The National Academies of SCIENCES ENGINEERING MEDICINE

ORIGINS, WORLDS, AND LIFE: A DECADAL STRATEGY FOR PLANETARY SCIENCE AND ASTROBIOLOGY 2023-2032 (2023)

Chapter 19 - Human Exploration

Statement of Task (1 of 2)

The report should provide a clear exposition of the following:

1. *An overview of planetary science, astrobiology, and planetary defense: what they are, why they are compelling undertakings, and the relationship between space- and ground-based research.*
2. *A broad survey of the current state of knowledge of the solar system.*
3. *The most compelling science questions, goals, and challenges that should motivate future strategy in planetary science, astrobiology, and planetary defense.*
4. *A coherent and consistent traceability of recommended research and missions to objectives and goals.*
5. *A comprehensive research strategy to advance the frontiers of planetary science, astrobiology, and planetary defense during the period 2023–2032 that will include identifying, recommending, and ranking the highest priority research activities (research activities include any project, facility, experiment, mission, or research program of sufficient scope to be identified separately in the final report). For each activity, consideration should be given to the scientific case, international and private landscape, timing, cost category and cost risk, as well as technical readiness, technical risk, lifetime, and opportunities for partnerships. The strategy should be balanced by consideration of large, medium, and small research activities for both ground and space.*

Statement of Task (2 of 2)

6. *Recommendations for decision rules, where appropriate, for the comprehensive research strategy that can accommodate significant but reasonable deviations in the projected budget or changes in urgency precipitated by new discoveries or technological developments.*
7. *An awareness of the science and space mission plans and priorities of NASA human space exploration programs and potential foreign and U.S. agency partners reflected in the comprehensive research strategy and identification of opportunities for cooperation, as appropriate.*
8. *The opportunities for collaborative research that are relevant to science priorities among SMD's four science divisions (for example, comparative planetology approaches to exoplanet or astrobiology research); between NASA SMD and the other NASA mission directorates; between NASA and the NSF; between NASA and other U.S. government entities; between NASA and private sector organizations; and between NASA and its international partners.*
9. *The state of the profession, including issues of diversity, inclusion, equity, and accessibility; the creation of safe workspaces; and recommended policies and practices to improve the state of the profession. Where possible, provide specific, actionable, and practical recommendations to the agencies and community to address these areas.*

Chapter 19: Human Exploration

1. The Pivotal Role of Science in Human Exploration
2. Science Enabled by Human Explorers
3. Near-Term Human Exploration Plans, Relationship to Science, and In Situ Resource Utilization
4. Integrating Science into Human Exploration
5. NASA Programmatic Considerations for Artemis and Beyond: Challenges of Integrating Science and Human Exploration
6. Scientific and Human Exploration of Mars
7. A Tale of Two Orbiters: LRO and IMIM
8. Research Programs to Enable and Optimize Human Exploration
9. Role of Commercial Space and Human-Scale Vehicle Capabilities
10. External Cooperation

1.0 The Pivotal Role of Science In Human Exploration

- Human exploration of space inspires our nation and the world while simultaneously benefiting our technology development, economic standing, and scientific knowledge.
- Human and robotic exploration of the solar system over the next decade and beyond will benefit from a logical, sustained, and science-focused approach.
- The committee's discussion and recommendations reflect an overarching premise: that a robust science program—that is, one capable of addressing decadal-level science—is a required element to ensure the maximum value and longevity of human exploration programs such as Artemis for the Moon and planned exploration of Mars.

1.0 The Pivotal Role of Science In Human Exploration

Finding: Human exploration is an aspirational and inspirational endeavor, and NASA's Moon-to-Mars exploration plans hold the promise of broad benefits to the nation and the world. Human exploration can potentially enable breakthrough science at the Moon and Mars. - *"Communicating the process and importance of scientific discovery, as enhanced by human explorers, will inspire the next generation of STEM professionals (NASA 2015)."*

Recommendation: Conducting decadal-level science should be a central requirement of the human exploration program.

2.0 Science Enabled By Human Explorers

- Planetary science and astrobiology field studies benefit from an astronaut's ability to observe sites in striking detail, recognize unexpected observations, analyze critically in real-time
- Humans can efficiently make targeted in situ measurements and conduct sampling activities that require careful [rapid] decisions based on local geological context.
- Even as robotic exploration capabilities have grown, human explorers can conduct scientific operations much more rapidly than robotic assets
- [Humans] are particularly adept at installing and operating complex infrastructure and scientific assets, especially when unforeseen issues or difficulties require decision-making and on-the-spot innovation

2.0 Science Enabled By Human Explorers

- Finding: A crucial driver of sustained human exploration is the ability of human explorers—with appropriate training and mission planning—to conduct and enable the highest quality, decadal-level science that expands humankind's understanding of Earth, the solar system, and the universe.

- Recommendation: NASA should engage with the science community to (1) define scientific goals for its human exploration programs at the early stages of program planning; and (2) ensure scientific expertise in field geology, planetary science, and astrobiology in its astronaut teams.

TABLE 19-1 Science Objectives (Non-Exhaustive List) Enabled or Facilitated by Humans at the Moon and/or Mars

Human Expertise	Science Objective
• Astronauts can be well-equipped to conduct sorties, and sample and return intact cores deeper (>1 m) than is easily accomplished by robotic missions	• Determine the origin, composition, and history of ice deposits. [4.3, 5.5, 6.1, 10.3, 10.4] • Establish internal heat flow and determine near-surface stratigraphy using geophysical probes and cores. [5.2, 5.5]
• Astronauts can collect more and better geologic samples than static robotic missions by virtue of their ability to more rapidly assess geologic context to select the optimal samples, conduct traverses to allow for increased sample diversity, and to return larger sample quantities. Astronauts could also retrieve samples robotically cached. On Mars, astronauts could deploy more widespread and sophisticated in situ monitoring to track gas fluxes and conduct sophisticated life detection investigations.	• Establish the impact flux through time in the inner solar system, the nature of impactors, and whether there was a late heavy bombardment. [2.4, 3.1, 3.2, 4.1, 4.2, 9.1, 10.2] • Probe of volcanic, tectonic, and magmatic processes, include ng the formation of planetary dichotomy/asymmetry [3.5, 4.3, 5.2, 5.3, 5.6, 8.2, 8.3] • Determine the timing and characteristics of the giant impact that produced the Earth-Moon system [8.3, 4.3] • Determine changes in the ancient atmosphere, climate, and habitable environments with liquid water [3.6, 4.3, 5.3, 5.4, 6.1, 6.2, 10.1, 10.2, 10.3, 10.5, 10.7] • Determine whether there is/was life [11.1, 11.3, 11.4]
• Astronauts can collect more and better geologic samples than static robotic missions by virtue of their ability to more rapidly assess geologic context to select the optimal samples, conduct traverses to allow for increased sample diversity, and to return larger sample quantities. Astronauts could also retrieve samples robotically cached. On Mars, astronauts could deploy more widespread and sophisticated in situ monitoring to track gas fluxes and conduct sophisticated life detection investigations.	• Measure interactions of atmospheres and exospheres with the space environment [4.1, 6.5, 10.2] • Determine interior structure and history of the magnetic field [3.3, 4.4, 5.1, 5.2, 8.2] • Determine if liquid water currently exists in subsurface aquifers [10.1, 10.3]

Brackets reflect "The most compelling science questions, goals, and challenges that should motivate future strategy in planetary science, astrobiology, and planetary defense" in OWL's statement of task.

[NEAR-TERM PLANS, RELATIONSHIP TO SCIENCE/RESOURCE UTILIZATION]

- Finding: With a renewed national human spaceflight program for destinations beyond Earth, as well as commercial entrants with interests in establishing space-based economic activities, there is ample opportunity for decadal science objectives to infuse, and ideally drive, choices of human destinations and activities on the Moon and Mars.

- Finding: A strategic plan is needed to identify measurements most critical to informing ISRU architecture options, ensuring sustainable exploration, and the connection to addressing decadal-level science questions.

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NASA PROGRAMMATIC CONSIDERATIONS FOR ARTEMIS AND BEYOND: CHALLENGES OF INTEGRATING SCIENCE AND HUMAN EXPLORATION

INTEGRATING SCIENCE INTO HUMAN EXPLORATION

- The decadal survey Vision and Voyages for Planetary Science in the Decade 2013–2022 emphasized the importance of budgetary firewalls between human and robotic spaceflight, reduction of “turmoil” caused by incorporation of human exploration requirements in robotic science mission post-selection, and the importance of carefully crafted collaboration (NRC 2011).

- For this decade with a near-term plan for human exploration of the Moon and preparatory activities at Mars, the committee emphasizes the importance of carefully crafted collaboration. A program of scientific exploration can be constructed this decade whereby science enables human exploration and human exploration enables science.

INTEGRATING SCIENCE INTO HUMAN EXPLORATION

- Finding: The separation of roles and responsibilities across multiple divisions and offices therein is not conducive to the development or implementation of a cohesive lunar science and exploration program. ESSIO has also not demonstrated the existence of a process for determining lunar science requirements for Artemis nor has ESSIO shown any plan or prioritization of specific science goals for Artemis.

- Finding: The systems engineering approach necessary to incorporate science objectives and requirements needs to occur in the early stages of human mission planning and hardware development. The later such integration occurs, the greater the risk of prohibitive expense associated with scientific requirements and/or the exclusion of priority science altogether.

INTEGRATING SCIENCE INTO HUMAN EXPLORATION

- Recommendation: PSD should develop a strategic lunar program that includes human exploration as an additional option to robotic missions to achieve decadal-level science goals at the Moon.
- Recommendation: NASA should adopt an organizational approach in which SMD has the responsibility and authority for the development of Artemis lunar science requirements that are integrated with human exploration capabilities. NASA should consider establishing a joint program office at the Associate Administrator level for the purpose of developing Artemis program-level requirements across SMD, ESDMD, SOMD, and other directorates as appropriate.
- Recommendation: PSD should have the authority and responsibility for integrating science priorities into the human exploration plans for Mars.

A TALE OF TWO ORBITERS: LRO AND IMIM

- Finding: LRO is perhaps the most successful example of cooperation and mission performance in a joint SMD and human exploration project and represents a template for how to initiate and manage joint collaborations between science and human exploration directorates at NASA in the future.

- In contrast…
  - iMIM measurements [do not or only minimally address the prioritized science goals and measurement requirements for Mars]

- Finding: With engagement of the scientific community in measurement definition, iMIM has the potential to be a pathfinding example…

RESEARCH PROGRAMS TO ENABLE AND OPTIMIZE HUMAN EXPLORATION

- Finding: SMD has not formulated an Artemis Science Team nor developed a plan for creating the science capabilities required for achieving high priority lunar science through human exploration. SMD has the potential to conduct higher priority science through Artemis by expeditiously identifying outstanding issues that need to be addressed in order to optimize Artemis science return and developing a funded program to conduct this work.

ROLE OF COMMERCIAL SPACE AND HUMAN-SCALE VEHICLE CAPABILITIES

- Finding: Commercial human spaceflight missions to the lunar and martian surfaces will provide unprecedented payload capacity and potentially offer tremendous opportunities for planetary science and astrobiology. These vehicles may lower the cost of surface access, which can enable a new paradigm for planetary science and astrobiology investigations, technology development and testing, and human exploration of space.

- Recommendation: NASA should develop a strategy to utilize opportunities to fly science payloads on commercial test flights and crewed missions to the Moon and Mars as such opportunities arise.

External Cooperation

- Finding: International participation in human programs has the benefit of (1) spreading the cost out over a larger number of participating entities and making it more affordable to each, (2) providing wider participation of scientists, engineers, and the public from different countries and cultures, and (3) enhancing international cooperation in peaceful endeavors.
- Finding: International participation carries with it enhanced risk, in terms of coordination and management of schedules, potential for increased cost, mismatch or miscommunication of requirements, and potential for withdrawal of partners at inopportune times.
- Finding: NASA's continued encouragement of international participation in human missions in the solar system (the Moon, Mars, near-Earth objects, other potential targets) is beneficial as a way of enhancing the scientific return from the missions and of providing a forum for constructive and peaceful interactions…

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Appendix

Lunar Outposts

Self-sustaining settlements on the Moon and capability (technology and know-how) to explore beyond

- Enabling Technologies and capabilities, including access to space/transportation in space
- Scientific observatories and experiments to advance knowledge and inform strategies and decisions
- Resources for energy production and storage
- Support infrastructure
- Habitats
- Mining, extracting, and processing of raw materials
- Farming
- Human survival in harsh environments
- International collaboration
- Stepping-stone to Mars and continued exploration beyond

Note: Slide not part of OWL