ASSESSMENT OF THE NASA PLANETARY SCIENCE DIVISION'S MISSION-ENABLING ACTIVITIES

By

Planetary Sciences Subcommittee
of the
NASA Advisory Council Science Committee

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EXECUTIVE SUMMARY

The remarkable success of NASA's Solar System exploration program has always depended on the ability to identify the highest priority bodies for investigation and to understand the critical Solar System processes operating today and in the past. This approach is particularly important in times of constrained budgets. Especially successful examples include the *"follow the water"* theme for the exploration of Mars and the discoveries that life on Earth and biological processes can exist in extreme environments, thus opening new vistas in the exploration for life beyond Earth. In the face of today's budget pressures and increased launch costs, prioritizing bodies for exploration and focusing of research activities requires thorough analysis of spaceflight data and the development of innovative scientific approaches and instruments for missions. Thus, NASA must fly critical Solar System missions with focused scientific objectives, balanced with a portfolio of mission enabling activities (i.e., *Supporting Research and Technology*, or SR&T), the subject of this report.

At the direction of Congress, the National Research Council (NRC) undertook a study leading to their report *An Enabling Foundation for NASA's Earth and Space Science Missions*. This report, published in 2010, recommended that 1) NASA ensure that the current mission-enabling activities are linked to the strategic goals of the agency and that absent activities required to support the strategic goals be identified, 2) an approach be developed and implemented to manage the portfolio of mission-enabling activities, and 3) the number of NASA program officers be increased to enable world-class space and Earth science programs.

In 2011, NASA's Science Mission Directorate appointed an SR&T Working Group of the Planetary Science Subcommittee (NASA Advisory Council Science Committee) to identify the mission enabling activities of the Planetary Science Division, map those activities to the Division strategic science plan, and provide recommendations regarding "active portfolio management." Activities that are primarily technology development were not included because a parallel study was underway in the Division dealing specifically with technology. The Working Group used the NRC report as a guide for the study, reviewed the various mission-enabling activities of the Division, held discussions with NASA Program Officers, and solicited comments from the planetary science community on the processes involved in proposing for research through the relevant mission-enabling programs. The results of the Working Group were reviewed and approved by the full Planetary Science Subcommittee.

The SR&T Working Group found that the current Planetary Science Division mission-enabling activities can be mapped clearly to the specific scientific objectives contained in the NASA 2010 Science Plan. However, many of the research and analysis programs overlap. Because the workload on the scientific community and NASA Program officers has increased substantially in the last decade with regard to proposal preparation, review, and implementation, the Planetary Science Division should consider consolidating programs to eliminate overlap as a part of the portfolio management strategy. This consolidation should be net revenue neutral (i.e., overlapping tasks as well as their corresponding funding are combined – this is not meant to be a means of reducing overall research program funding). The Working Group recommends that this action should be undertaken as part of a *Senior Review* of all mission-enabling activities. The implementation of such a senior review would require that the Division develop clearly articulated criteria for evaluating the success of the mission-enabling activities and that the funding levels for all SR&T activities be made available for the review. The senior review would include assessment of workforce requirements needed to support these activities.

Results from the community survey relating to portfolio management include mechanisms for improving the proposal and grant process, such as an annual publication indicating the approximate times when specific review panels will meet, the potential for award durations to be as long as five years, better communication between NASA and proposers on the status of programs and their specific proposals, and means to improve the pool of qualified reviewers.

The mission-enabling (SR&T) activities of the Planetary Science Division remain a critical cornerstone for the exploration of the Solar System through programs that exploit the incredible wealth of data from previous and on-going missions, develop new scientific approaches for future missions, provide the solid basis for understanding the complex processes operating in the Solar System, and generate the technology to expand our capabilities and reach in pursuing these goals. These activities should be efficient and they must continue at a vigorous pace to ensure NASA's preeminent lead in Solar System exploration.

1.0 INTRODUCTION

This document responds to recommendations made in the National Research Council report "An Enabling Foundation for NASA's Earth and Space Science Missions" (NRC 2010), which was written in response to Congress. Congress had directed the NRC to assess NASA's research and analysis activities and had asked particularly for advice about how to assess whether levels of support for specific mission-enabling activities were too high, about right, or too low. Subsequently, a working group of the Planetary Science Subcommittee of the NASA Advisory Council Science Committee was formed (**Appendix 1**) to address the NRC recommendations relevant to NASA's Planetary Science Division. The NRC recommendations are given in their entirety in **Section 2** (below) and can be summarized as follows:

- *Ensure that the mission-enabling activities are linked to the strategic goals of NASA and that there is an ongoing means for identifying absent activities that are needed to meet those strategic goals and incorporating them into the portfolio of supported activities.*
- *Develop and implement an approach for managing the portfolio of activities*
- *Increase the number of scientific and technical officers to enable and efficiently manage world-class programs*

The NASA Science Plan (NASA, 2010) provides the strategic agency goals for the Science Mission Directorate (SMD) and each of its divisions. The plan for the Planetary Science Division (PSD) includes the science strategy, the principal objectives to carry out the strategy, an outline of the current and planned flight projects, and a summary of planetary research and technology activities.

Section 2 gives the NRC definition of *mission-enabling activities* and the NRC *metrics* to be applied to those activities in deciding how well they are linked to NASA's strategic goals. In preparing this report, The Planetary Science Subcommittee (PSS) adopted a two-step process. The first step was to identify PSD mission-enabling activities by mapping the specific programs currently supported by the Division to the NASA Science Plan objectives. The second step was to apply the NRC-defined metrics to each activity.

Section 3 is a listing and brief description of the relevant PSD mission-enabling activities included in this assessment. **Section 4** summarizes briefly how each of the PSD science objectives is met and includes a table showing current mission-enabling activities and their linkage to the objectives. **Section 5** is the evaluation of the PSD activities following the NRC recommendations and metrics and **Section 6** provides the findings and recommendations from this study.

2.0 MISSION-ENABLING ACTIVITIES

2.1 Definition

As defined by the NRC (2010), mission-enabling activities are *not* dedicated to a single specific spaceflight mission; instead they provide a broad enabling foundation for NASA's scientific spaceflight projects. To quote the NRC, the principal purposes of mission-enabling activities are to provide (NRC 2010):

- A knowledge base that allows NASA and the scientific community to explore new frontiers in research and to identify, define, and design cost-effective space and Earth science missions required to address the strategic goals of the agency;
- A wide range of technologies that enable NASA and the scientific community to equip and

conduct spaceflight missions to pursue the agency's scientific goals; and

- A robust, experienced technical workforce to plan, develop, conduct, and utilize the scientific missions.

The NRC (2010) identified NASA's principal programs to accomplish these purposes as:

- Research projects (especially via the research and analysis grants programs) and special research facilities (including suborbital flight payloads and operations, ground-based telescopes and dedicated laboratories, and high-end computer systems and data archives);
- Development of advanced sensors, research instruments, and spaceflight mission system technologies;
- General data analysis (including archival data studies and synthesis of new and/or long-term data sets from multiple spaceflight missions); and
- Earth science applications (including research to apply NASA Earth science results to fields such as agriculture, ecology, and public health and safety).

While the NRC definition includes technology development of sensors, research instruments, and spaceflight components, the Planetary Science Subcommittee report given here excludes these activities because a parallel study is currently underway by the PSD, chaired by Tibor Kremic.

2.2 NRC recommendations

The following detailed recommendations, taken directly from the NRC (2010), report were made to the NASA Science Mission Directorate (SMD) regarding mission-enabling activities.

Recommendation 1: *NASA should ensure that SMD mission-enabling activities are linked to the strategic goals of the agency and of SMD and that they are structured so as to:*

- *Encompass the range and scope of activities needed to support those strategic goals,*
- *Provide the broad knowledge base that is the context necessary to interpreting data from spaceflight missions and defining new spaceflight missions,*
- *Maximize the scientific return from all spaceflight missions,*
- *Supply a continuous flow of new technical capabilities and scientific understanding from mission-enabling activities into new spaceflight missions, and*
- *Enable the healthy scientific and technical workforce needed to conduct NASA's space and Earth science program.*

Recommendation 2: *NASA's Science Mission Directorate should develop and implement an approach to actively managing its portfolio of mission-enabling activities.*
Active portfolio management should include the following elements:

- *Clearly defined science division mission-enabling mission statements, objectives, strategies, and priorities that can be traced back to the overall strategic goals of NASA, SMD, and the division.*
- *Flexibility to accommodate differences in the scientific missions and programmatic options that are most appropriate to the different science discipline divisions.*
- *Clearly articulated relationships between mission-enabling activities and the ensemble of ongoing and future spaceflight missions that they support.*
- *Clear metrics that permit program managers to relate mission-enabling activities to strategic goals, evaluate the effectiveness of mission-enabling activities, and make informed decisions about priorities, programmatic needs, and portfolio balance.*

- *Provisions for integrating support for innovative high-risk/high-payoff research and technology, interdisciplinary research, and scientific and technical workforce development into mission-enabling program strategies.*
- *Active involvement of the scientific community via an open and robust advisory committee process.*
- *Transparent budgets that permit program managers to effectively manage mission-enabling activity portfolios and permit other decision makers and the research community to understand the content of mission-enabling activity programs.*

Recommendation 3: *NASA should increase the number of scientifically and technically capable program officers so that they can devote an appropriate level of attention to the tasks of actively managing the portfolio of research and technology development that enables a world-class space and Earth science program.*

2.3 NRC Metrics

The NRC (2010) outlined the metrics that should be applied to the SMD divisions for each of the mission-enabling activities. These are:

- A simple statement of what the component of the mission-enabling activity is intended to accomplish and how it supports the strategic or tactical plans of the division.
- A statement as to how the component is to accomplish its task.
- An evaluation of the success of the activity relative to the stated mission, unexpected benefits, and lessons learned.
- A justification for the resource allocation that is being applied to the component vis-à-vis other mission-enabling activities within the division.

3.0 PLANETARY SCIENCE DIVISION MISSION-ENABLING ACTIVITIES

PSD mission-enabling activities **(Table 1)** can be subdivided into 1) basic research, 2) target-focused programs, 3) mission data analysis, 4) technology development, 5) recruiting and training the next generation of planetary scientists and technologists, and 6) supporting and infrastructure activities. Not included in this study are activities related primarily to technology development, which are the subject of another PSD study. The activities listed are available as of FY 2010 opportunities or are currently being conducted from previous opportunities but are no longer open for new proposals.

In addition to the activities listed in **Table** 1, *Planetary Analysis Groups* (PAGs) constitute a critical activity supported by the PSD to help meet the scientific objectives and guide strategies in planetary exploration. PAGs are topically-oriented and are the *Curation and Analysis Planning Team for Extraterrestrial Materials, Lunar Exploration Analysis Group, Mars Exploration Program Analysis Group, Outer Planet Analysis Group, Small Bodies Analysis Group,* and the *Venus Exploration Analysis Group.* These groups are formally chartered by NASA with the chair of each group serving on the Planetary Science Subcommittee. Meetings of each group are typically held twice a year and are open to the planetary science community. Meeting agendas are organized and conducted by the chair and a steering committee for each group, with the relevant NASA Program Officer serving *ex officio*. Agendas include discussions of current interest for the relevant topics and results are documented in various reports. For example, many PAGs generated "white papers" for the NRC “Decadal Survey” for planetary science, and include research "roadmaps" with suggested research priorities. As such, PAGs provide an important venue for broad community involvement in NASA’s Planetary Science Division issues.

Table 1. NASA Planetary Science Division mission-enabling activities.

Basic research	In Space Propulsion**‡
Astrobiology-Exobiology & Evolutionary Biology	Moon and Mars Analog Missions Activities
Cosmochemistry	Mars Instrument Development*‡
NASA Astrobiology Institute	Planetary Instrument Definition and Development
NASA Lunar Science Institute	**Recruiting and training the next generation**
Origins of Solar Systems	Education and Public Outreach Supplements
Planetary Astronomy	Fellowships for Early Career Researchers
Planetary Atmospheres	NASA Earth and Space Science Fellowships
Planetary Geology and Geophysics	NASA Postdoctoral Program
Target-focused research	**Supporting infrastructure activities**
Lunar Advanced Science Exploration Research	Curation (samples)
Mars Fundamental Research	Infrared Telescope Facility (IRTF, Hawaii)
Near-Earth Object Observations	Lunar and Planetary Institute (LPI)
Outer Planets Research	Mars Climate Modeling Center (proposed)
Planetary Protection Research	NASA Advanced Supercomputing
Mission data analysis	National Astronomy & Ionosphere Center/Arecibo
Cassini Data Analysis	Planetary Radar System
Jupiter Data Analysis*	Planetary Aeolian Laboratory (PAL, ARC)
Laboratory Analysis of Returned Samples	Planetary Cartography (USGS, Flagstaff)
Mars Data Analysis	Planetary Data System (PDS)
Planetary Mission Data Analysis	Planetary Major Equipment
Technology development	Reflectance Experiment Laboratory (RELAB, Brown U.)
Astrobiology Science & Technology Instrument Development‡	Regional Planetary Image Facilities (RPIF)
Astrobiology Science & Technology for Exploring Planets‡	Venus Chamber (GSFC)
	Vertical Gun Range (AVGR, Ames)

**not in 2010 ROSES call, but still active grants* ***not in current ROSES call* *‡relevant to, but not addressed in detail in this study*

The following is an alphabetical listing of the programs and activities of the Planetary Science Division that are mission-enabling. These short descriptions are paraphrased from the NASA Research Opportunities in Space and Earth Sciences 2010 announcement or from other documents that describe PSD programs and activities. All activities are currently ongoing, although some are closed for new proposals.

Astrobiology-Exobiology and Evolutionary Biology Program research is to understand the origin, evolution, distribution, and future of life in the Universe. Research is centered on the origin and early evolution of life, the potential of life to adapt to different environments, and the implications for life elsewhere.

Astrobiology Science and Technology Instrument Development (ASTID) Program is to develop instrument capabilities that will help meet Astrobiology science requirements on future space flight missions, as well as unique Astrobiology science objectives on Earth.

Astrobiology Science and Technology for Exploring Planets (ASTEP) Program is for investigations to explore the Earth's extreme environments in order to develop a sound technical and scientific basis to search for life on other planets.

Cassini Data Analysis Program (CDAP) is to enhance the scientific return of the Cassini mission by broadening the scientific participation in the analysis and interpretation of the data returned by the mission.

Cosmochemistry Program supports investigations of extraterrestrial materials that are aimed at understanding the geochemistry of Solar System bodies (planets, satellites, including Earth's Moon, and small Solar System bodies).

Curation protects, preserves, and distributes for study samples from the Moon, Mars, and interplanetary space in support of Solar System exploration. Sample collections include lunar rocks and regolith, Antarctic meteorites, interplanetary dust particles, space-exposed hardware, Genesis solar wind samples, and Stardust cometary and interstellar samples.

Education and Public Outreach Supplemental Awards are for investigators currently funded through a research investigation. PSD offers the opportunity for small awards for education or outreach activities related to the parent investigation. By adding an education component to their research investigation, researchers can design an education effort that capitalizes on their own talents, interests, and scientific expertise.

Infrared Telescope Facility (IRTF, Hawaii) is a 3.0 meter telescope optimized for infrared observations and located on Mauna Kea, Hawai`i. The observatory is operated and managed for NASA by the University of Hawai`i Institute for Astronomy. NASA provides funds for operation and NSF provides funding for new focal plane instruments. Observing time is open to the astronomical community with 50% of the observing time reserved for studies of Solar System objects.

In-Space Propulsion (ISP) solicits promising propulsion-system approaches (solid, liquid, etc) that can achieve TRL-6 within three years with a premium placed on minimizing both development and flight risks.

Fellowships for Early Career Researchers facilitate the integration of new Planetary Science Division researchers into established research programs and provide tools and experience useful when searching for a more advanced (i.e., tenure-track, civil servant, or equivalent) position.

Jupiter Data Analysis Program (JDAP) enhances the scientific return of the Jupiter science data obtained by the New Horizons spacecraft, as well as the Voyager, Galileo, and Cassini missions through broad scientific participation in the analysis and interpretation of the data returned by these missions.

Laboratory Analysis of Returned Samples (LARS) research is to maximize the scientific return from extraterrestrial samples from NASA missions and to develop laboratory instruments and advanced analytical techniques.

Lunar and Planetary Institute (LPI), a division of the Universities Space Research Association, was established during the Apollo program to foster international collaboration and to be a repository for information gathered during the early years of the space program. The Institute now serves as a scientific forum attracting world-class visiting scientists, postdoctoral fellows, students, and resident experts; supports and serves the research community through newsletters, meetings, and other activities; collects and disseminates planetary data while facilitating the community's access to NASA science; engages, excites, and educates the public about space science; and invests in the development of future generations of explorers.

Lunar Advanced Science and Exploration Research (LASER) Program supports and enhances lunar basic science and lunar exploration science to optimize the return from previous and future robotic and human missions to the Moon.

Mars Climate Modeling Center (possible future) would support studies to understand the nature of the general circulation of the atmosphere of Mars, how that circulation is driven, and how it affects martian long term climate. These studies would lead to better understanding of martian water, dust, and atmospheric pressure cycles. Results would also support Mars missions either underway or under study.

Mars Data Analysis Program (MDAP) is to enhance the scientific return from Mars missions by broadening scientific participation in the analysis of their respective data sets and to fund high-priority areas of research that support planning for future Mars missions.

Mars Fundamental Research Program (MFRP) sponsors scientific research concerning atmospheric, climatologic, geologic, and geochemical processes on Mars and offers opportunities for Mars research beyond those available from analysis of spacecraft data alone.

Mars Instrument Development Project supports the advancement of instrument technologies that show promise for the Mars Exploration Program.

Moon and Mars Analog Missions Activities (MMAMA) Program addresses the need for integrated interdisciplinary field experiments as an integral part of preparation for planned human and robotic missions to the Moon, Mars and other destinations.

National Astronomy and Ionosphere Center/Arecibo Planetary Radar System consists of the 305 m radio telescope, the largest single-aperture telescope ever constructed. It enables research in radio astronomy, aeronomy, and radar astronomy observations of the Solar System. This system is one of only two active planetary radars in the world. The other is the NASA Goldstone Deep Space Tracking Station, which is fully steerable, but is only 4 percent as sensitive as the Arecibo system.

NASA Advanced Supercomputing (NAS) division at Ames Research Center provides integrated supercomputing services through the life cycle of science and engineering projects. The High End Computing (HEC) resources are integrated with mass data storage, and high-speed network technologies, augmented with software performance optimization, advanced scientific visualization, and 24/7 user services.

NASA Astrobiology Institute (NAI) is one element of the Astrobiology Program and is a virtual institute. NAI's mission is to carry out, support and catalyze collaborative, interdisciplinary research; train the next generation of astrobiology researchers; provide scientific and technical leadership on astrobiology investigations for current and future space missions; explore new approaches using information technology for interdisciplinary and collaborative research among widely-distributed investigators; and support outreach by providing scientific content for education programs and by communicating directly with the public.

NASA Earth and Space Science Fellowships (NESSF) were created to ensure continued training of a highly qualified workforce in disciplines needed to achieve NASA's scientific goals. Awards resulting from the competitive selection are made in the form of training grants to the respective universities with the advisor serving as the principal investigator. Students are eligible from accredited U.S. Universities pursuing Master of Science or Doctoral degrees in Earth and space sciences, or related disciplines.

NASA Lunar Science Institute (NLSI) is a virtual institute headquartered at Ames Research Center comprised of competitively selected teams across the U.S., some with international partnerships. The NLSI is funded by the Science Mission Directorate (SMD) with contributions from the Exploration Systems Mission Directorate (ESMD). The mission of the NLSI is to advance lunar science through collaborative research, enabling cross-disciplinary partnerships, providing scientific and technical perspectives to NASA, training the next generation of lunar scientists, and encouraging education and public outreach.

Near-Earth Object Observation (NEOO) Program supports investigations to inventory and characterize the population of NEOs that may represent a hazard for impacting the Earth with the potential to affect its climate and biosphere.

NASA Postdoctoral Program (NPP), administered by Oak Ridge Associated Universities, offers research opportunities to highly talented national and international individuals to engage in ongoing NASA research programs at NASA Centers, NASA Headquarters, or a NASA-affiliated research institution. The one- to three-year appointments are competitive and are designed to advance NASA's missions in space science, Earth science, aeronautics, space operations, exploration systems, and astrobiology.

Outer Planets Research (OPR) Program supports diverse scientific investigations that contribute to the understanding of the giant planets in the outer Solar System, as well as the smaller solid bodies including comets, asteroids, and the Kuiper Belt.

Origins of Solar Systems (OSS) Program supports basic research to investigate the formation and early evolution of planetary systems and to provide the fundamental research and analysis necessary to detect and characterize other planetary systems. The investigations may involve analytical and numerical modeling, laboratory research, and observational studies of star formation and the relationship to planetary system formation, solar nebula processes, accumulation and dynamical evolution, analysis of primitive materials, and the detection and characterization of other planetary systems.

Planetary Aeolian Laboratory (PAL) at Ames Research Center is a unique facility used for conducting experiments and simulations of windblown processes under different planetary atmospheric environments, including Earth, Mars, and Titan. Experiments are conducted to assess wind speeds needed to initiate the movement of particles, rates of wind erosion, and analysis of various "bedforms" such as ripples. The results are used to interpret planetary spacecraft data.

Planetary Astronomy (PAST) Program supports ground-based astronomical observations and suborbital investigations involving sounding rockets, balloons, or reusable sub-orbital vehicles. Proposals are solicited for observations over the entire range of wavelengths from the ultraviolet to radio that contribute to understanding the general properties and evolution of the Solar System, its planets, their satellites, and of asteroids and comets. Additional facilities supported by SMD's Astrophysics Division offer other crucial planetary observational capabilities, including Hubble, Spitzer, Keck, Chandra, GALEX, and WISE observatories.

Planetary Atmospheres (PATM) Program supports scientific investigations that contribute to the understanding of the origin and evolution of the atmospheres of planets and their satellites and of comets. Its broad objectives include determining the compositions, dynamics, energetics, and chemical behaviors of planetary atmospheres.

Planetary Cartography (USGS, Flagstaff) supports mapping (including geology) of planetary bodies (except Earth) coordinated under the auspices of the NASA Planetary Cartography and Geologic Mapping Working Group. USGS provides (1) participation in working groups charged with developing planetary geologic mapping program plans, (2) management and coordination of individual mapping projects, (3) oversight and expertise in meeting the requirements of USGS map standards, (4) editorial support in map reviews and revisions, (5) generation of geologic base maps and databases for map investigators, (6) prepress preparation and printing of maps in the USGS Scientific Investigation Map (SIM) Series, and (7) development and maintenance of software for cartographic analysis of planetary images.

Planetary Data System (PDS) archives and distributes scientific data from planetary missions, astronomical observations, and laboratory measurements. Its purpose is to ensure the long-term usability and access of planetary data and to stimulate advanced research. All PDS-produced products are peer-reviewed, documented, and accessible via a system of online catalogs and interfaces that are organized by planetary disciplines.

Planetary Geology and Geophysics (PGG) Program supports scientific investigations of planetary surfaces and interiors, satellites (including the Moon), satellite and ring systems, and smaller Solar System bodies such as asteroids and comets through data analysis, laboratory simulations, field analog investigations, and computer modeling.

Planetary Instrument Definition and Development Program (PIDDP) supports the advancement of spacecraft-based instrument technology that shows promise for use in scientific investigations on future planetary missions.

Planetary Major Equipment (PME) Program supports upgrading the analytical, computational, telescopic, and other instrumentation required by investigations sponsored by PSD research programs. PME is open to those that have a qualifying grant through Cosmochemistry, Planetary Geology and Geophysics, Planetary Astronomy, Planetary Atmospheres, Outer Planets Research, Lunar Advanced Science and Exploration Research, Near Earth Object Observations, Mars Fundamental Research, Astrobiology: Exobiology and Evolutionary Biology, or Origins of Solar Systems.

Planetary Mission Data Analysis Program (PMDAP) is to enhance the scientific return of completed PSD missions by broadening the scientific participation in the analysis of data and samples collected by those missions. The PMDAP is intended to complement and not to overlap other active data analysis programs such as Mars Data Analysis (MDAP), Cassini Data Analysis, and Outer Planets Research.

Planetary Protection Research (PPR) Program supports research in exobiology that have implications for contamination of extraterrestrial environments by terrestrial organisms carried by spacecraft launched from Earth and, conversely, for understanding the potential hazards associated with possible extraterrestrial organisms that could be brought to Earth by sample-return missions.

Reflectance Experiment Laboratory (RELAB, Brown University) is a multi-user spectroscopy facility made available to NASA-funded investigators. RELAB has a near-ultraviolet, visible, and near-infrared bidirectional spectrometer and a near- and mid-infrared FT-IR spectrometer. The bidirectional spectrometer is used to obtain high precision, high spectral resolution, bidirectional reflectance spectra of Earth and planetary materials, and is designed to measure samples using viewing geometries specified by the user. This allows investigators to simulate the geometry of natural observing conditions for small particulates.

Regional Planetary Image Facilities (RPIF) are an international network of planetary image libraries. These facilities maintain photographic and digital data and associated mission documents and cartographic data of planets. The image facilities are open to the public and are primarily reference centers for browsing, studying, and selecting planetary maps. Experienced staff assists scientists, educators, students, media, and the public regarding planetary data.

Venus Chamber at Goddard Space Flight Center is available to the community for testing small flight components/instruments and short-term experiments under high temperatures and pressures. The chamber can maintain a temperature of 740K and pressure of 95.6 bar for ~48 hours under a carbon dioxide atmosphere. The working dimensions of the chamber are five inches in diameter and twelve inches deep. Running at lower temperatures is also possible.

Vertical Gun Range (AVGR) at Ames Research Center is a national facility used to conduct studies of impact processes and for programmatic support for planetary missions (such as Stardust, Deep Impact, and LCROSS). Using its 0.30 cal light-gas gun and powder gun, the AVGR can launch projectiles to velocities of 0.5 to ~ 7 km/sec. By varying the gun's angle of elevation with respect to the target vacuum chamber, impact angles from 0° to 90° relative to the gravitational vector are possible.

4.0 LINKAGE BETWEEN THE PLANETARY SCIENCE DIVISION GOAL AND OBJECTIVES TO MISSION-ENABLING ACTIVITIES

The overarching science goal of the Planetary Science Division is to *ascertain the content, origin, and history of the Solar System, and the potential for life elsewhere*. The five scientific objectives to meet this goal are posed in the NASA Science Plan (NASA, 2010) as:

1. Inventory Solar System objects and identify the processes active in and among them
2. Understand how the Sun's family of planets, satellites, and minor bodies originated and evolved
3. Understand the processes that determine the history and future of habitability of environments on Mars and other Solar System bodies
4. Understand the origin and evolution of Earth life and the biosphere to determine if there is or ever has been life elsewhere in the universe
5. Identify and characterize small bodies and the properties of planetary environments that pose a threat to terrestrial life or exploration or provide potentially exploitable resources

The scientific objectives are addressed through approaches that include analyses of data returned from missions, laboratory experiments, numerical and analytical simulations, theoretical studies, studies of features and processes on Earth that are potential analogs to those on other planets and bodies, and analysis of samples from space, either returned by spacecraft or delivered to Earth in the form of meteorites. These approaches are supported by the mission-enabling activities described in **Section 3**. **Table 2** summarizes the linkage between the activities and the five scientific objectives of the Division.

The following sections give brief descriptions of the approaches used for each objective and examples of scientific findings that resulted from PSD mission enabling activities. **Appendix 2** includes examples of research investigations that trace the activities to each PSD objective. *It is stressed that these examples are not all-inclusive, but represent the kinds of work done in the >900 specific investigations currently supported by the Planetary Science Division.*

4.1 Objective 1: *Inventory Solar System objects and identify the processes active in and among them*

Knowledge of the inventory of Solar System objects and the relevant processes that affect them has been greatly expanded by spaceflight missions and the mission-enabling activities. To achieve this broad objective and to digest the large amounts of data generated by planetary missions, a wide variety of activities is required, including focused data analysis programs (such as the *Cassini Data Analysis Program*), activities that encompass theoretical and modeling studies needed to elucidate the physical processes operating in the Solar System (such as the *Planetary Atmospheres Program*), and supporting facilities such as the *NASA Advanced Supercomputing Division*.

Table 2. Relevance of activities to the PSD science objectives (●=directly relevant, ○=somewhat relevant)

Program element	Objective 1 (objects, processes)	Objective 2 (origin, evolution)	Objective 3 (habitability)	Objective 4 (life: Earth, elsewhere)	Objective 5 (small bodies)
Astrobiology-Exobiology & Evolutionary Biology	○	○	●	●	
Astrobiology Science & Technology Instrument Development	○	○	●	●	
Astrobiology Science & Technology for Exploring Planets	○		●	●	
Cassini Data Analysis	●	●	●	○	○
Cosmochemistry	●	●	○	○	●
Laboratory Analysis of Returned Samples	●	●	○	○	○
Lunar Advanced Science Exploration Research	●	○		●	●
Mars Data Analysis	●	●	●	●	○
Mars Fundamental Research	●	●	●	○	
Mars Instrument Development	●	●	●	●	
Moon & Mars Analog Missions Activities	●	●	●	●	○
NASA Astrobiology Institute	○	○	●	●	
NASA Lunar Science Institute	○	●			○
Near-Earth Object Observations	●	○			●
Origins of Solar Systems	●	●	○	○	
Outer Planets Research	●	●	○		○
Planetary Astronomy	●	●	●		●
Planetary Atmospheres	●	●	○	○	
Planetary Geology & Geophysics	●	●	●		○
Planetary Instrument Definition & Development	●	●	●	●	●
Planetary Mission Data Analysis	●	●	○		●
Planetary Protection Research			●	●	○
Supporting infrastructure activities					
Curation	●	●	○	○	●
Infrared Telescope Facility	●	●	●	●	●
Lunar and Planetary Institute	●	●	●	●	●
Mars Climate Modeling Center (proposed)	○	○	●	●	
NASA Advanced Supercomputing	●	○	○	○	○
National Astronomy & Ionosphere Center/Arecibo Planetary Radar System	●	●			●
Planetary Aeolian Laboratory	●	○	○		
Planetary Cartography	●	●	●		●
Planetary Major Equipment	●	●	●	●	○
Planetary Data System	●	●	●	●	●
Reflectance Experiment Laboratory	●	○	●		●
Regional Planetary Image Facility	●	○	○	○	○
Venus Chamber	●	●	○		
Vertical Gun Laboratory	●	●	○	○	●

For example, studies of impact cratering show how PSD activities contribute to understanding fundamental planetary processes: fieldwork on natural impact structures on Earth is supported by the *Mars Fundamental Research* program and provides insight into the full complexity of impact structures, such as the nature of ejecta and rim deposits. This work is complemented by impact experiments conducted at the *Ames Vertical Gun Range* in which the physics of the impact process can be studied under controlled and known conditions. Both the fieldwork and the laboratory experiments then provide information for numerical modeling, which is supported by the *Planetary Geology and Geophysics* program. Results from these mission-enabling activities have been applied to the design and operation of spaceflight missions, such as the *Mars Exploration Rovers* and missions involving active impacts. For example, an understanding of impact crater rim structure was applied to planning the traverse of the rover, *Opportunity*, at Victoria crater on Mars, while knowledge of the fundamental physics of impacts was applied to the design of the *Deep Impact* mission experiment on comet Tempel 1 and the spacecraft *LCROSS* impact on the Moon.

For another example of how PSD activities support flight projects, the Cassini-Huygens mission observed plumes emanating from the south polar region of Saturn's icy satellite, Enceladus, that contain water, carbon dioxide, and other volatiles in both gaseous and solid forms. Research from the *Cassini Data Analysis Program* showed that the water molecules from Enceladus are spread throughout the inner magnetosphere in a torus surrounding Saturn.

4.2 Objective 2: *Understand how the Sun's family of planets, satellites, and minor bodies originated and evolved*

This objective is addressed through experimental, analytical, and theoretical investigations that include laboratory studies of extraterrestrial materials such as meteorites and samples returned by spacecraft missions. Such work is supported by *Curation* as an infrastructure facility responsible for housing and distributing samples for analysis through the *Cosmochemistry, Lunar Advanced Science and Exploration Research,* and related programs. Results include the determination of radiogenic ages and compositions for Solar System materials that place constraints on models of planetary origin and evolution. In turn, the collective results are applied to the design and capabilities of active missions such as *Dawn*, which will encounter the asteroid *Vesta.* Earth-based spectroscopic analyses of this object, supported by the *Planetary Astronomy* program, have long been compared to those of meteorite samples and to terrestrial igneous rocks, and have led to the hypothesis that *Vesta* is a differentiated body. This hypothesis was posed from the studies supported by a variety of mission-enabling activities and will now be tested by the *Dawn* project.

The wealth of data returned from previous missions can continue to yield new insights into planetary origin and evolution. For example, seismic data obtained from Apollo lunar landings in the 1970s were recently re-analyzed (see *Science 6 Jan 2011*) using modern array-processing methods in an investigation supported by the *Planetary Geology and Geophysics* program. Results indicate that the Moon contains a solid inner core and a fluid outer core, which constrains models of the geochemical evolution the interior.

4.3 Objective 3: ***Understand the processes that determine the history and future habitability of environments on Mars and other Solar System bodies***

PSD research advances the understanding of potential habitability in the Solar System through a wide variety of approaches. PSD activities support investigations of Earth analog materials and environments as they relate to knowledge of habitability in general, as well as Earth-based evaluations of planetary materials and environments. Other classes of investigations that are supported focus on studies of the environmental requirements for emergence of life and for habitability, the preservation of records of habitable environments, and the development of analytical methods for evaluating habitability potential. Results from these studies contribute to analyses of data from missions flown to Mars and other Solar System objects.

For example, research supported by the *Planetary Geology and Geophysics Program* and analysis of data from the *Mariner 9* and *Viking* missions helped to identify features related to erosion by water on Mars and guided the definition of the objectives for the *Mars Global Surveyor* (MGS) mission. Analyses of data returned from MGS through the *Mars Data Analysis* and *Planetary Atmospheres* programs were coupled with studies supported by the *Mars Fundamental Research* program to confirm the past occurrence of a robust hydrologic cycle on Mars. Such results contributed to defining the goals of the *Mars Exploration Rovers* (MER) geared toward understanding past settings where water occurred while the *Astrobiology-Exobiology & Evolutionary Biology Program* supported the interpretation of deposits on Mars that have preserved evidence of habitable environments. Ongoing analyses of data returned from the *MER* and *Mars Reconnaissance Orbiter* by all of the above programs set the stage for future evaluation of the potential habitability of a location on Mars through the *Mars Science Laboratory*.

In the outer Solar System, the likely presence of a liquid ocean beneath the ice crust of Jupiter's moon, Europa, raises this object to a high priority in the search for habitable zones beyond Earth. Recent analysis of Galileo data coupled with modeling supported by the *Astrobiology-Exobiology & Evolutionary Biology Program* shows that deformation of the crust could provide a viable mechanism for introducing oxygen from surface materials into the ocean in sufficient quantities to support life. This work involved analysis of data obtained a decade ago and geophysical modeling studies, thus helping to define the scientific objectives of a future flagship mission.

4.4 Objective 4: ***Understand the origin and evolution of Earth life and the biosphere to determine if there is or ever has been life elsewhere in the universe***

This objective encompasses investigations to understand the mechanisms involved in the development of life and the environments expected to support life. These address many of the science themes of the *NASA Astrobiology Roadmap* that deal with origins of life, Earth's biosphere evolution, evolutionary mechanisms, environmental limits, and the identification of biosignatures. Relevant investigations rely on a variety of techniques and benefit from multidisciplinary approaches combining experimental work, field studies, and theoretical modeling. The results of these investigations lay the ground for assessing the significance of potential astrobiological targets in the Solar System and beyond, and for defining observations and measurements that will eventually define the development of new technological capabilities, instruments, and mission concepts.

For example, an approach for assessing whether life could emerge in extraterrestrial environments is to study chemical processes in the field and in laboratory conditions simulating those expected in astrobiological targets. Such research is supported by *Astrobiology Exobiology and Evolutionary Biology* and it is also investigated by the *NASA Astrobiology Institute*. Constraints about extraterrestrial environments also come from ground-based and space borne observations, such as by the *Cassini-Huygens* mission objectives for *Titan*. Experimental research supported by the *Planetary Atmospheres* program shows that prebiotic molecules such as amino acids and nucleotides can form in Titan's upper atmosphere. These results shed new light on the role of atmospheric chemistry in the production of life-forming molecules for both Titan and Earth. The mass spectrometer onboard *Cassini-Huygens* detected the elements of Titan's atmospheric compounds and laboratory simulations helped to constrain the nature of that material. Some of these large molecules are likely to accumulate in Titan's lakes and to lead to further chemical processes, a possibility that can be studied by further experimental and theoretical research. Research results can help to identify scenarios to be tested by *Cassini* and enhance planning for future flybys of Titan during the *Cassini Solstice* mission.

Research by the *Astrobiology-Exobiology & Evolutionary Biology Program* and the *NASA Astrobiology Institute* deepens our understanding of the diversity and nature of biosignatures, which are molecules, isotopic patterns, minerals, and structures that require biological processes for their formation. Preserved biosignatures have documented Earth's early biosphere, and so they are prime exploration targets to characterize any extraterrestrial life.

4.5 Objective 5: *Identify and characterize small bodies and the properties of planetary environments that pose a threat to terrestrial life or exploration or provide potentially exploitable resources*

Ground-based and space-based observations reveal extensive and diverse population of small asteroids that orbit in near-Earth space and/or occasionally cross the Earth's orbit. Some of these near-Earth objects (NEOs) could impact Earth and pose a threat to life. Additionally, some of these objects likely contain water ice, metals, or solar-implanted helium, and most likely contain oxygen bound into rocky silicate minerals – making them important potential targets for resources that could be exploited for future human and robotic exploration. Assessing the number of objects in this population, their physical and orbital properties, their composition and resource potential, and the potential environmental consequences of their impact is an important research objective.

Existing PSD programs and supporting facilities provide a means to study and understand small bodies and to provide key information to support current and future missions. For example, the *Near-Earth Object Observations* and *Planetary Astronomy* programs include investigations to identify and characterize the orbits and physical/compositional properties of NEOs using observations from the *Arecibo Planetary Radar* and *NASA Infrared Telescope Facility*. Such investigations have led to the discovery of nearly 1000 large NEOs and 8000 total NEOs over the past decade. These investigations have directly supported the development and operation of missions such as *NEAR* and *Hyabusa*, and played a key role in the planning, execution, and analysis of the recent EPOXI mission flyby of comet Hartley-2 (see Nov 8, 2010 issue of *Science News* online). In addition, studies through the *Planetary Mission Data Analysis* program are revealing important new information about small bodies based on data from Galileo, NEAR, Deep Impact, Deep Space 1, Hayabusa, Stardust-NExT, and other missions, and directly influence the design and operation of future space missions to NEOs and other small bodies.

5.0 ANALYSIS

This analysis is structured according to the NRC (2010) overall recommendations and metrics outlined by the NRC for the Planetary Science Division. Responses are informed by the NRC Planetary Decadal Survey (Vision and Voyages for Planetary Science in the Decade 2013-2022), hereafter referred to as the Survey.

5.1 NRC recommendations

In the following section, the NRC Recommendations are quoted and given in bold, the NRC Recommendation specifics are quoted and given as "bullets," and the report responses to the bullets are given in indented text.

NRC Recommendation 1: ***NASA should ensure that SMD mission-enabling activities are linked to the strategic goals of the agency and of SMD and that they are structured so as to:***

- ***Encompass the range and scope of activities needed to support those strategic goals***

    Response: Since all PSD program elements are linked to strategic goals in Table 2, any activity within a program element will be linked. However, there are undoubtedly activities not currently supported by the PSD through the research and analysis programs and supporting activities that are arguably needed to meet the objectives of the Division (e.g., systematic ongoing synoptic monitoring of planetary atmospheres, systematic physical characterization of main belt asteroids, laboratory measurements of reflectance and emission properties of planetary materials and ices over submillimeter wavelengths). These unsupported activities will change and expand with time as new questions arise from new knowledge achieved in the pursuit of these objectives.

    One means of identifying these unsupported activities would be to add language to a program element AO that requests whether work proposed, in addition to being relevant to the program, is an activity falling within an area of activities not previously funded that directly support a PSD strategic objective or objectives and to describe how this area of activities supports that objective or objectives. Such areas of previously unfunded activities should be collected by the program officer and used in the active management of the program element by identifying the areas that fall within the existing scope of the program element, determining whether the scope should be expanded, or in coordination with other program officers determining if it is an area best undertaken by another program element. Once such information is collected across PSD, the program officer should submit a PSD-wide report on the subject to PSS.

- ***Provide the broad knowledge base that is the context necessary to interpreting data from spaceflight missions and defining new spaceflight missions***

  Response: The "basic research" activities **(Table 1)** of the Division are organized to provide this knowledge through disciplinary programs such as Astrobiology, Planetary Atmospheres, Cosmochemistry, Outer Planets Research, and Planetary Geology and Geophysics. To ensure that the content of these programs continues to meet this objective, the topics available for funding should be reviewed as part of a decadal assessment of the PSD programs (see **Section 6**, Finding 1).

- ***Maximize the scientific return from all spaceflight missions***

  Response: Specific data analysis programs enable the extraction of new scientific results beyond those obtained by the original project teams during and after planetary missions are flown; examples include the Mars Data Analysis, Cassini Data Analysis, Planetary Mission Data Analysis, and Laboratory Analysis of Returned Samples research programs.

  Relevant to this is the Survey's recommendation regarding the importance of maintaining the Planetary Data System, which is the permanent archive for all NASA planetary data and provides the principal means by which the community accesses that data. Also relevant is the recommendation by the Survey that "For future missions, Announcements of Opportunity (AOs) should mandate that instrument teams propose and be funded to generate derived products before missions have completed Phase E." to ensure that high-level data products are available for analysis in addition to the usual low-level data products.

- ***Supply a continuous flow of new technical capabilities and scientific understanding from mission-enabling activities into new spaceflight missions***

  Response: Although not the primary focus of this study, relevant programs identified for technology infusion include the Planetary Instrument Definition and Development and Mars Instrument Development programs. These and related programs should be sustained and competed with sufficient frequency in order to meet this requirement (see **Section 6**, Finding 2).

  This continuous flow of capabilities and understanding will be supported by implementing the Survey's recommendations to "increase R&A budget by 5% above the total finally approved FY2011 expenditures in the first year of the coming decade, and increase budget by 1.5% above the inflation level for each successive year of the decade" and "a substantial program of planetary exploration technology development should be reconstituted and carefully protected against all incursions that would deplete its resources [and] consistently funded at approximately 6-8 percent of the total NASA Planetary Science Division budget."

- ***Enable the healthy scientific and technical workforce needed to conduct NASA's space and Earth science program.***

  Response: The next generation of NASA planetary scientists is encouraged through a variety of programs, including the NASA Earth and Space Science Fellowships, summer internships at the undergraduate and graduate levels at the NASA Lunar and Planetary Science Institute and through the Planetary Geology and Geophysics Program, and other programs through specific field centers. In addition, maturation of planetary scientists is enabled by the NASA Post-doctoral and Early Career Fellowship programs. The planetary science workforce is sustained as a whole largely by NASA research and analysis programs. The effects of volatile funding for these programs on that workforce are of concern. (see **Section 6**, Finding 3 for closely-related issue).

  A healthy workforce is also supported by implementing the Survey's recommendations to "increase R&A budget by 5% above the total finally approved FY2011 expenditures in the first year of the coming decade, and increase budget by 1.5% above the inflation level for each successive year of the decade" and "a substantial program of planetary exploration technology development should be reconstituted and carefully protected against all incursions that would deplete its resources [and] consistently funded at approximately 6-8 percent of the total NASA Planetary Science Division budget."

NRC Recommendation 2: ***NASA's Science Mission Directorate should develop and implement an approach to actively managing its portfolio of mission-enabling activities. Active portfolio management should include the following elements:***

- ***Clearly defined science division mission-enabling mission statements, objectives, strategies, and priorities that can be traced back to the overall strategic goals of NASA, SMD, and the division.***

  Response: Section 4.0 of this report shows the traceability from goal to objective to specific mission-enabling activities of the PSD. These "traceabilities" demonstrate that the activities currently supported are clearly relevant to NASA's scientific goals for Planetary Science as defined in the science plan of 2010. However, the PSD has not established priorities among the program elements and their respective activities (see **Section 6**, Finding 1).

- ***Flexibility to accommodate differences in the scientific missions and programmatic options that are most appropriate to the different science discipline divisions.***

  Response: This element applies at the SMD level, and is not relevant within a single division such as the PSD.

- ***Clearly articulated relationships between mission-enabling activities and the ensemble of ongoing and future spaceflight missions that they support.***

  Response: The basic research, target-focused research, and technology development activities listed in Section 2.4 provide the links between on-going and future flight projects. For example, the Planetary Geology and Geophysics and the Mars Data Analysis programs directly support future Mars surface activities through analysis of potential landing sites, while instrument development programs support future flight instrumentation.

- ***Clear metrics that permit program managers to relate mission-enabling activities to strategic goals, evaluate the effectiveness of mission-enabling activities, and make informed decisions about priorities, programmatic needs, and portfolio balance.***

  Response: Such metrics do not exist within the PSD (see **Section 6**, Finding 4).

- ***Provisions for integrating support for innovative high-risk/high-payoff research and technology, interdisciplinary research, and scientific and technical workforce development into mission-enabling program strategies.***

  Response: The investment in high-risk/high payoff activities appears to vary among the various PSD programs. Interdisciplinary research is fostered through programs such as the NASA Astrobiology Institute and the NASA Lunar Science Institute, which also foster mission-enabling program strategies.

- ***Active involvement of the scientific community via an open and robust advisory committee process.***

  Response: The PSD actively seeks planetary science community involvement at all levels of activities and it takes into account diversity, discipline, and geographic distribution. Examples include membership on formal advisory panels, such as the PSS, Science Definition Teams for future missions, proposal review panels, and broad community involvement such as through the Planetary Analysis Groups.

- ***Transparent budgets that permit program managers to effectively manage mission-enabling activity portfolios and permit other decision makers and the research community to understand the content of mission-enabling activity programs.***

  Response: Work is needed in this area by PSD. The budgets available for new awards for most research and analysis activities are published with the annual call for proposals. Planned total program budgets for a given fiscal year are not made available. Sometime after the end of the fiscal year, final budgets may be posted on the SARA website. Budgets for many of the supporting activities and facilities are not generally accessible (see **Section 6**, Finding 1).

The effective management of mission-enabling activity portfolios requires that individuals who manage program budgets must know the subject matter of their programs, as is the case with program officers and the Division Director. Unfortunately, internal controls on program budgets are weak. Budgets can be modified by financial analysts without program officer knowledge or approval and even without initial knowledge of the division director. Lack of knowledge and control of budgets equals lack of transparency to program managers, undermining effective management.

NRC Recommendation 3: ***NASA should increase the number of scientifically and technically capable program officers so that they can devote an appropriate level of attention to the tasks of actively managing the portfolio of research and technology development that enables a world-class space and Earth science program.***

Response: Program officers in the PSD are very capable scientists who strive to manage their programs effectively. Many appear to have more responsibilities than are reasonable, with the result that there tends to be a breakdown in management, manifested in part by inconsistent communication with their investigators and long delays organizing review panels and generating program plans afterwards. While additional Program Officers could alleviate this problem by reducing the number of activities per Program Officer, this approach seems unlikely in the current fiscal environment. This situation may be addressed at some level by providing program officers the support and tools with which they could more efficiently manage their programs, and by making changes that enhance the overall scientific productivity of these programs and also improve program management. PSD (as a part of its active grants management) should monitor program officer performance using objective criteria, such as response time to investigator, the time between program proposal due dates and panel reviews, and the time between panel reviews and award letters.

Support and tools for program officers would include:

- Hiring program staff whose job is to support program officers for repetitive tasks such as data entry.
- Program officers are tasked with managing both missions and R&A programs, which can be very difficult, with the result in some cases that R&A programs preferentially suffer. This should be monitored, and when an R&A program is not being well managed in this situation, the program officer should be assigned to either missions or R&A programs, but not both.
- Internal controls of program funds should be improved to prevent modifications to program budgets without prior approval from program officers and the division director.
- Improve IT support for program officers by NSPIRES and NRESS to include access to records of past reviews, panel members, and external reviewers through an archived database.

Programmatic changes that could reduce the burden on program officers include:

- Consolidating programs by reducing subject-matter duplications across programs, thereby reducing the number subdisciplines covered within a given program on average (See Finding 5 and Recommendation).

- Increasing grant size and duration, thereby theoretically reducing the number of proposals submitted to a given program (See Finding 5 and Recommendation).

These are consistent with Survey recommendations.

(see **Section 6**, Finding 5).

5.2 NRC metrics

The NRC (2010) outlined the metrics that should be applied to the SMD divisions for each of the mission-enabling activities. In the following section, the NRC metrics are given as "bullets" and the report responses are given in indented text.

- ***A simple statement of what the component of the mission-enabling activity is intended to accomplish and how it supports the strategic or tactical plans of the division.***

  Response: For the most part, the activities and programs listed in The NASA Research Opportunities in Space and Earth Sciences (ROSES) and in Requests for Proposals (RFPs) for contracts indicate the objectives (see, for example, abbreviated activity descriptions in Section 3.0).

- ***A statement as to how the component is to accomplish its task.***

  Response: For the most part, the activities and programs listed in ROSES and in RFPs for contracts indicate the approaches that can be applied (i.e., data analysis, field studies, laboratory experiments). However, care must be taken to ensure that the descriptions of these programs are updated as program content and goals evolve.

- ***An evaluation of the success of the activity relative to the stated mission, unexpected benefits, and lessons learned.***

  Response: The mechanism(s) for such an evaluation seem ill defined, or not defined at all (See **Section 6**, Finding 4).

- ***A justification for the resource allocation that is being applied to the component vis-à-vis other mission-enabling activities within the division.***

  Response: Although raw funding levels for most (but not all) of the mission-enabling activities were made available for the study reported here, the justifications for the funding levels appear to be lacking.

6.0 PSS FINDINGS AND RECOMMENDATIONS

The findings and recommendations in this section are derived from the PSS Working Group and from discussions within the full PSS. In addition, an important part of the study processes was to incorporate results from a survey of the planetary science community on the effectiveness of the grant proposal, review, and award process currently used by the PSD. This survey was conducted as part of the analysis of the "portfolio management" recommendation of the NRC. The survey was announced through the *Planetary Exploration Newsletter* and at various planetary meetings, and conducted through an electronic website. There were 438 respondents to the survey; as shown in **Figure 1**, the respondents appear to represent the community in terms of the types of institutions funded.

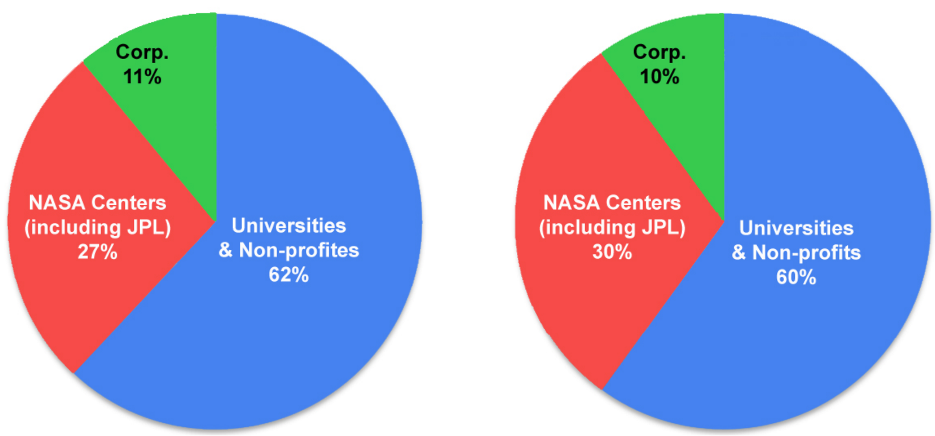

Figure 1. Survey of the planetary science community conducted 14 September to 11 October 2010, showing the distribution by institution of the 438 respondents (left side) compared to the distribution of NASA-funded Principal Investigators (right side)

1. Finding: Budget volatility across PSD SR&T programs degrades the healthy scientific and technical workforce needed to conduct NASA's space and Earth science program and undermines the continuous flow of new technical capabilities and scientific understanding from mission-enabling activities into new spaceflight missions.

Recommendation: The PSS echoes the Survey recommendation that "NASA increase the research and analysis budget for planetary science by 5 percent above the total finally approved FY2011 expenditures in the first year of the coming decade, and increase the budget by 1.5 percent above the inflation level for each successive year of the decade" and that "a substantial program of planetary exploration technology development should be reconstituted and carefully protected against all incursions that would deplete its resources [and] consistently funded at approximately 6-8 percent of the total NASA Planetary Science Division budget".

A declining PSD budget does not allow for the strict implementation of the Decadal recommendation of the 5% increase in R&A funding. However, implementation of the decadal language supporting increased funding for these programs would, at a minimum, call for an FY11 budget level no less than the FY10 level, with no cuts to the R&A programs going forward. It is not clear that the proposed flat budget of $200M for R&A programs going forward meets this criterion.

Additional information should be provided to PSS that demonstrates this to be the case, or the funding should be increased to a level that meets this condition. In determining the FY10 funding level for R&A programs, funds re-phased to FY11 should be included.

In addition, implementation of the Survey recommendation regarding R&A should be revisited from year to year in the context of updated budget prospects for PSD with the intent of implementing that recommendation when the budget environment improves.

Funding for the R&A program should not be diluted by adding significant new responsibilities. Such new responsibilities added to the R&A program should be accompanied by the additional funds needed to support it.

2. Finding: Many of the PSD mission-enabling activities have evolved over the years, but do not appear to be evaluated "across the board" on any regular basis.
Recommendation: The PSD should consider implementing division-wide coordination and evaluation of the mission-enabling activities by NASA and the community by holding a "Senior Review" at least every 10 years, which could be linked to the NRC Surveys. The review should include articulation by the PSD of the current priorities, budget allocations for all mission-enabling activities (including supporting activities), and how the various activities have met their specific program objectives in the past. Such a review should become part of the PSD "portfolio-management" process to ensure that resources are apportioned appropriately. The review could be conducted within a year of the release of the NRC Decadal Survey report. It is important to note, however, that many of the PSD mission-enabling activities have longer time-scales than a decade and so a balance with the NRC Decadal Survey priorities should be maintained.

3. Finding: PSD has a variety of technology-related activities to support near-term and long-term flight projects, including specific instrument-development programs. It has been recognized that support for development has been sporadic and is often inadequate to reach the Technology Readiness Level sufficient for proposing an instrument for flight.
Recommendation: The PSD should establish its own balanced mission-enabling technology program and make available substantial, stable funding through the competed process to develop technology and scientific instruments for flight qualification (TRL ~6). To stimulate technology proposals, the PSD should expand its program of future mission studies to identify early technology drivers for high priority science and common needs for future missions. Implementation of the Survey recommendation to reconstitute a substantial technology development program with consistent funding in the 6-8% range of the PSD budget should help to realize this.

4. Finding**:** Long-term flight projects, such as those to the outer Solar System, can occupy a significant part of a planetary scientist's career. Recognizing that some individuals on active flight teams may no longer participate in the project suggests that a mechanism for replacement and augmentation of mission science teams would be desirable.

Recommendation: The PSD should consider establishing a uniform policy and procedure for ensuring healthy turnover in science team membership on long duration projects and for augmenting mission science teams.

5. Finding: The PSD has a wide variety of mission-enabling activities that are traceable to the Division's scientific objective. However, there do not appear to be clear directives on how the activities are to be evaluated for success.
Recommendation: PSD should consider establishing specific criteria for evaluating the success of each activity in meeting the stated purpose of the activity. Since program elements consist of several areas of such activities identified in their AOs, this might in part consist of first stating how each area supports a PSD strategic objective or objectives and to identify metrics by which one decides that the objective is advanced by that area. These might be qualitative. The metrics are then applied against the activities funded over the previous year. In order to minimize the burden on the program officer, investigators might be tasked with applying these metrics to their funded activities in their annual and final reports, to then be collated by the program officer.

6. Finding: The Planetary Community is stretched "thin" in the preparation and review of proposals; on the one hand, there are many opportunities for support, as indicated in **Table 1**, but on the other hand, the funding levels have not kept pace with inflation, with the result that multiple grants are often required to maintain viable research programs. As a consequence, many investigators spend substantial time writing multiple proposals each year for effectively smaller funding levels. In turn, this increases the workload on Program Officers and the planetary community for providing reviews and serving on review panels. Moreover, many PSD programs appear to have substantial overlap in research activities.
Recommendation: Pressure on the proposal process may be ameliorated by increasing grant size and grant duration up to 5 years if fully justified and applied relatively uniformly to PSD programs (reviewers would need to "adjust" thinking to accept this), however, such a recommendation should not be implemented without modeling the effects of such changes, including their potential impact on the workforce; consideration should also be given to reducing overlap among programs.

7. Finding: The proposal process needs to be more transparent with better communication with proposers, especially from the Program Officers on the status of the process.
Recommendation: 1) Program Officers are encouraged to communicate with their communities more frequently, either directly or through vehicles such as the *Planetary Exploration Newsletter* (PEN) and the NASA *Service and Advice for Research and Analysis* (SARA) website and 2) A table should be published annually by PSD giving the approximate dates when all Division review panels will meet and when proposers should expect the award selections to be announced.

8. Finding: Most of the respondents to the planetary community survey felt that PIs should be able to cover up to 50% of their salary in a single proposal, if justified; some felt that 100% is reasonable, if justified
Recommendation: The following statement should be included in the announcement of the program "Well-justified proposals for significantly greater than average budgets could be considered for funding."

9. Finding: The quality and usefulness of summary reviews sent to proposers appear to be inconsistent across programs and from year to year within the PSD. While some summary reviews are well written, many do not include sufficient content to enable improvements in the proposed research, especially for those proposals that are rejected. The community understands that it is not the responsibility of the review panels to "re-write" proposals, but the review forms should clearly indicate specific areas of weaknesses and suggestions for improvement.
Recommendation: The Division should establish standard instructions that are given to all review panels, which would include a statement of the "charge" to the panels that is uniform and include instructions to the panel to be as specific as possible on the summary review forms with regard to major and minor weaknesses.

10. Finding: Some PIs propose for > 3 years, but are funded for less time; however, they are often not informed of the reason for the shorter duration.
Recommendation: The letter from the Program Officer should include a section that explains the justification for the shorter duration.

11. Finding: The identification of qualified panel members and external reviewers is difficult. Some programs "socialize" new people into the community by having senior graduate students serve on their panel as Executive Secretaries. Also, the manner of implementing conflict of interest standards has had the impact of significantly reducing the pool of knowledgeable reviewers.

Recommendations: 1) Solicitation of qualified panelists and reviewers should be made routinely by the Division Director through announcements, such as in PEN, 2) Senior graduate students can serve as Executive Secretaries, but they should not serve as reviewers, 3) application of conflict of interest standards on reviewers need to take into consideration whether simple means of mitigation could be applied that would allow the expansion of the pool of reviewers (e.g., allowing co-Investigators to serve on a review panel, but leave the room when their proposal is under consideration).

12. Finding: Notifications from HQ of proposal review results are often too late to be useful.
Recommendation: The current policy of notification no later than six months from the proposal due date and one month from the meeting of the review panel should be followed.

13. Finding: There are possibilities for sample return missions in the next decade from multiple targets (including Mars, the Moon and comets, as recommended by the Planetary Science Decadal Survey). Materials returned from these targets are likely to require special considerations, curation, sample handling and analysis capabilities that currently do not exist.
Recommendation: PSD needs to consider the establishment of a well-coordinated and integrated program for development of the next generation of laboratory instruments to be used in sample characterization and analysis. In addition, the NASA's advisory group for returned samples (CAPTEM) should be involved in the early planning phases of sample return missions to plan for appropriate collection, characterization (including containment and hazard assessment, if required), curation, handling and allocation of returned materials.

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APPENDIX 1: Terms of Reference for the study

PLANETARY SCIENCE SUBCOMMITTEE SUPPORTING RESEARCH AND TECHNOLOGY WORKING GROUP

TERMS OF REFERENCE
(DRAFT 1.0)

The Supporting Research and Technology (SR&T) Working Group (WG) is a temporary working group of the Planetary Science Subcommittee (PSS) of the NASA Advisory Council's Science Committee. It supports the PSS and the Planetary Science Division of the Science Mission Directorate. Its task is to:

1. Identify those mission-enabling, research and analysis activities (the activities) that are required to support the strategic goals of the NASA SMD Planetary Division;
2. Map these activities onto existing PSD program elements and identify activities that overlap multiple elements and activities unsupported by any element;
3. Provide recommendations to PSD regarding the application of "active portfolio management" to meet its strategic goals.

The activities to be identified include, but are not limited to, those comprising basic research, data analysis, instrument development, ground-based facilities, special research facilities, high-end computing facilities and data archiving. This WG will not prioritize activities, recommend the premature termination of existing SR&T tasks, nor will its efforts duplicate those of the Planetary Science Technology Review Panel — a group of Civil Servants chartered by the PSD Division Director to provide advice on the structure of technology development programs in PSD.

Per NPD 1150.11, the Working Group will be managed under procedures that ensure the same spirit of openness and public accountability that is embodied by the Federal Advisory Committee Act (FACA). This includes public meetings as appropriate and public access to WG records.

MEMBERSHIP

The membership of the WG shall consist of members of the Planetary Science Subcommittee and, as needed, leading scientists with relevant expertise drawn from industry, academia, independent researchers and Government institutions. The appointment of members to the WG who are not already members of the PSS shall be made by the SMD Associate Administrator in consultation with the PSD Division Director and the PSS Chair. The size of the WG shall not exceed seven members. The PSS Chair will serve on the WG *ex officio.* The PSS Chair, in consultation with the PSD Division Director shall choose one of the WG members to serve as the Chair of the WG.

In the course of its operations, the WG may choose to entertain comments and findings from members of the scientific community or from the chartered Program Analysis Groups of the PSS.

MEETINGS

The WG will meet as often as necessary to accomplish its task. Meetings may be in-person or by telephone and will be open to the public to the greatest extent possible.

REPORTING

The WG shall report to the Science Committee through the Planetary Science Subcommittee. Records of WG meetings such as notes and summaries of findings shall be posted on the Web for public access after approval by the WG Chair.

ADMINISTRATIVE PROVISIONS

The Executive Secretary of the PSS shall serve as the Executive Secretary of the WG.

DURATION

The WG shall terminate on August 1, 2011 unless its Terms of Reference are renewed by the SMD AA.

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Edward J. Weiler	Date
Associate Administrator	
for Science Mission Directorate	

APPENDIX 2: Example Investigations

This appendix includes the five scientific objectives for the Planetary Science Division, as given in the NASA Science Plan (NASA 2010). For each objective, a set of example investigations is listed to represent some of the kinds of studies that are undertaken to address the objective, along with the mission-enabling activities (i.e., *Programs* and *Infrastructure Facilities)* of the PSD that support the investigations. These examples show the linkage or traceability from NASA's planetary science objectives through investigations to specific mission-enabling activities, but are not all-inclusive. Many of the example investigations are derived from discussions held in NASA's Planetary Analysis Groups.

A1.1 Objective 1: *Inventory Solar System objects and identify the processes active in and among them*

Example Investigation: *Constrain the composition of planetary bodies*

Programs: Cassini Data Analysis, Cosmochemistry, Mars Data Analysis, Mars Fundamental Research, Planetary Astronomy, Planetary Atmospheres, Planetary Geology and Geophysics, Planetary Mission Data Analysis

Facilities: Curation, Infrared Telescope Facility, NAIC/Arecibo Planetary Radar System, Planetary Data System, Reflectance Experiment Laboratory

Example Investigation: *Map the distribution of small bodies throughout the Solar system; characterize their physical, chemical, and dynamical properties*

Programs: Cassini Data Analysis, Cosmochemistry, Near Earth Objects Observations, Planetary Astronomy

Facilities: Infrared Telescope Facility, NAIC/Arecibo Planetary Radar System, Planetary Data System, Reflectance Experiment Laboratory, Regional Planetary Image Facilities

Example Investigation: *Constrain the composition of the interior layers in planetary bodies: metallic core, mantle, deep ocean, icy shell (e.g., impurities within the shell), regolith, etc.*

Programs: Astrobiology-Exobiology and Evolutionary Biology, Cassini Data Analysis, Lunar Advanced Science and Exploration Research, NASA Astrobiology Institute, Outer Planets Research, Origins of Solar System, Planetary Geology and Geophysics

Facilities: Infrared Telescope Facility, Planetary Data System

Example Investigation: *Constrain the origin of planetary ring systems*

Programs: Cassini Data Analysis, Origins of Solar System, Outer Planets Research, Planetary Geology and Geophysics

Facilities: NASA Advanced Supercomputing

Example Investigation: *Simulate geological processes, including the modeling of tectonic deformation, crater relaxation, volcanism, and surface-atmosphere interactions to constrain the evolution and current state of planetary bodies*

Programs: Cassini Data Analysis, Lunar Advanced Science and Exploration Research, Mars Data Analysis, Mars Fundamental Research, NASA Astrobiology Institute, Outer Planets Research, Planetary Geology and Geophysics, Planetary Mission Data Analysis,

Facilities: Ames Vertical Gun Range, NASA Advanced Supercomputing, Planetary Aeolian Laboratory, Planetary Data System, Venus Chamber

Example Investigation: *Characterize the interaction of planetary bodies with the solar wind and with solar ionizing radiation*

Programs: Outer Planets Research, Cassini Data Analysis, Planetary Atmospheres, Mars Data Analysis, Mars Fundamental Research, Lunar Advanced Science and Exploration Research, NASA Astrobiology Institute

Facilities: NASA Advanced Supercomputing, Planetary Data System

Example Investigation: *Characterize the structure, dynamics, and energetics of magnetospheres and ionospheres of planets with magnetic fields.*

Programs: Outer Planets Research, Mars Data Analysis, Mars Fundamental Research, Cassini Data Analysis, Jupiter Data Analysis, Planetary Atmospheres

Facilities: NASA Advanced Supercomputing, Planetary Data System

Example Investigation: *Determine and understand the dynamical processes operating in atmospheres of Solar System objects*

Programs: Planetary Atmospheres, Planetary Geology and Geophysics, Outer Planets Research, Mars Fundamental Research, Cassini Data Analysis, Mars Data Analysis, Planetary Astronomy, NASA Astrobiology Institute, Astrobiology-Exobiology and Evolutionary Biology

Facilities: NASA Advanced Supercomputing, Mars Climate Modeling Center (proposed), Planetary Data System

A1.2 Objective 2: *Understand how the Sun's family of planets, satellites, and minor bodies originated and evolved*

Example Investigation: *Studies of the petrology, geochemistry and geochronology of extraterrestrial materials to understand the processes and timescales of how planets and small bodies were formed.*

Programs: Cosmochemistry, Origins of Solar Systems, NASA Lunar Science Institute, Lunar Advanced Science Exploration Research, Mars Fundamental Research

Facilities: Planetary Major Equipment, Curation, Lunar Planetary Institute

Example Investigation: *Laboratory studies of phase stability, chemical partitioning, and other processes necessary to interpret planetary data and to understand processes and conditions on planetary bodies.*

Programs: Cosmochemistry, Origins of Solar Systems, NASA Lunar Science Institute, Planetary Geology and Geophysics, Lunar Advanced Science Exploration Research, Mars Fundamental Research, Outer Planets Research, NASA Astrobiology Institute, Astrobiology-Exobiology and Evolutionary Biology

Facilities: Planetary Major Equipment, Planetary Aeolian Laboratory, Reflectance Experiment Laboratory, Venus Chamber, Ames Vertical Gun Range

Example Investigation: *Study of terrestrial samples that may be analogs for extraterrestrial bodies to understand the processes and conditions on planetary bodies.*

Programs: Cosmochemistry, NASA Lunar Science Institute, Planetary Geology and Geophysics, Lunar Advanced Science Exploration Research, Mars Fundamental Research, Reflectance Experiment Laboratory, Planetary Data System, NASA Astrobiology Institute, Astrobiology-Exobiology and Evolutionary Biology

Example Investigation: *Development and production of cartographic products from planetary datasets and use of reduced, calibrated, publicly available data from planetary missions or ground-based observational databases to address geological or geophysical questions on specific Solar System objects.*

Programs: Planetary Geology and Geophysics, Outer Planets Research

Facilities: Planetary Astronomy, Planetary Cartography, Planetary Data System

Example Investigation: *Theoretical and dynamical modeling applied to geologic and geophysical processes on specific Solar System objects, and to understand dynamical evolution of planets, satellites, small bodies and ring systems.*

Programs: Origins of Solar Systems, NASA Lunar Science Institute, Lunar Advanced Science Exploration Research, Mars Fundamental Research, Planetary Geology and Geophysics, Outer Planets Research, Planetary Data System, NASA Astrobiology Institute, Astrobiology-Exobiology and Evolutionary Biology

Facilities: Planetary Data System

Example Investigation: *Development of new analytical instrumentation or combinations of analytical instruments, or new components of analytical instruments, leading to significant improvements in the precision, resolution, or sensitivity of measurements of extraterrestrial materials compared to the existing state of the art.*

Programs: Cosmochemistry, Laboratory Analysis of Returned Samples, Astrobiology Science and Technology Instrument Development

Facilities: Planetary Major Equipment, Curation

A1.3 Objective 3: *Understand the processes that determine the history and future of habitability of environments on Mars and other Solar System bodies*

Example Investigation: *Field, theoretical and experimental studies, including laboratory studies, of environments and samples that may be analogs for extraterrestrial bodies that could support habitable conditions and can help define the conditions and settings required for habitable environments.*

Programs: Cosmochemistry, Planetary Geology and Geophysics, Mars Fundamental Research, Moon and Mars Analog Mission Activities, NASA Astrobiology Institute, Astrobiology-Exobiology and Evolutionary Biology

Facilities: Reflectance Experiment Laboratory, Planetary Aeolian Laboratory, Ames Vertical Gun Range

Example Investigation: *Studies of the pathways and processes leading from the origin of planetary bodies to life, the nature of the most primitive organisms and the environments in* *which they evolved, and the prebiotic significance of specific molecular processes on Earth to identify what molecules are signatures for habitability*

Programs: Astrobiology Science and Technology for Exploring Planets, Astrobiology Science and Technology Instrument Development, Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute, Planetary Protection

Facilities: Planetary Data System

Example Investigation: *Studies that characterize the composition and preservation potential of present and prior surface and subsurface environments on Mars and other Solar System bodies to help define whether their occurrence may require habitable conditions and to identify possible biosignatures.*

Programs: Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute, Cosmochemistry, Mars Data Analysis, Planetary Data System, Cassini Data Analysis, Outer Planets Research

Facilities: Curation, Planetary Data System

Example Investigation: *Mapping planetary objects in the Solar System that can help to identify the range of settings and processes responsible for shaping planetary surfaces, the nature and distribution of potentially habitable regions, and identify candidate future landing sites.*

Programs: Planetary Geology and Geophysics, Planetary Mission Data Analysis, Planetary Cartography, Mars Data Analysis, Planetary Atmospheres, NASA Astrobiology Institute, Astrobiology-Exobiology and Evolutionary Biology

Facilities: Venus Chamber, Regional Planetary Image Facilities, Lunar and Planetary Institute, Planetary Data System

Example Investigation: *Modeling, theoretical, or laboratory investigations related to the origin, evolution, and stability of habitable conditions on bodies within and outside of the Solar System.*

Programs: Outer Planets Research, Origins of the Solar System, NASA Astrobiology Institute, Astrobiology-Exobiology and Evolutionary Biology

Facilities: NASA Advanced Supercomputing

Example Investigation: *Studies that characterize volatile cycles on Mars, emphasizing likely changes in the location and chemistry of inventories over time as they may relate to the distribution of (present or past) habitable (surface and subsurface) settings on Mars.*

Programs: Mars Data Analysis, Planetary Atmospheres, Planetary Mission Data Analysis, Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute

Facilities: Ames Vertical Gun Range, Regional Planetary Image Facilities, Lunar and Planetary Institute, NASA Advanced Supercomputing, Mars Climate Modeling (proposed), Planetary Data System

Example Investigation: *Search for evidence of ancient climates, extinct life, and potential habitats for extant life on Mars.*

Programs: NASA Astrobiology Institute, Astrobiology-Exobiology and Evolutionary Biology, Planetary Geology and Geophysics, Mars Data Analysis

Facilities: Mars Climate Modeling Center (proposed), Planetary Data System

Example Investigation: *Studies focused on resolving key issues related to the outer planets and their atmospheres and moons that include interpretation of geologic settings and definition of potentially habitable settings to help establish and refine future exploration plans.*

- ***Programs:*** Outer Planets Research, Cassini Data Analysis, Planetary Atmospheres, Planetary Mission Data Analysis, Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute
- ***Facilities:*** Lunar and Planetary Institute, Regional Planetary Image Facilities, NASA Advanced Supercomputing, Planetary Data System

Example Investigation: *Development of laboratory instrumentation and advanced analytical techniques required for the search for evidence of ancient climates, extinct life, and potential habitats for extant life on Mars and for the complete analyses of the samples from recent Planetary Science Division missions, including Genesis and Stardust, as related to evaluating habitability of the source body.*

- ***Programs:*** Cosmochemistry, Astrobiology Science and Technology Instrument Development, Mars Fundamental Research, NASA Astrobiology Institute, Astrobiology-Exobiology and Evolutionary Biology
- ***Facilities:*** Curation

A1.4 Objective 4: *Understand the origin and evolution of Earth life and the biosphere to determine if there is or ever has been life elsewhere in the universe*

Example Investigation: *Investigate the planetary and molecular processes that set the physical and chemical conditions within which living systems may have arisen and evolved on the early Earth*

- ***Programs:*** Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute

Example Investigation: *Determine the nature of the most primitive organisms and the environments in which they evolved.*

- ***Programs:*** Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute, Moon and Mars Analog Missions Activities

Example Investigation: *Determine the original nature of biological energy, transduction, membrane function, and information processing.*

- ***Programs:*** Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute

Example Investigation: *Determine the chemical systems that could have served as precursors of metabolic and replicating systems on Earth and elsewhere, including alternatives to the current DNA-RNA-protein basis for life.*

- ***Programs:*** Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute

Example Investigation: *Characterize the atmosphere and ancient climate of early Earth and identify photochemical reactions leading to the formation of complex organics molecules.*

Programs: Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute, Planetary Atmospheres

Example Investigation: *Study the co-evolution of microbial communities, and the interactions within such communities, that drive major geochemical cycles.*

Programs: Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute

Example Investigation: *Evaluation of environmental factors (extraterrestrial and planetary processes) on the appearance and evolution of multicellular life; investigate how life on Earth and its planetary environment have co-evolved through geological time.*

Programs: Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute, Astrobiology Science and Technology for Exploring Planets, Mars Fundamental Research, Outer Planet Research, Planetary Geology and Geophysics, Origins of Solar Systems

Facilities: Ames Vertical Gun Range

Example Investigation: *Understand the limits and constraints (or lack thereof) of life in extreme environments and identify, and characterize life and life-related chemistry that may exist or have existed on other Solar System bodies.*

Programs: Astrobiology Exobiology and Evolutionary Biology, NASA Astrobiology Institute, Astrobiology Science and Technology for Exploring Planets, Mars Fundamental Research, Outer Planet Research, Planetary Geology and Geophysics

Example Investigation: *Develop universal approaches for detecting evidence of life forms that help distinguish between forward contamination and in situ extraterrestrial life.*

Programs: Planetary Protection Research, Astrobiology Science and Technology Instrument Development, NASA Astrobiology Institute, Astrobiology Science and Technology for Exploring Planets

Example Investigation: *Implement new research capabilities for Astrobiology, such as in situ detection of novel chemical/organic/mineral biomarkers and precision measurements of isotopic abundances of the elements C, H, N, O, P, S, and other life-related elements such as Fe, Mn, Mo, etc.*

Programs: Astrobiology Science and Technology Instrument Development, Astrobiology-Exobiology and Evolutionary Biology, NASA Astrobiology Institute

A1.5 Objective 5: ***Identify and characterize small bodies and the properties of planetary environments that pose a threat to terrestrial life or exploration or provide potentially exploitable resources***

Example Investigation: *Complete the inventory of Near-Earth Objects (NEOs) with diameters greater than or equal to 1 km and to provide capabilities to detect Potentially Hazardous Objects (PHOs) down to 140 meters in size.*

Programs: Near-Earth Object Observations, Planetary Astronomy
Facilities: Infrared Telescope Facility, NAIC/Arecibo Planetary Radar System

Example Investigation: *Perform a sustained, productive search for NEOs and/or obtain follow-up observations of sufficient astrometric precision to allow the accurate prediction of the trajectories of discovered objects.*
Programs: Near-Earth Object Observations
Facilities: NAIC/Arecibo Planetary Radar System, Infrared Telescope Facility

Example Investigation: *Characterize a representative sample of NEOs/PHOs by measuring their sizes, shapes, and compositions.*
Programs: Near-Earth Object Observations, Planetary Cartography, Planetary Mission Data Analysis
Facilities: NAIC/Arecibo Planetary Radar System, Infrared Telescope Facility, Reflectance Experiment Laboratory, Planetary Data System

Example Investigation: *Determine the parameters necessary to understand the characteristics of PHOs important for implementation of mitigation actions against a detected impact threat such as operations designed to disrupt or deflect the trajectory of an asteroid on an impending Earth impact trajectory.*
Programs: Near-Earth Object Observations, Outer Planets Research, Planetary Mission Data Analysis, Planetary Cartography
Facilities: NAIC/Arecibo Planetary Radar System, Infrared Telescope Facility, Reflectance Experiment Laboratory, Planetary Data System

Example Investigation: *Synthesize, analyze, and compare data that will improve the understanding of the extent and influence of planetary geological and geophysical processes on small Solar System bodies.*
Programs: Planetary Geology and Geophysics, Outer Planets Research, Planetary Mission Data Analysis
Facilities: Reflectance Experiment Laboratory, Ames Vertical Gun Range, Planetary Data System

Example Investigation: *Investigate extraterrestrial materials to understand the geochemistry of small Solar System bodies, the chemical origin of the Solar System, and the processes by which small bodies have evolved to their present states.*
Programs: Cosmochemistry
Facilities: Curation