael Manga, NAS
Hap McSween, NAS
Claire Newman
Miguel San Martin, NAE
Kirsten Siebach
Amy Williams
Robin Wordsworth

Small Bodies
Nancy Chabot
Carol Raymond
Paul Abell
Bill Bottke
Megan Bruck Syal
Harold Connolly
Tom Jones
Stefanie Milam
Ed Rivera-Valentin
Dan Scheeres, NAE
Rhonda Stroud
Myriam Telus
Audrey Thirouin
Chad Trujillo
Ben Weiss

Ocean Worlds & Dwarf Planets
Alex Hayes
Francis Nimmo, NAS
Morgan Cable
Alfonso Davila
Glen Fountain
Chris German
Chris Glein
Candice Hansen
Emily Martin
Marc Neveu
Carol Paty
Lynnae Quick
Jason Soderblom
Krista Soderlund

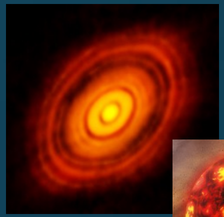
Giant Planet Systems
Jonathan Lunine, NAS
Amy Simon
Frances Bagenal, NAS
Richard Dissly
Leigh Fletcher
Tristan Guillot
Matthew Hedman
Ravit Helled
Kathleen Mandt
Alyssa Rhoden
Paul Schenk
Michael Wong

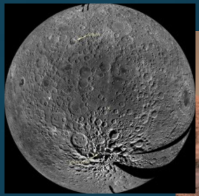
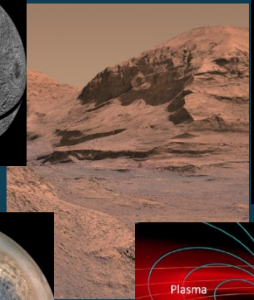
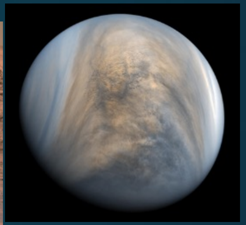
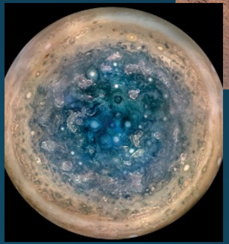
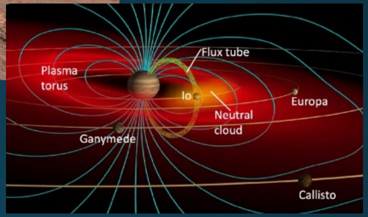
Each Panel vice chair was also a member of Steering Group

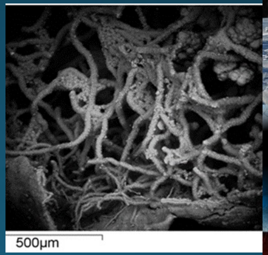
Decadal Process

- > 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)

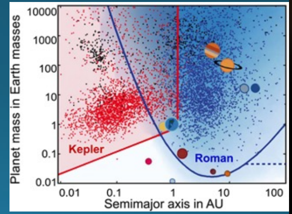
Themes	Priority Science Question Topic and Scope
Origins	**Q1. Evolution of the protoplanetary disk** What were the initial conditions in the Solar System? What processes led to the production of planetary building blocks, and what was the nature and evolution of these materials?
	Q2. Accretion in the 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?
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?
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?

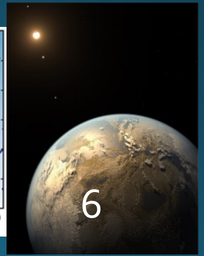










Science Question Chapter Format

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

State of Profession Recommendations

1) Evidence gathering imperative

Prioritize obtaining currently lacking data on the size, identity, and demographics of the planetary science and astrobiology community, and workplace climate.

2) Education about bias and improvement of practices, and policies

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

3) Broadening outreach to under represented communities (URCs)

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.

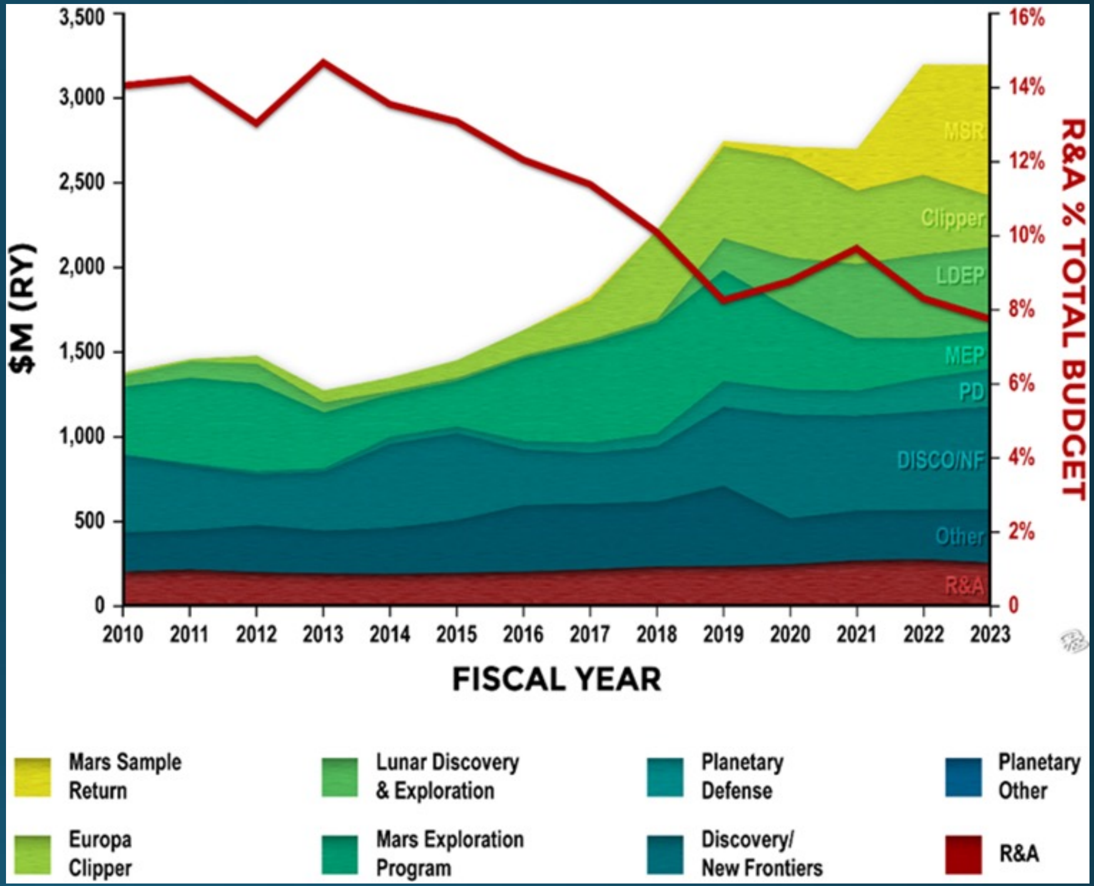
4) Creating and sustaining an inclusive community free of hostility and harassment

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

Research & Analysis (R&A)

- Intellectual foundation that ensures NASA's activities maximize the expansion of knowledge
- Key importance: openly competed programs that drive innovation & support broad access and DEIA
- NASA's fractional investment in planetary R&A has decreased from near 15% in 2013 to ~ 8% currently
- Reversing this trend of decreasing fractional investment in R&A is essential to success of NASA's planetary program

NASA Planetary Division Budget Breakdown by Year



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.

Astrobiology

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

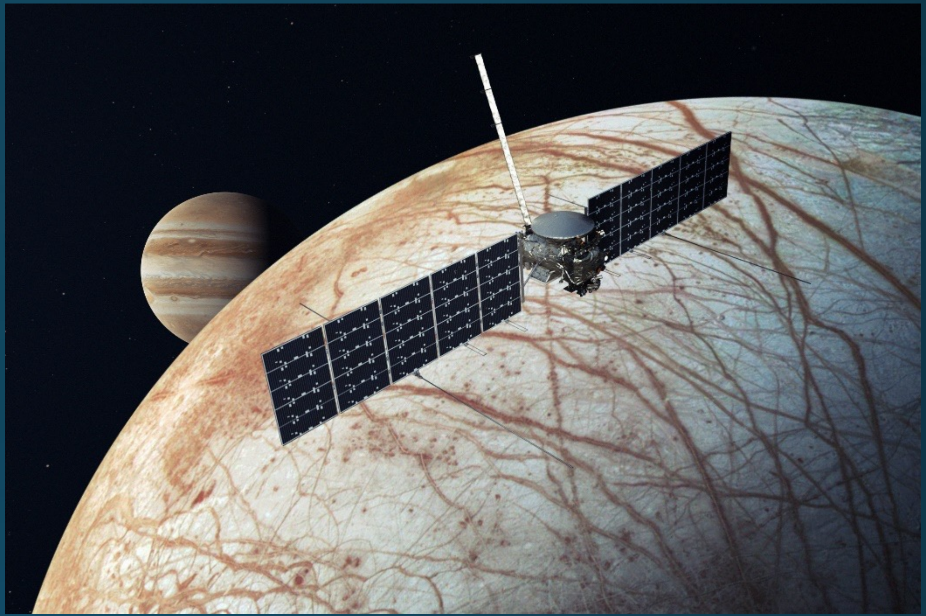
Dynamic habitability and the co-evolution of planets and life are key concepts that require mechanisms to support interdisciplinary and cross-divisional collaboration*

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*

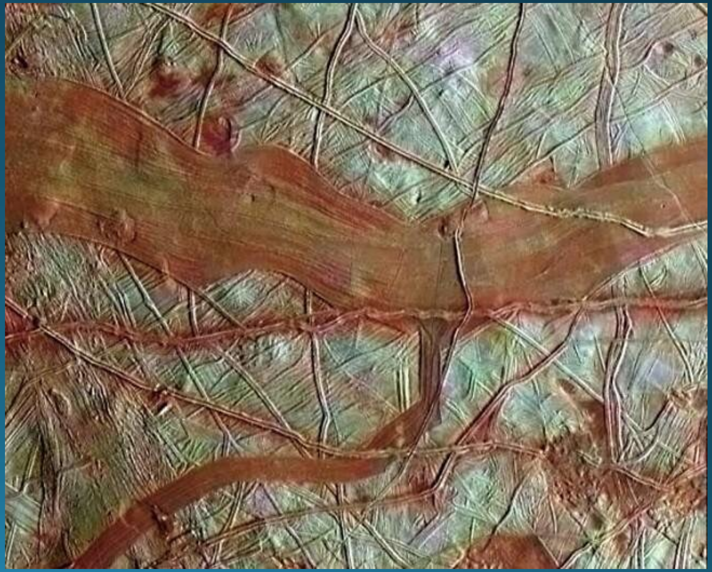
*From 2019 NASEM *Astrobiology Strategy for the Search for Life in the Universe*

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 and closely monitor its cost



Mars Sample Return (MSR)

- In 2017 NASA announced a “focused and rapid” concept to return samples cached by Perseverance to Earth with strong ESA participation

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

- Mars exploration has comprised ~25-35% of the PSD annual budget over the past three decades

- **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)

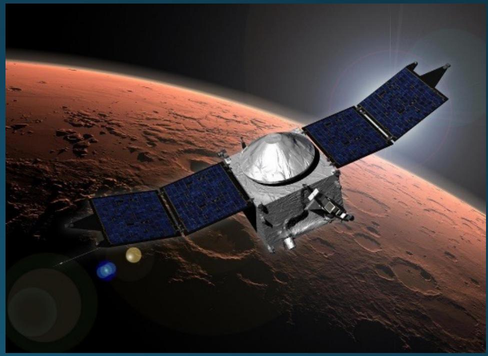
The Mars Exploration Program is a scientific success story that enables:

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

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



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:

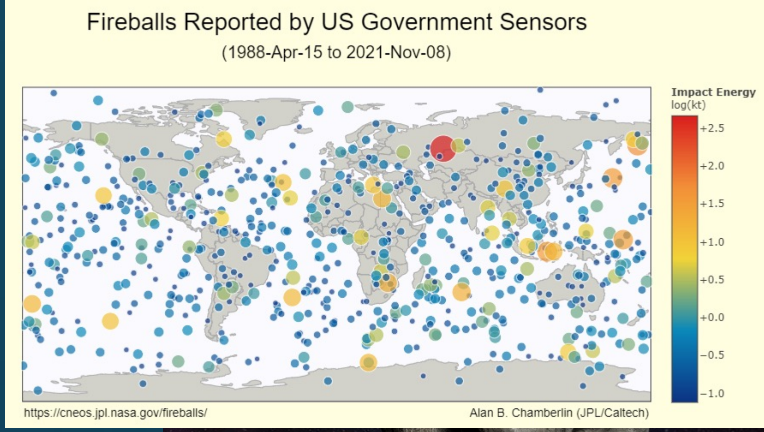
- Utilize CLPS for delivery to the lunar surface
- Collect ~100 kg of samples in a ~10^3 km traverse across diverse terrains in the South Pole Aiken basin
- Deliver the samples for return to Earth by astronauts

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



- 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

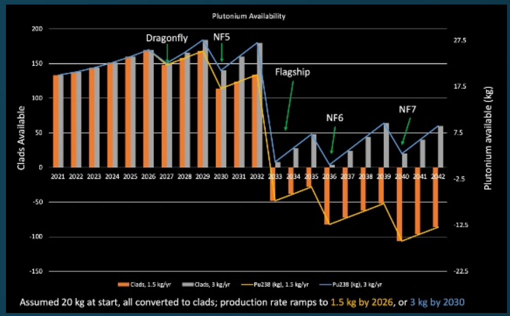
NASA should fully support the development and timely launch of NEO Surveyor to achieve the highest priority planetary defense NEO survey goals

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**

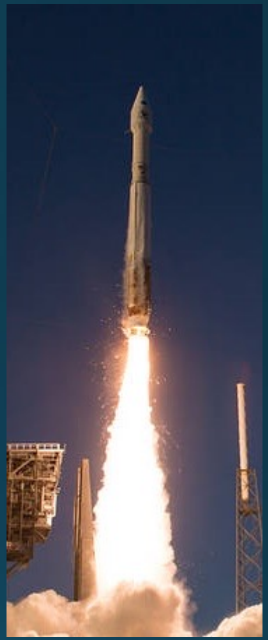
NASA and NSF should develop a plan to replace ground-based radar capabilities lost with Arecibo, which are crucial for planetary defense and Near Earth Object studies

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

- Highly successful program open to all science achievable within specified cost cap

- 2014 and 2018 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 selected missions are about a factor of two larger than the Phase A-D cost cap, a large mismatch

- Recommend return to a single (but substantially increased) cost cap for Phases A-F

  - Maximizes scientific return per total dollar cost, in keeping with core philosophy of Discovery program
  - Allows each team to allocate costs between development and operations to best suit their mission
  - Better aligns cost cap with true LCC of recent selections
  - Launch vehicle costs should continue to be excluded; beyond proposer’s control and (largely) predictable

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 Cost Structure

Crucial program of PI-led, medium-class missions that address specified mission themes

- Recommend Phase E costs be included in the cost cap to better align cap with true Life Cycle Cost
- 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

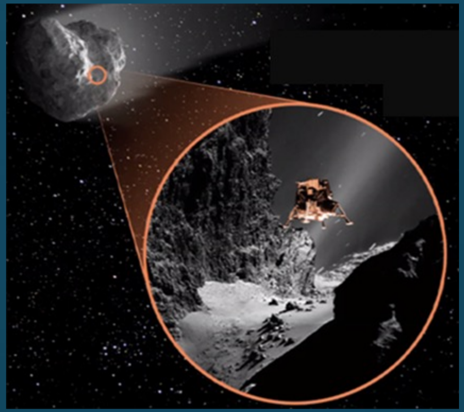
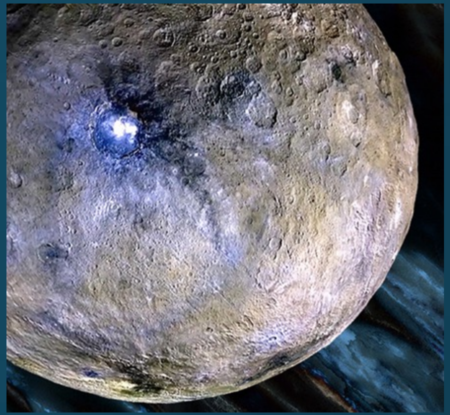
- **The NF Phase A-F cost cap, exclusive of quiet cruise and launch vehicle costs, should be increased to $1.65 billion in FY25 dollars**
- **A quiet cruise allocation of $30 million per year should be added to this cap, with quiet cruise to include normal cruise instrument checkout and simple flyby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

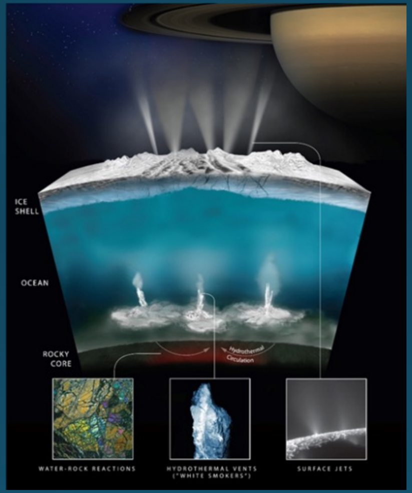
NF-6 Mission themes (alphabetical):

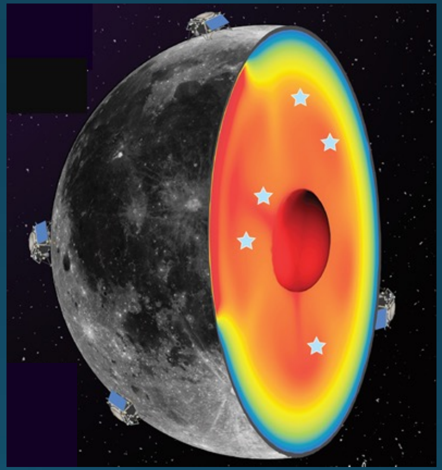
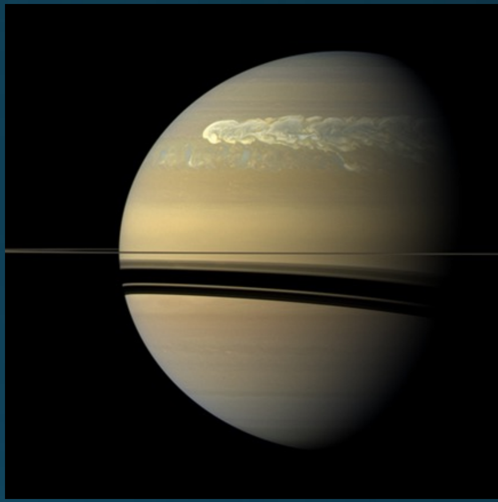
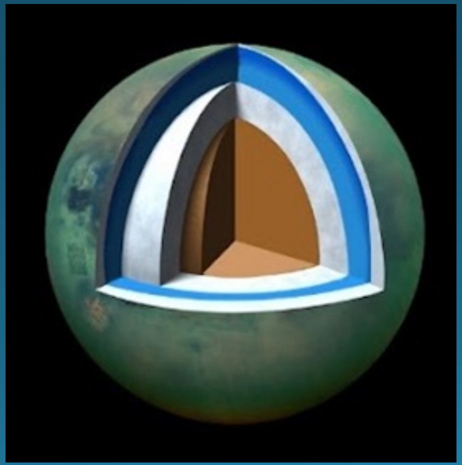
- Centaur Orbiter and Lander
- Ceres sample return
- Comet surface sample return
- Enceladus multiple flyby
- Lunar Geophysical Network
- Saturn probe
- Titan orbiter
- Venus In Situ Explorer

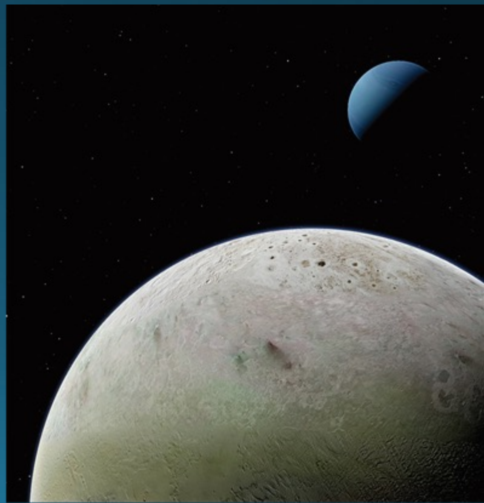
NF-7: All non-selected from NF-6 plus

- Triton Ocean World Surveyor



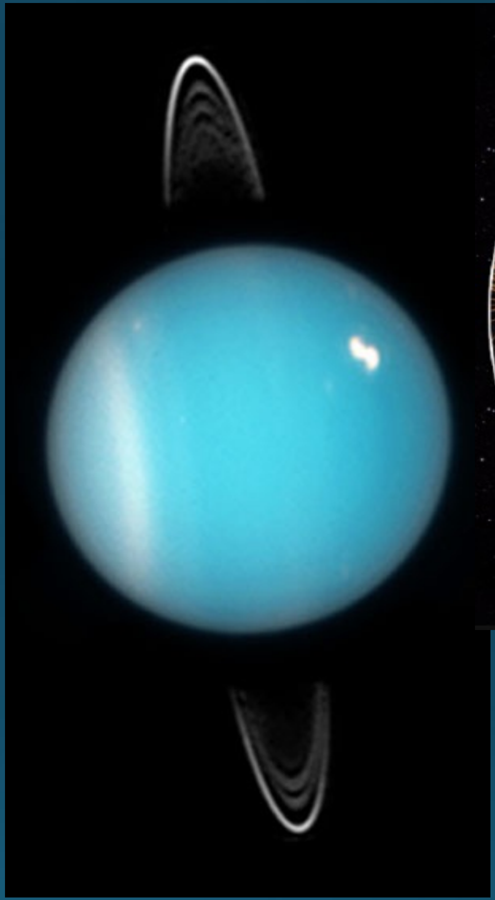



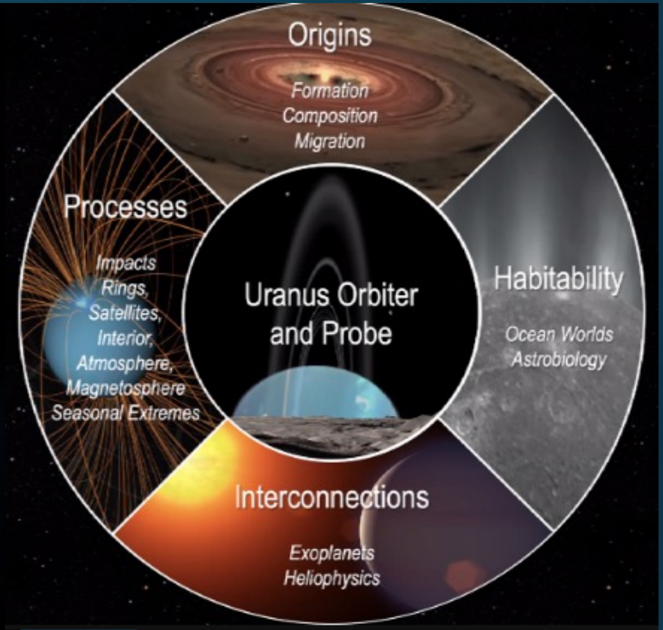
Highest priority new flagship: Uranus Orbiter and Probe

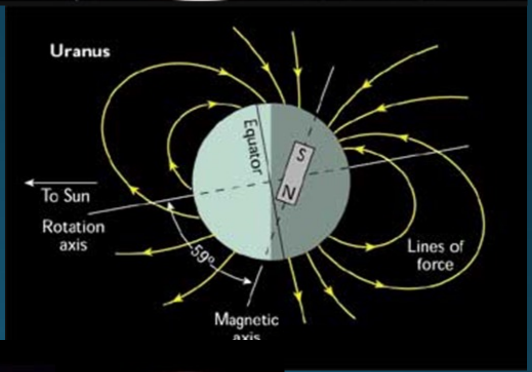
- In situ probe & multi-year orbital tour: atmosphere, interiors, magnetosphere, rings, and satellites
- First dedicated study of class of planets that may be most common in the universe
- Technically ready to start now, Low-Medium Risk rating
- Launch on Falcon Heavy Expendable

  → 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)

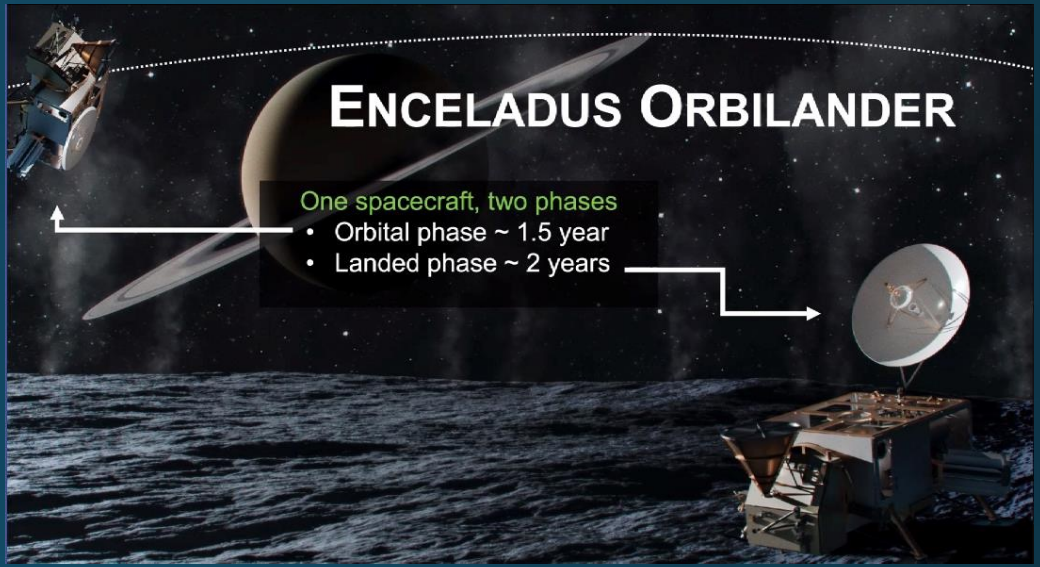




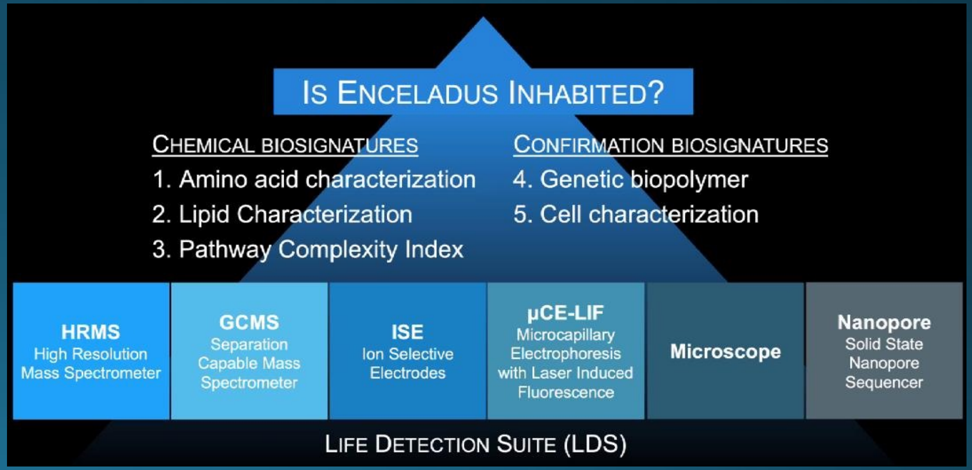


Second priority new flagship: Enceladus Orbilander

- 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
  - Starts with PSD’s FY23 planning 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

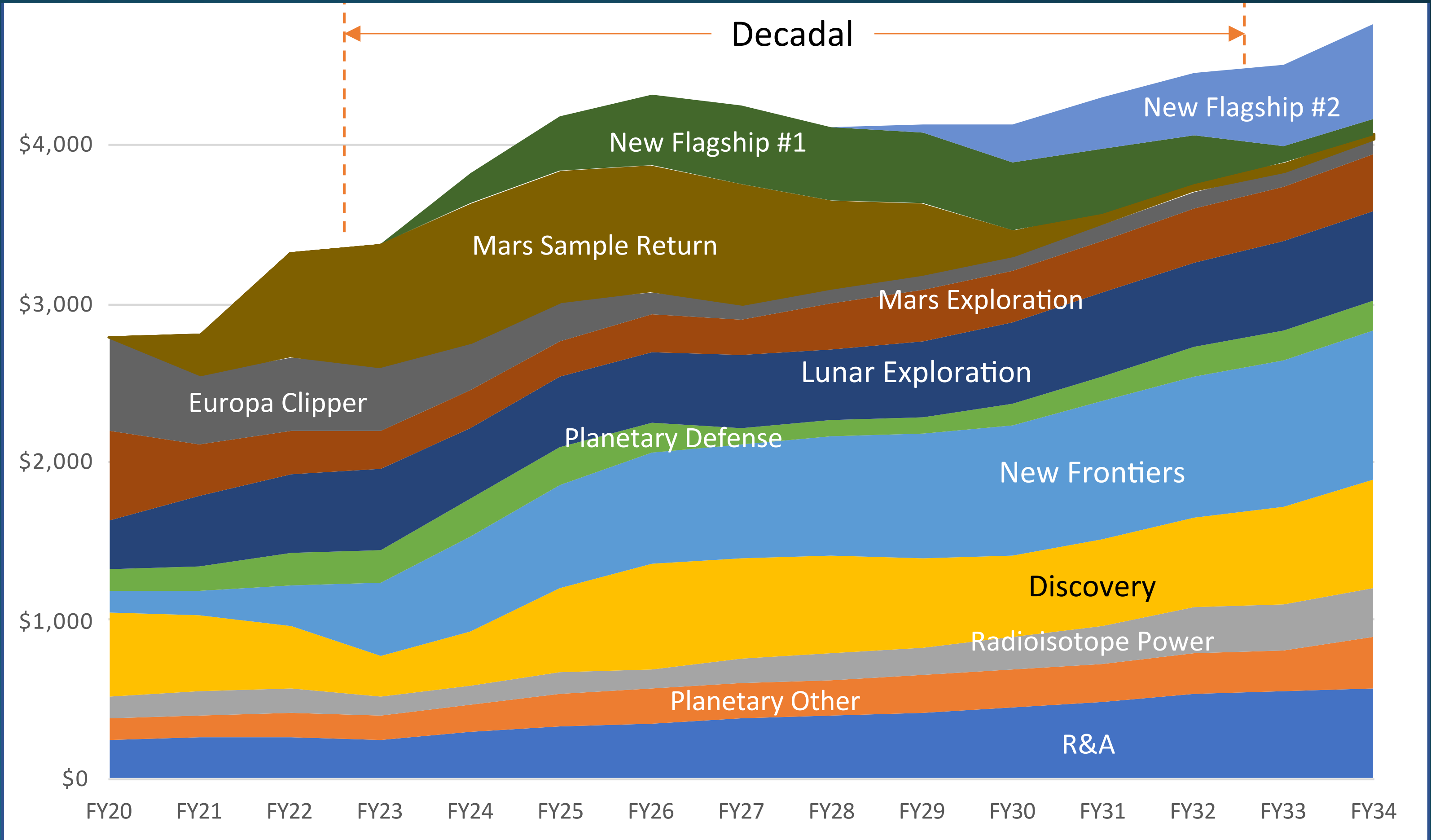
- Continues support for missions in operation and development
- Continues the Mars Sample Return campaign as currently planned
- Increases R&A funding to 10% of the annual PSD budget by mid-decade ($1.25 billion increase)
- Initiates the Uranus Orbiter and Probe Flagship mission in FY24
- Initiates five 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
- Continues support for the Lunar (LDEP) Program with mid-decade start of Endurance-A
- 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
- Initiates the Enceladus Orbilander in FY29

The Recommended Program

Priorities for total investment across decade

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**

Notional per-year budgetary sandchart



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 new 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

Recommended vs. Level

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**

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

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												

Substantial → Transformative

Decadal Survey Rollout

Presentations to date:

- Pre-release briefings to NASA, NSF, and congressional staffers (remote)
- Public release (from DC)
- Testimony before the House Space Subcommittee (remote)
- MEPAG (Denver)
- Exoplanets IV (Las Vegas)
- AbSciCon (Atlanta)
- LEAG Town Hall (remote)
- SBAG (remote)
- OPAG (DC)
- Space Studies Board (DC)
- AAS (Pasadena)
- PAC (remote)

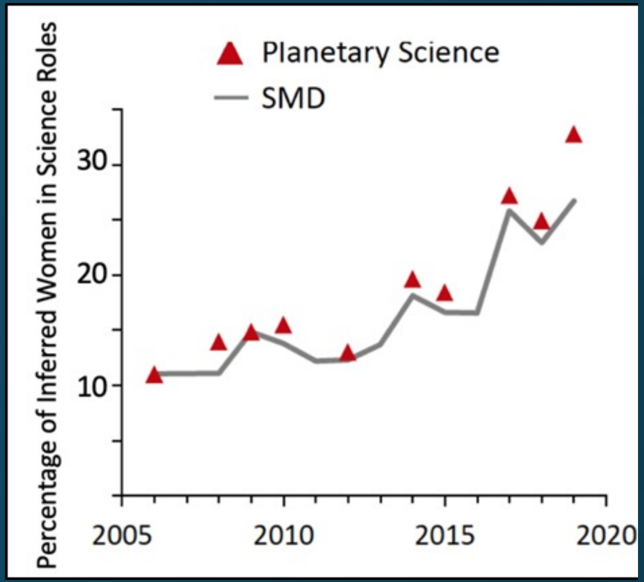
Future/in progress:

- SSERVI Exploration Forum
- COSPAR
- EPSC
- JPL, APL

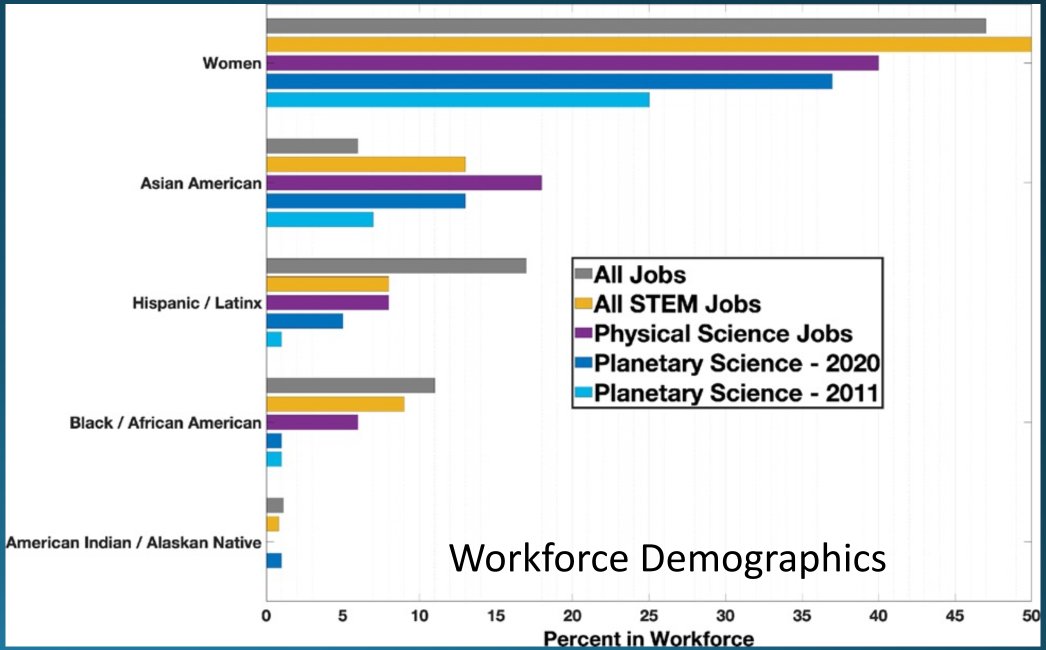
Backup

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

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?"

Lessons Learned

1. Science question based structure: seen as very successful
   - Orients everything to science, breaks down silos, drives broad interaction and discussion
   - Time consuming the first time implemented, should be easier next time
2. Destination-based panels were still beneficial, particularly in identifying needed mission studies
3. Virtual meetings:
   - Many benefits: a lot more time to digest material, deliberate & reach consensus → more mature thinking/reasoning than a few in-person meetings
   - COVID may have led to more attentive remote participation
   - Downside: longer to establish group dynamics and more time to reach consensus on difficult decisions

   → In person meetings near beginning & end, with lots of virtual meetings mid-way in process
4. White papers: more advance guidance to community (clarity of argument and creative ideas more important than author list or number of papers submitted, e.g.); consider shortening to 5 pages; also need an accessible system to sort papers by topical keywords
5. Need to re-think pre-survey mission studies:
   - How to insure broadly important studies are completed; difficulty in a study PI developing sense of "ownership"
   - Perhaps more like SDTs? With at least some concepts identified in advance by a body like CAPS with inputs from AGs?
   - Encourage teams to consider descope options and available LVs
6. SoP Treatment: writing group comprised of members of all panels, together with NAS member social scientist on steering group, worked well
7. Re-instate intern/graduate student note-takers

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

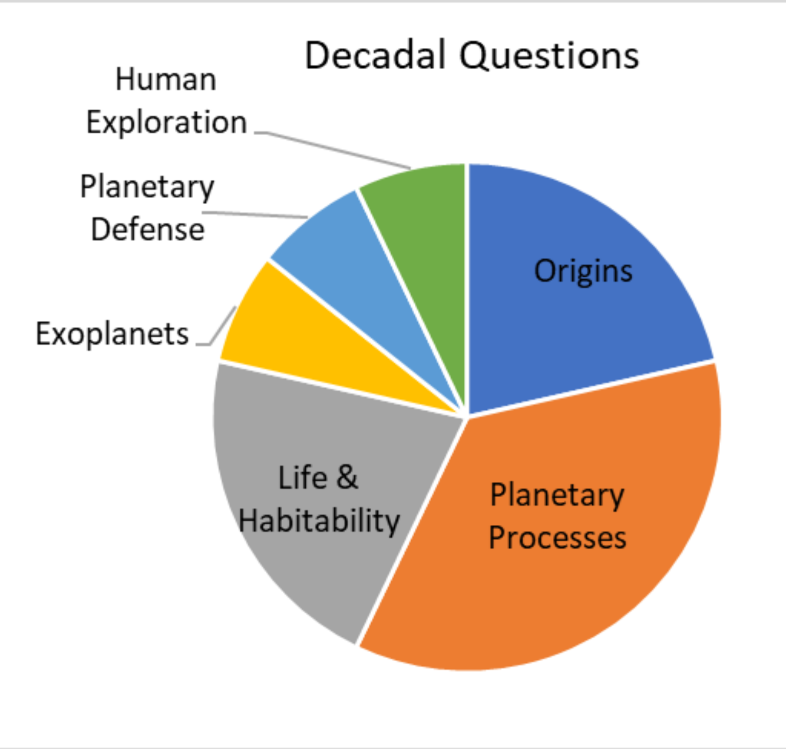
NASA should implement decision rules in the following order:

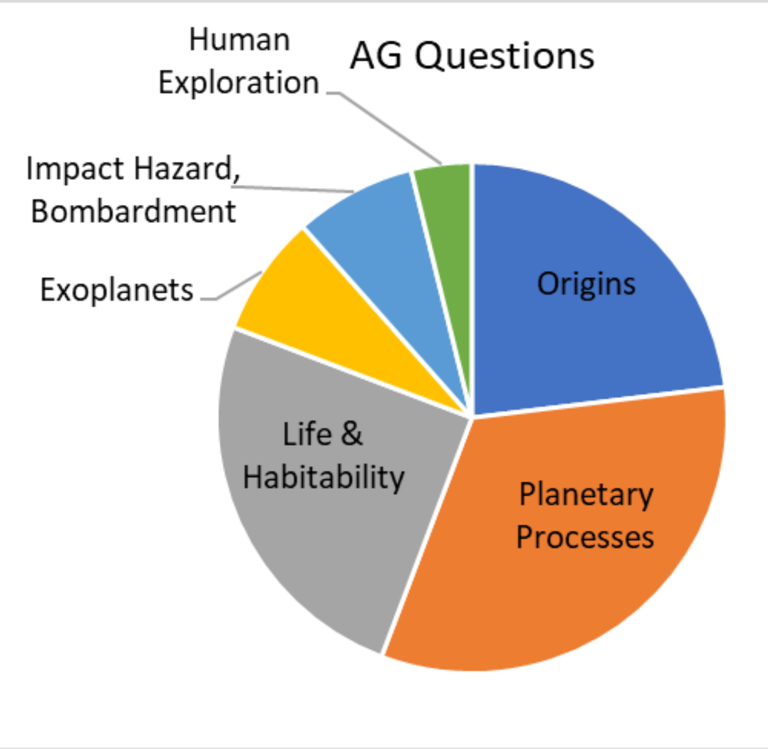
1) Delay the start of the Uranus Orbiter/Probe flagship mission
2) Reduce the number of new Discovery missions from five to four
3) Reduce the funding level for Planetary Defense by removing the new-start flyby characterization mission
4) Reduce the cadence of New Frontiers in the coming decade
5) Reduce 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

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
- 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