Decadal Survey

The process and the prioritized recommendations to the Planetary Science Mission Directorate

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July 18th, 2022

Summer Student Lecture Series

Acknowledgements

- The nearly 800-page Decadal Report:

  Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032

  Can be downloaded from the National Academies Website:

  https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032

- Majority of the information presented here are taken from the presentation by the Co-Chairs of the Decadal Study available at:

  https://nap.nationalacademies.org/resource/26522/public-briefing-slides-april-19-2022.pdf

- Materials prepared by David Hash*, NASA ARC based on the Decadal report were used in the technology sections of this presentation.

*Entry Systems and Technology Division Chief

What is this Talk about?

- Have you ever wondered about how NASA decides what missions to pursue?
  - Is there a process? What is the process like? Is it transparent? Who decides? Can anyone influence such a process?
- What are the missions, in the coming decades, NASA is going is likely undertake and what is needed to enable these missions?

Knowing the prioritized missions and the challenges may allow you to prepare yourself to become part of the missions and/or be part of technology development to enable these missions.

Planetary Science and Astrobiology Decadal Survey (2023-2032) provides the insight into the "why?, what? and when?" of NASA's robotic science missions in the coming decade(s)

Early History of NASA Space Missions

Space Shuttle System
(1981 – 1990)

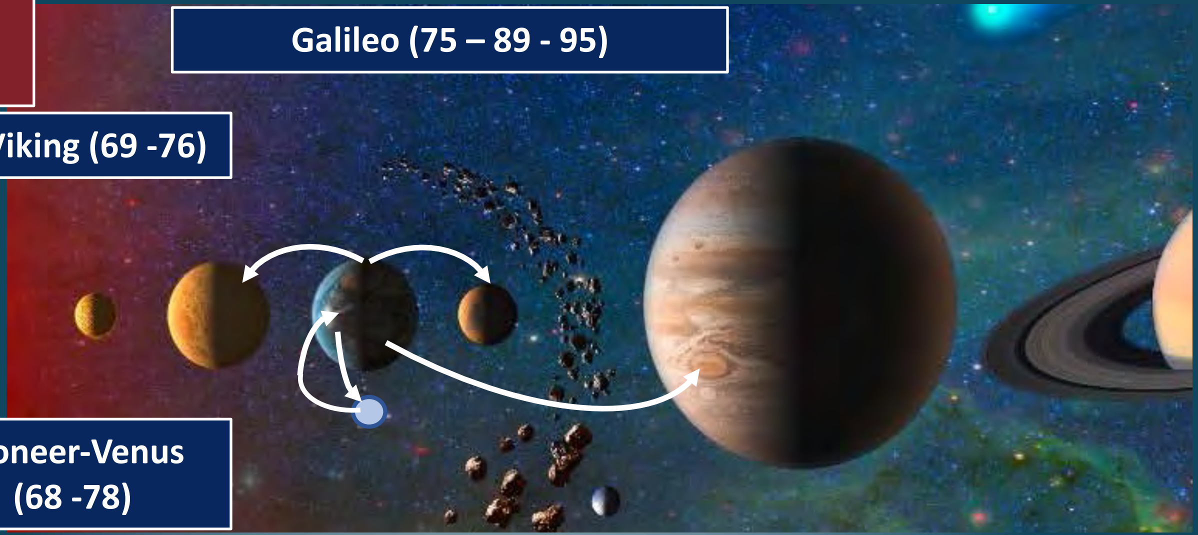
International Space Station
(1984 – 1998)

1950	1960	1970	1980	1990	2000	2010	2020

Apollo
(61 – 72)

Galileo (75 – 89 - 95)

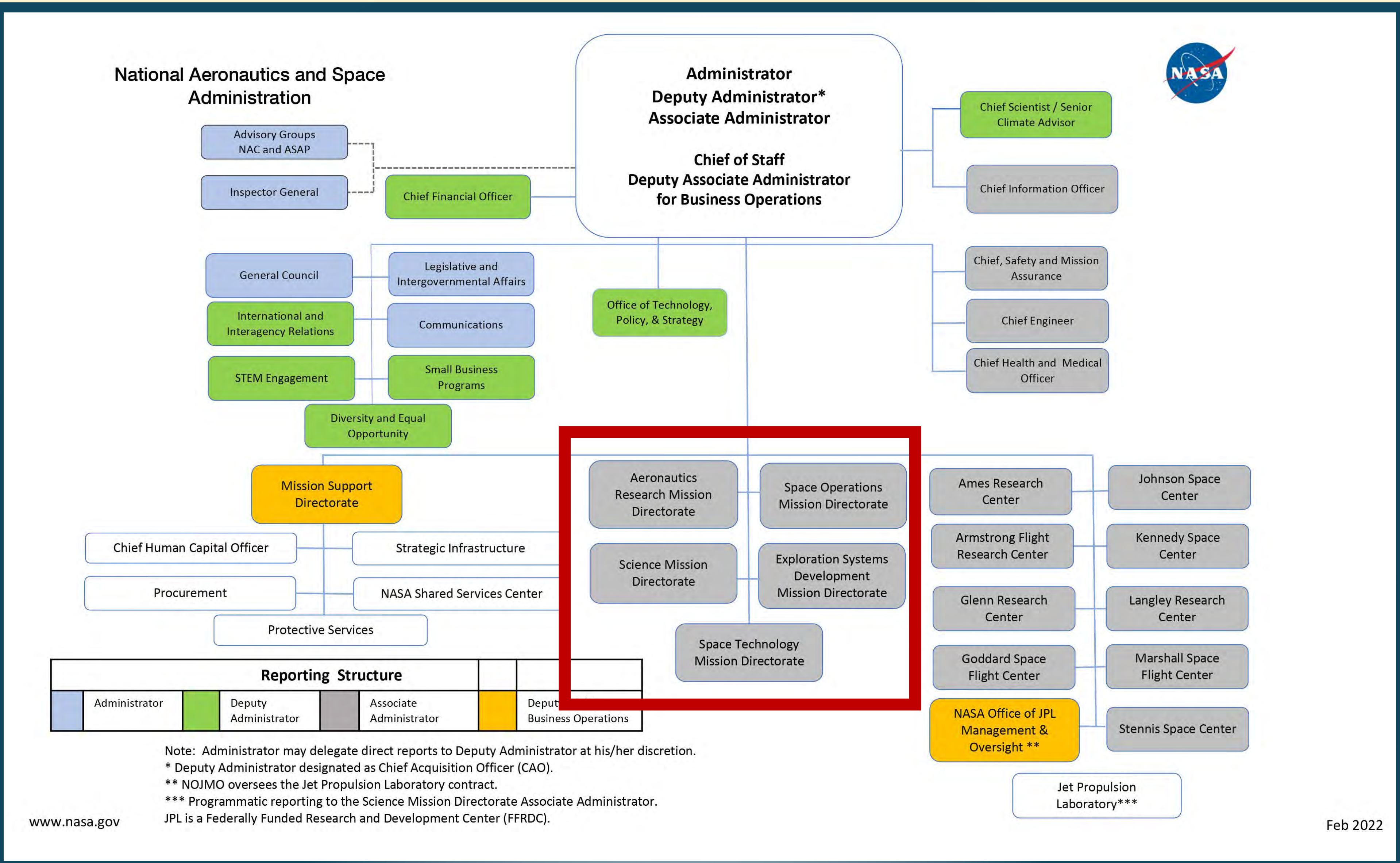
Viking (69 -76)



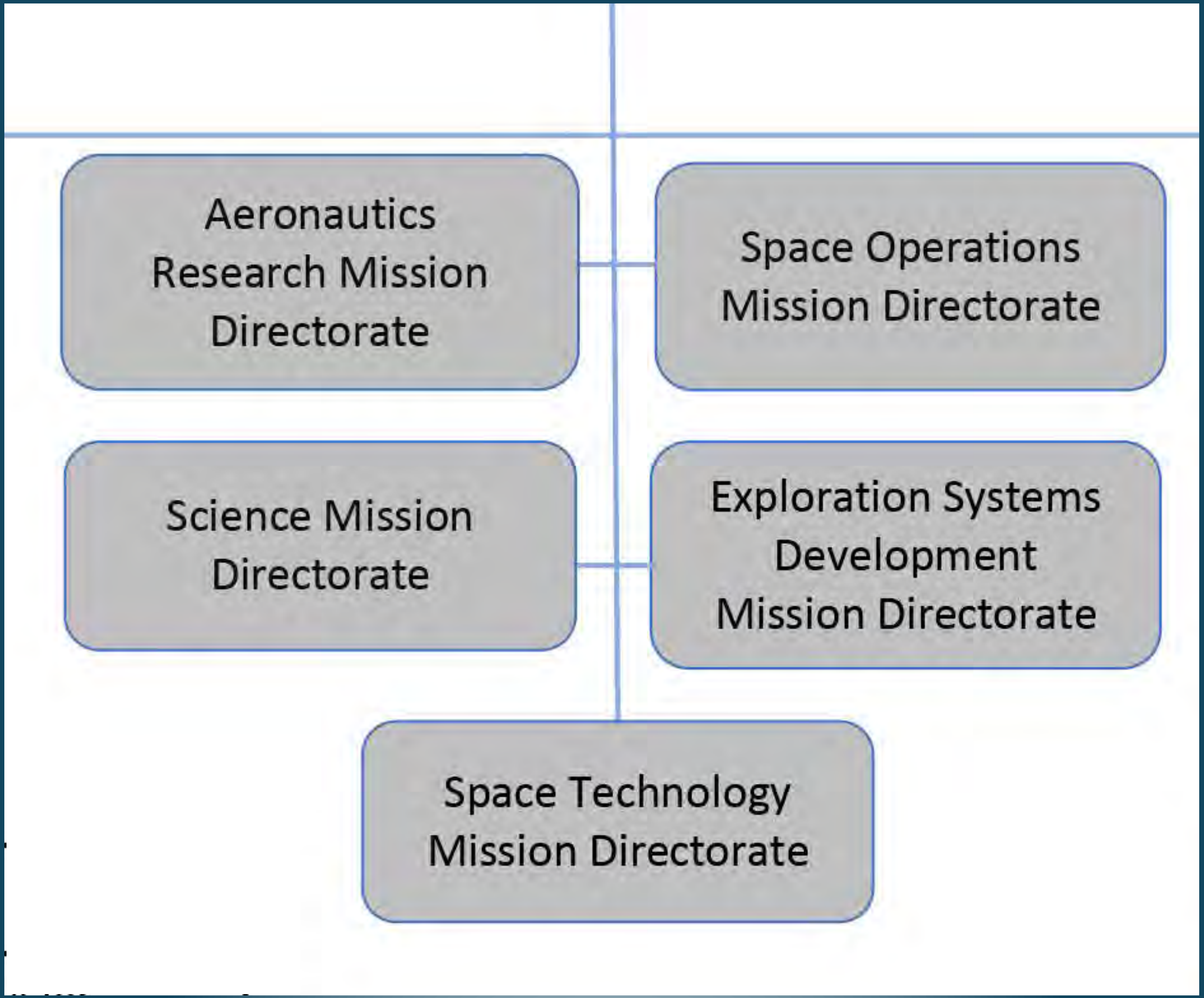
Pioneer-Venus
(68 -78)

Lunar and Planetary Missions (1960 – 1990)

NASA Organization Today



Organizations Responsible for NASA Missions



NASA's Mission Directorates

ARMD:

- Focused on **transforming aviation to make it more sustainable and more accessible** than ever before. Vision includes enabling new options for air travel using vehicles propelled by electricity, flying passengers faster than the speed of sound, and by managing air traffic at every altitude with the help of new automated systems that are even safer and more efficient than today.
- NASA's aeronautics research is primarily conducted at four NASA centers: Ames Research Center and Armstrong Flight Research Center in California, Glenn Research Center in Ohio, and Langley Research Center in Virginia.

STMD:

- Focused on **advancing technologies and testing new capabilities at the Moon**. Moon will serve as a technology testbed and proving ground for Mars.
- Investments in revolutionary, American-made space technologies provide solutions on Earth and in space.
- Space technology research and development take place at NASA centers, universities and national labs and leverages partnerships with other government agencies as well as commercial and international partners.

NASA's Missions – Selection and Implementation?

ESDMD:

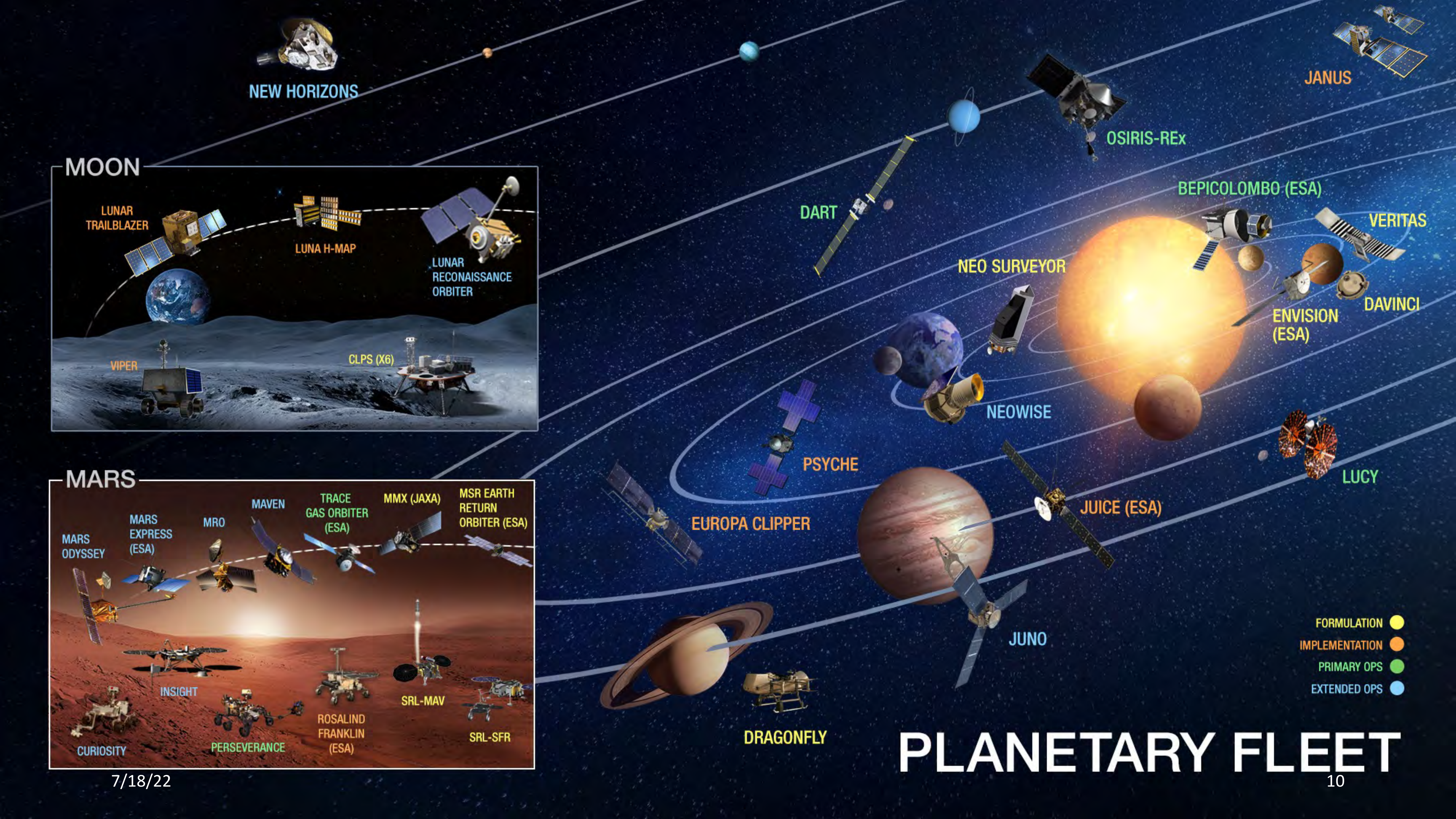
- The Exploration Systems Development Mission Directorate **defines and manages systems development for programs critical to the NASA's Artemis program and planning for NASA's Moon to Mars exploration approach in an integrated manner**. ESDMD manages the human exploration system development for lunar orbital, lunar surface, and Mars exploration. ESDMD leads the human aspects of the Artemis activities as well as the integration of science into the human system elements. ESDMD is responsible for development of the lunar and Mars architectures. Programs in the mission directorate include Orion, Space Launch System, Exploration Ground Systems, Gateway, Human Landing System, and Extravehicular Activity (xEVA) and Human Surface Mobility.

SOMD:

Space Operations Mission Directorate manages **NASA's current and future space operations in and beyond low-Earth orbit (LEO), including commercial launch services to the International Space Station**. SOMD operates and maintains exploration systems, develops and operates space transportation systems, and performs broad scientific research on orbit. In addition, SOMD is responsible for managing the space transportation services for NASA and NASA-sponsored payloads that require orbital launch, and the agency's space communications and navigation services supporting all NASA's space systems currently in orbit.

Science Mission Directorate

- The Science Mission Directorate (SMD) engages the Nation's science community, sponsors scientific research, and develops and deploys satellites and probes in collaboration with NASA's partners around the world to answer fundamental questions requiring the view from and into space.
  - **SMD seeks to understand the origins, evolution, and destiny of the universe and to understand the nature of the strange phenomena that shape it.**
- SMD organizes its work into five broad scientific pursuits. Each of these pursuits is managed by a Division within the Directorate, each having its own science sub-goals.
  - Earth Science: Study planet Earth from space to advance scientific understanding and meet societal needs
  - **Planetary Science: 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**
  - Heliophysics: Understand the Sun and its effects on Earth and the solar system
  - Astrophysics: Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets
  - Biological and Physical Sciences: Learn how biological and physical systems work at a fundamental level by studying them in space.


PLANETARY FLEET
NEW HORIZONS
JANUS
OSIRIS-REx
DART
BEPICOLOMBO (ESA)
VERITAS
NEO SURVEYOR
DAVINCI
ENVISION (ESA)
NEOWISE
PSYCHE
LUCY
EUROPA CLIPPER
JUICE (ESA)
JUNO
DRAGONFLY
MOON
LUNAR TRAILBLAZER
LUNA H-MAP
LUNAR RECONAISSANCE ORBITER
VIPER
CLPS (X6)
MARS
MARS ODYSSEY
MARS EXPRESS (ESA)
MRO
MAVEN
TRACE GAS ORBITER (ESA)
MMX (JAXA)
MSR EARTH RETURN ORBITER (ESA)
INSIGHT
SRL-MAV
CURIOSITY
PERSEVERANCE
ROSALIND FRANKLIN (ESA)
SRL-SFR
FORMULATION
IMPLEMENTATION
PRIMARY OPS
EXTENDED OPS

Planetary Science Mission Classes

Flagship or Large Strategic Science Missions:

- NASA's **large strategic science missions** or **large strategic missions**, known as **Flagship missions** are the most capable NASA science mission and they are also most expensive. These are non-competed missions. NASA plans and develops the mission concept and manages the implementation through one of the mission management organization (e.g. JPL)
  - Recent Flagship Missions include Mars 2020, Mars Science Laboratory.
  - Future missions include Europa Clipper (2024) and Uranus Orbiter and Lander (2030+)

Medium Class Science Missions (New Frontiers Program):

- The **New Frontiers program** is a series of medium-class missions (~ $1 B) with the purpose of furthering the understanding of the Solar System and provide high science returns.
  - The New Frontiers program was advocated by NASA and granted by Congress in CY 2002 and 2003
  - Decadal Survey provides a list of missions (science) without prioritization and NASA through NF-Announcement of Opportunity invites proposals. Through a two-step selection process, NASA competitively selects and funds the mission. PI led. Managed by 1 of 3 centers (JPL, APL or GSFC).
  - *New Horizons*, a mission to Pluto (2006), Juno (2011) and Osiris-REx (2016) are recent examples.
  - Future possibilities are: Saturn Atmospheric Entry Probe, Enceladus Multiple Flyby and Titan Orbiter

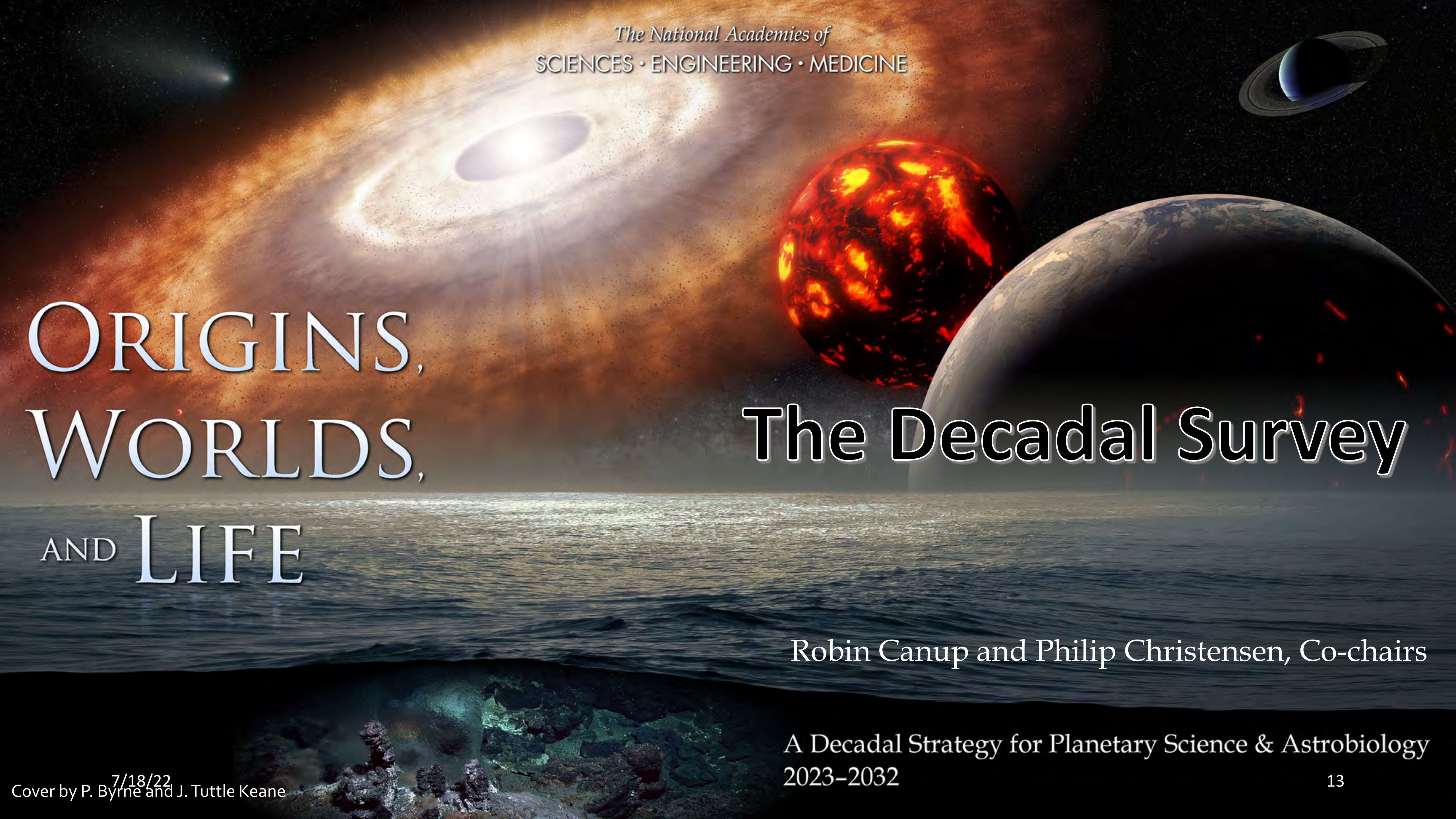
Planetary Science Smaller Mission Classes

Discovery Program:

- The goal of NASA's Discovery Program is to provide frequent flight opportunities for high quality, high value, focused, planetary science investigations that can be accomplished under a not-to-exceed cost cap of ~ $450M.
- The Discovery Program was a way to implement the "Faster, Better, Cheaper" policy of the then-NASA administrator Daniel S. Goldin.
- Discovery missions are competed on any science topic and assessed through peer review. Selected missions are led by a scientist (PI) and may include contributions from industry, universities or government laboratories.
- Mars Pathfinder, Stardust, Genesis, Mars InSight and recently selected Veritas (Venus) and DAVINCI (Venus)

SIMPLEX:

- SIMPLEx (Small Innovative Missions for Planetary Exploration) is NASA's smallest planetary mission with $55M cost cap (or about 1/10 of a Discovery mission).
- Using small spacecraft -- less than 400 pounds, or 180 kilograms in mass -- SIMPLEx will conduct stand-alone planetary science missions. Each will share their ride to space with either another NASA mission or a commercial launch opportunity.
- Lunar Trailblazer, Janus & EscaPADE are the three SIMPLEx missions selected in 2019



The Decadal Survey

Robin Canup and Philip Christensen, Co-chairs

Cover by P. Byrne and J. Tuttle Keane

What is Decadal Survey?

- It is a process, sponsored by NASA and created by the National Academies of Sciences, Engineering, and Medicine, **to reach consensus on a visionary 10-year program to advance the highest-priority science.**
  - It reviews a science discipline's progress in the previous decade and engages its community to prioritize science at the frontier.
  - A successful survey program also serves **societal goals, resonates with the interests and curiosity of the public, motivates Congress, aligns with the initiatives of the executive branch, and fits within the fiscal constraints of the federal budget**.
  - Decadal survey reports have been widely cited and praised, adopted as definitive roadmaps by some federal offices and agencies and Congress, and read as guidebooks by the universities and research centers whose science programs nourish and serve society.

Writing the decadal survey requires significant effort over the course of nearly two years.

- Dozens of scientists serve on its steering committee, and hundreds more provide input via specific topic panels and formal paper submissions.

The planetary science community produced its first decadal survey in 2003.

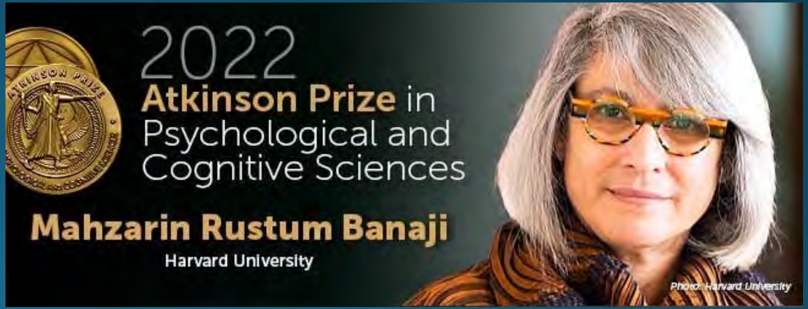
- The second planetary decadal survey, "Vision and Voyages", in 2012, outlined the recommendations for Planetary Science in the Decade (2013-2022)
- The third decadal survey, "Origins, Worlds and Life" was recently delivered to NASA and covers recommendations for the period (2023-2032)

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
- 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."



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

Panels (chairs and vice chairs listed first)

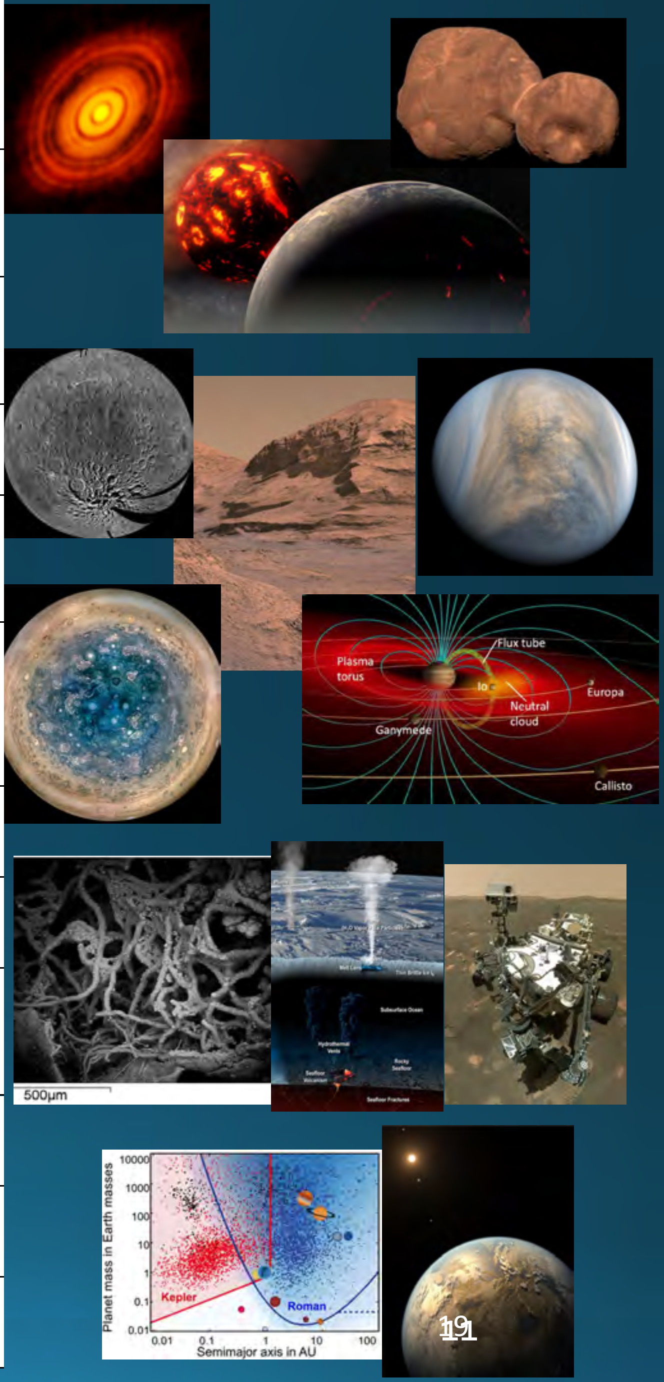
Moon and Mercury	Venus	Mars	Small Bodies	Ocean Worlds & Dwarf Planets	Giant Planet Systems
Tim Grove, NAS	Paul Byrne	Vicky Hamilton	Nancy Chabot	Alex Hayes	Jonathan Lunine, NAS
Brett Denevi	Larry Esposito	Bethany Ehlmann	Carol Raymond	Francis Nimmo, NAS	Amy Simon
James Day	Giada Arney	Will Brinckerhoff	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)

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

Astrobiology

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

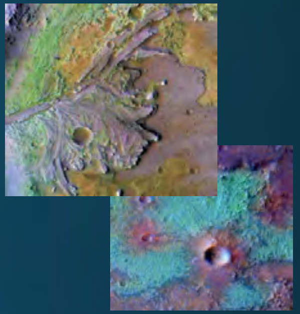
Dynamic habitability and the co-evolution of planets and life are key concepts that require mechanisms to support interdisciplinary and cross-divisional collaboration

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

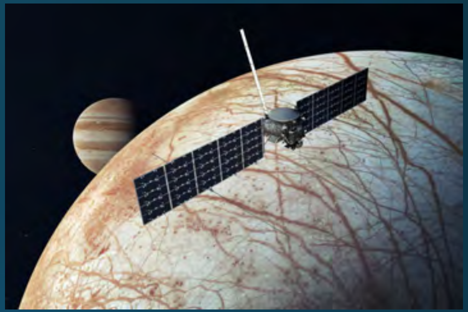
*From 2019 NASEM *Astrobiology Strategy for the Search for Life in the Universe*

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)

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

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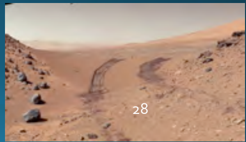
Mars Exploration Program (MEP)



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**

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**

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

Lunar Discovery and Exploration Program (LDEP)

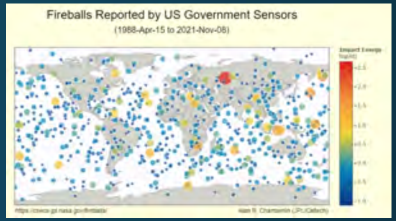
- Commercial Lunar Payload Services (CLPS) program goal is to enable reliable and affordable access to the lunar surface by helping to establish a viable commercial lunar sector
- Promising and innovative approach that will benefit PSD and lunar science

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**

The importance of Planetary Defense

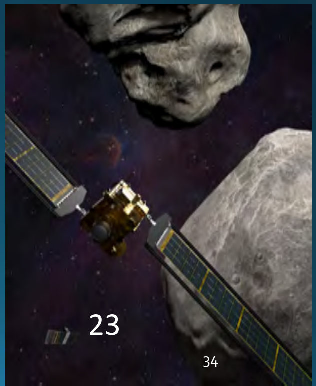
- NASA's Planetary Defense Program coordinates and supports activities to detect and track all Near-Earth Objects (NEOs) and assess their threat
- PSD provides expertise on small body science, spaceflight technology, and missions
- NEO deflection demonstrations, like DART, provide technology building 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**



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

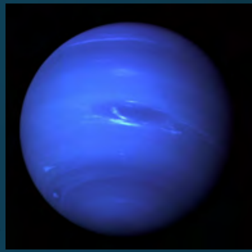
→ Ice giant mission judged to be the top priority, primarily for ability to produce transformative, breakthrough science for only class of planets never studied with a dedicated orbital tour

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

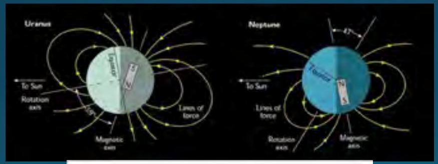
Both Uranus & Neptune are scientifically compelling

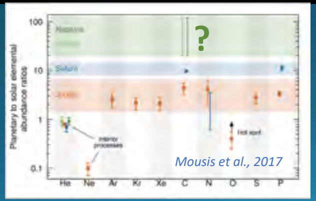
- Offset, tilted magnetic field
- Regular satellite system
- Possible ocean worlds (Ariel, Titania)
- Ring system
- Extreme seasons and storms
- Low internal heat

- 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



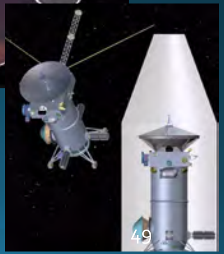


Highest priority new flagship: Uranus Orbiter and Probe

- 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)



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)

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

<u>Cost structure</u>:

- 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

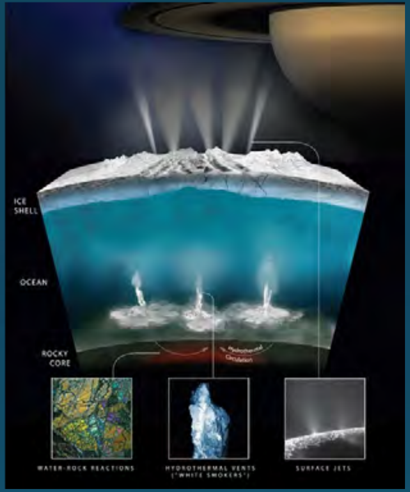
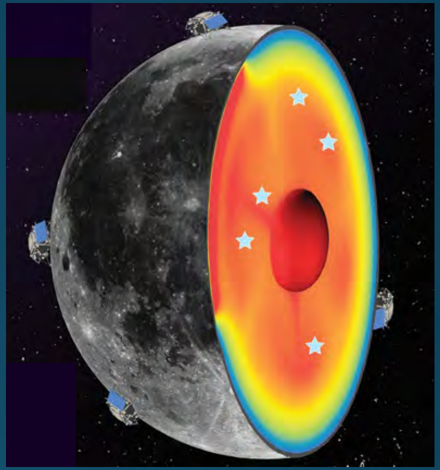
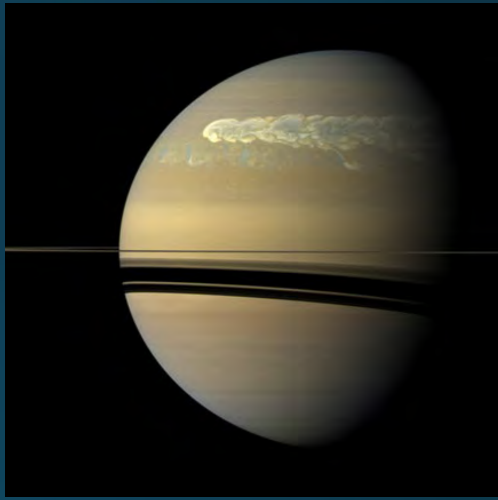
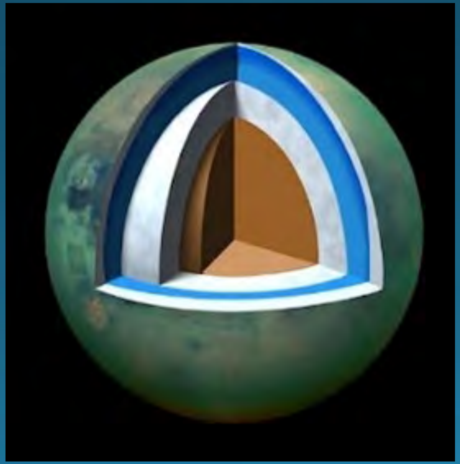
NF-6 Mission themes (alphabetical):

- 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

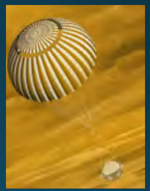



Discovery Program








- 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

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

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%

Some of the EDL Technology Focused White Papers Submitted to the Decadal Survey

- “TPS and Entry Technologies for Future Outer Planet Exploration,” Donald Ellerby,, et al.
- “Entry, Descent, and Landing Instrumentation,” Jose Santos, et al.
- “TPS and Entry System Technologies for Future Mars and Titan Exploration,” Robin Beck, et al.
- “Thermal Protection System to Enable Ice Giant Aerocapture Mission for Delivering both an Orbiter and an in-situ Probe,” Ethiraj Venkatapathy, et al.
- “Sustaining Mature Thermal Protection Systems Crucial for Future In-Situ Planetary Missions,” Ethiraj Venkatapathy, et al.
- “Thermal Protection System Materials for Sample Return Missions,” Todd White, et al.
- “Guidance and Control Approaches that Enable Titan Aerogravity Assist for an Enceladus Mission,” Benjamin Tackett, et al.
- “Aerocapture as an Enhancing Option for Ice Giants Missions,” Soumyo Dutta, et al.
- “Enabling and Enhancing Science Exploration Across the Solar System: Aerocapture Technology for SmallSat to Flagship Missions,” Alex Austin, et al.
- “Understanding and Mitigating Plume Effects During Powered Descents on the Moon and Mars,” Ryan Watkins, et al.

Michelle Munk and I were invited to give presentations to the Giant Planet and Venus sub-committees

On Technology

- **Finding:** NASA has not sustained the recommended level of planetary technology funding, 6-8 percent of the Planetary Science Division (PSD) budget, with the level declining to about 4 percent over the last five years. This is now significantly below the level of investment recommended in Visions & Voyages.
- **Recommendation:** NASA PSD should strive to consistently fund technology advancement at an average of 6 to 8 percent of the PSD budget.
- **Finding:** The committee found it difficult to uncover what technology activities were currently active and how much funding was being allocated to technology development, an issue that was also identified in the Visions & Voyages Midterm. Transparency is important to the science community as they plan for and develop approaches to accomplishing the next set of science objectives so that their implementation approaches can take advantage of the technology work being pursued by PSD and STMD.
- **Recommendation:** The PSD technology program should create a **PSD Technology Program Plan** that provides the details on what the program goals are, how the program operates, who is involved, and how the science community and supporting organizations can play a role.
- **Recommendation:** PSD should establish a standard mechanism for the science community and other relevant organizations to provide input into PSD on technology needs, including new and creative approaches to technology, similar to how the science community provides input through the various science assessment groups (AG). Two possible examples could be a **PSD Technology AG**, similar to the science AGs, or a collaboration among existing AG technology leads.

On Technology

- **Finding:** There are a number of important technologies that could improve PSD's science return on investment that are not being integrated into flight projects because they are deemed too risky by the flight projects.
- **Recommendation:** This second obstacle (technology at TRL-6 deemed too risky) should be addressed by PSD, and a solution implemented that considers the long-term return on investment of all technologies under development.
- Solutions could include:
  - Directing some technologies to be used or providing incentives for using technologies in this category, such as increasing the number of technologies offered in AOs; allowing technology demonstration mission in SIMPLEx AOs; or similar approaches in any new programs;
  - Allow missions to include technologies with high ROI for future missions by allocating additional reserves over and above any cost caps to cover unknowns;
  - Creating a separate technology line similar to the former New Millennium program where multiple technologies could be demonstrated in small flight missions;
  - Adopting a systematic way of bounding the risks, the cost, and the schedule of technologies at TRL 6 by requiring additional information at TRL 6 such as defining work required to complete the space qualification of all components necessary to achieve flight status and documenting the attendant list of technical and programmatic risks.

On Technology Maturation

- NASA requires that any new technologies be at TRL level 6 before a mission's preliminary design review to ensure the successful incorporation of that technology. **Visions & Voyages identified the transition of technologies from TRL 4 to TRL 6 as a 'valley of death', where there was no mechanism to bring these technologies to a level of maturity needed for insertion in flight projects**.
  - PSD embraced this recommendation and created the MatISSE (Maturation of Instruments for Solar System Exploration) program to help solve this obstacle for instrumentation and worked with STMD to include planetary technologies in their flight project technology lines. These changes have been very beneficial.
  - Now, NASA's technology development efforts are geared to bringing new technologies to TRL-6 with the expectation that flight projects will bring those technologies from TRL-6 to flight readiness status (TRL-8) and fly them.
- In some cases, when a TRL-6 technology is evaluated for insertion by a flight project during its early phases (e.g., Pre-Phase A), the technology might be deemed too programmatically and/or technically risky to be included in the mission. There are several reasons that might lead to this situation. Amongst the most important are: 1) TRL definitions still have a certain degree of ambiguity that might result in a premature conclusion of a technology development task, leaving too much scope for a flight project to accomplish within its resources; and 2) not all technologies at TRL-6 are created equal. Some take more resources and risks to mature them than flight projects can afford. **This has created a second obstacle where technologies judged to be insertable at TRL 6 are not being used (e.g., aerocapture).**

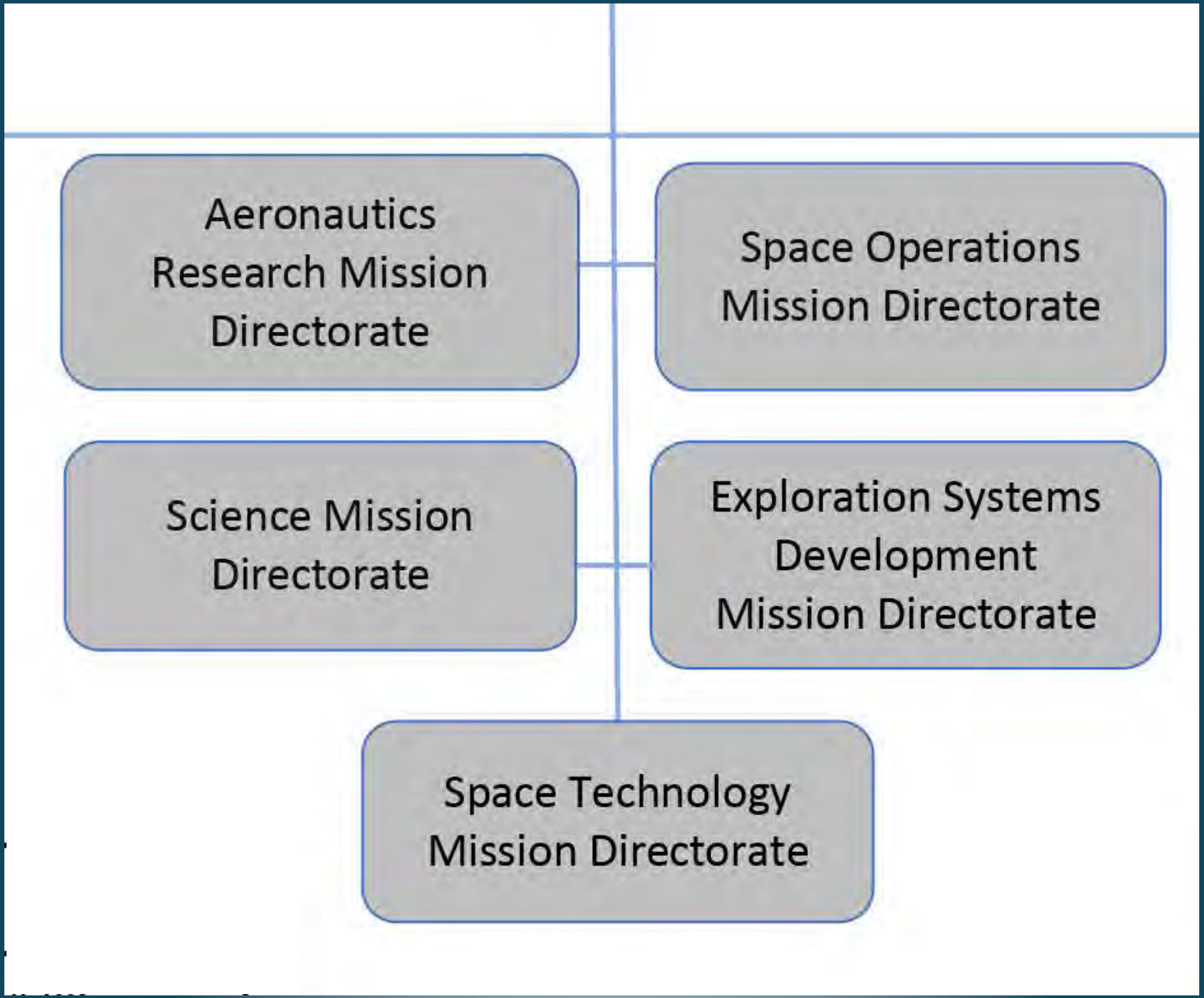
Entry/Deorbit, Descent, and Landing Systems

- NASA has invested considerable resources in the development of **Thermal Protection Systems (TPS) like the Heatshield for Extreme Entry Environment Technology (HEEET)**, and the **Phenolic-Impregnated Carbon Ablator (PICA).** These TPS technologies are currently capable of operating over a wide range of entry conditions and **are crucial for the landing of larger payloads on Mars and for enabling atmospheric probes on Venus, Saturn, Titan, Uranus, and Neptune.** HEEET (currently at TRL 6 for certain conditions) was developed in the last decade, as the heritage carbon phenolic used for the Galileo entry probe is no longer available (Ellerby et al. 2020).
- **Finding:** NASA's investments on TPS technologies have enabled several landing missions and atmospheric probes in the past and together with current developments like HEEET stand to enable many future missions to multiple destinations.
- In addition to these enabling technologies there are also **enhancing technologies** and engineering developments that can also benefit from investments prior to a project start. NASA has invested considerable resources in the **development of deployable aero-decelerators (e.g., HIAD, SIAD, and ADEPT)** that have the potential to dramatically increase landed mass on future missions. These technologies, however, seem to fall into the second valley of death, i.e., too risky, and do not yet seem to being considered for future missions.
- **Finding:** NASA and the science community would benefit from studying how the **maturing aero-decelerator technologies can be integrated into future missions to increase science value.**

Launch, Cruise, and Encounter Optimization

- **Aerocapture** is an orbital insertion technique which utilizes a single pass through a planetary atmosphere to dissipate enough orbital energy for planetary capture (Som Dutta, 2020). It can deliver large orbit insertion ΔVs with minimum fuel, resulting in significant reductions in transit time, and/or increases in science payload mass. Aerocapture can also enable planet orbit **insertion of SmallSats, launched as secondary payloads, on targets like Venus and Mars (Alex Austin, 2020).** Advances in atmospheric entry guidance and control techniques as demonstrated successfully by Curiosity and Perseverance on Mars and advances in **autonomous optical navigation** as demonstrated by the Deep Impact mission on comet Tempel 1, combined with the **development of new thermal protections systems (TPS)**, like the Phenolic-Impregnated Carbon Ablator (PICA) used also by Curiosity and Perseverance and the Heatshield for Extreme Entry Environments Technology (HEEET) that will be used by the Mars Sample Return’s Earth Entry Vehicle (EEV), **make Aerocapture a technology ready for mission infusion**. Because Aerocapture is not being proposed for use in missions, it is considered a “dormant” technology that is perceived as high risk in a mission competitive environment.
- **Finding: Aerocapture is a technology that is ready for infusion and that can enhance/enable a large set of missions, but that will require special incentives by NASA to be proposed and used in a science mission.**

Organizations Responsible for NASA Missions



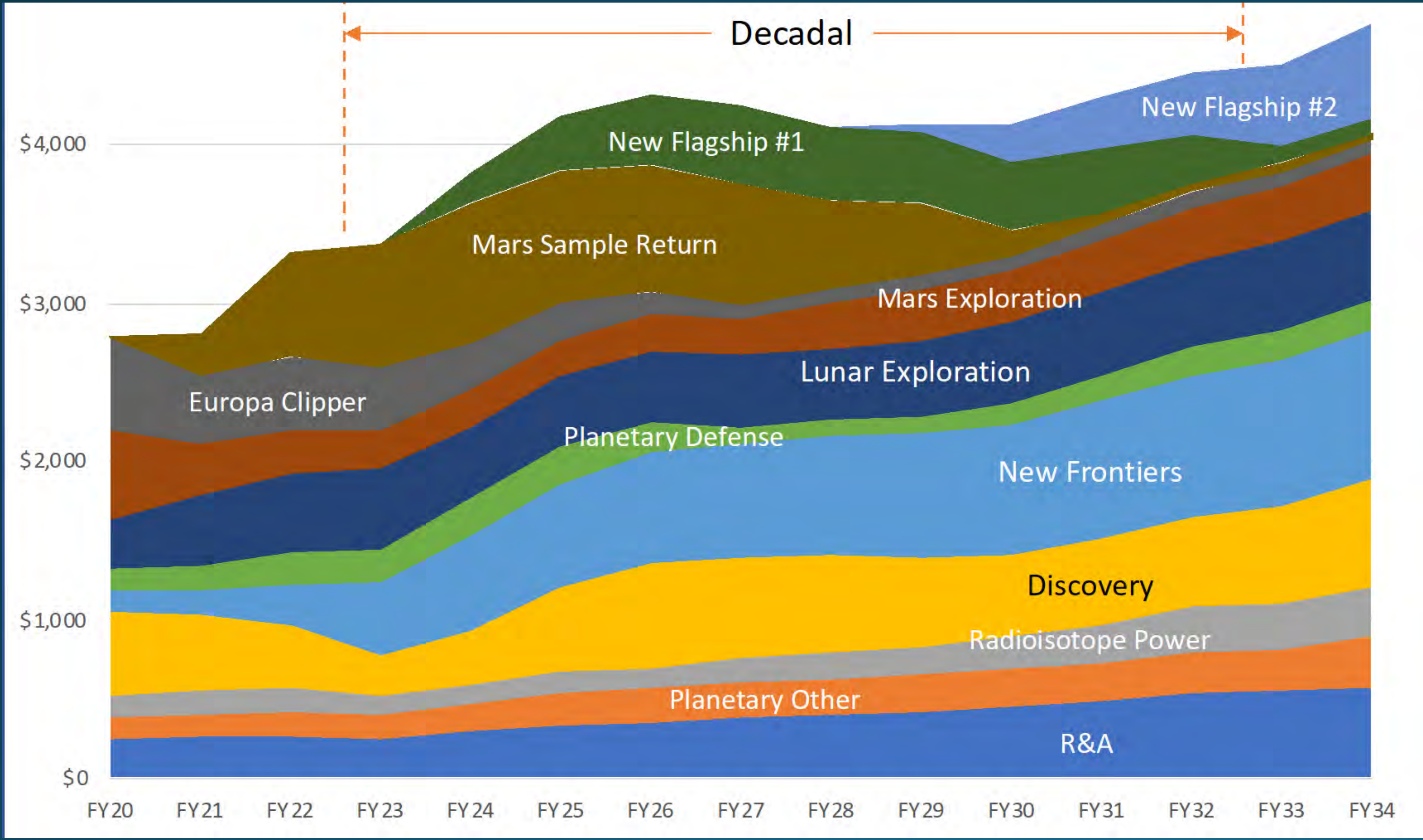
Decadal Thoughts on STMD

- **Collaboration between SMD and STMD has enabled technology development for a number of significant planetary spaceflight exploration technologies.**
- An analysis of STMD spending over the last five years shows that it has invested approximately 10.6 percent of its budget on planetary science technologies. STMD's investment has been about right.
- **Finding:** During the last decade, SMD/PSD and STMD have worked together on developing high risk technologies important to the future of planetary and astrobiology missions.
- **Finding:** STMD investment in PSD technology needs can be reprioritized by other parts of the Agency when other Agency needs are deemed greater.
- **Recommendation:** STMD should ensure that its level of investment in SMD mission technologies is balanced at approximately 30 percent of its overall budget with the PSD portion at no less than 10 percent.

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 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**

Thank You All Kindly for Your Time