Executive Summary

In recent years, planetary science has seen a tremendous growth in new knowledge. Deposits of water ice exist at the Moon’s poles. Discoveries on the surface of Mars point to an early warm wet climate, and perhaps conditions under which life could have emerged. Liquid methane rain falls on Saturn’s moon Titan, creating rivers, lakes, and geologic landscapes with uncanny resemblances to Earth’s. Comets impact Jupiter, producing Earth-sized scars in the planet’s atmosphere. Saturn’s poles exhibit bizarre geometric cloud patterns and changes; its rings show processes that may help us understand the nature of planetary accretion. Venus may be volcanically active. Jupiter’s icy moons harbor oceans below their ice shells: conceivably Europa’s ocean could support life. Saturn’s tiny moon Enceladus has enough geothermal energy to drive plumes of ice and vapor from its south pole. Dust from comets shows the nature of the primitive materials from which the planets and life arose. And hundreds of new planets discovered around nearby stars have begun to reveal how our solar system fits into a vast collection of others.

This report was requested by NASA and the National Science Foundation (NSF) to review the status of planetary science in the United States and to develop a comprehensive strategy that will continue these advances in the coming decade. Drawing on extensive interactions with the broad planetary science community, the report presents a decadal program of science and exploration with the potential to yield revolutionary new discoveries. The program will achieve long-standing scientific goals with a suite of new missions across the solar system. It will provide fundamental new scientific knowledge, engage a broad segment of the planetary science community, and have wide appeal for the general public whose support enables the program.

A major accomplishment of the committee’s recommended program will be taking the first critical steps toward returning carefully selected samples from the surface of Mars. Mars is unique among the planets in having experienced processes comparable to those on Earth during its formation and evolution. Crucially, the martian surface preserves a record of earliest solar system history, on a planet with conditions that may have been similar to those on Earth when life emerged. It is now possible to select a site on Mars from which to collect samples that will address the question of whether the planet was ever an abode of life. The rocks from Mars that we have on Earth in the form of meteorites cannot provide an answer to this question. They are igneous rocks, whereas recent spacecraft observations have shown the occurrence on Mars of chemical sedimentary rocks of aqueous origin, and rocks that have been aqueously altered. It is these materials, none of which are found in meteorites, that provide the opportunity to study aqueous environments, potential prebiotic chemistry, and perhaps, the remains of early martian life.

If NASA’s planetary budget is augmented, then the program will also carry out the first in-depth exploration of Jupiter’s icy moon Europa. This moon, with its probable vast subsurface ocean sandwiched between a potentially active silicate interior and a highly dynamic surface ice shell, offers one of the most promising extraterrestrial habitable environments in our solar system and a plausible model for habitable environments outside it. The Jupiter system in which Europa resides hosts an astonishing diversity of phenomena, illuminating fundamental planetary processes. While Voyager and Galileo taught us much about Europa and the Jupiter system, the relatively primitive instrumentation of those missions, and the low data volumes returned, left many questions unanswered. Major discoveries surely remain to be made. The first step in understanding the potential of the outer solar system as an abode for life is a Europa mission with the goal of confirming the presence of an interior ocean, characterizing the satellite's ice shell, and understanding its geological history.

The program will also break new ground deep in the outer solar system. The gas giants Jupiter and Saturn have been extensively studied by the Galileo and Cassini missions, respectively. But Uranus and Neptune represent a wholly distinct class of planet. While Jupiter and Saturn are made mostly of hydrogen, Uranus and Neptune have much smaller hydrogen envelopes. The bulk composition of these planets is dominated instead by heavier elements; oxygen, carbon, nitrogen, and sulfur are the likely candidates. What little we know about the internal structure and composition of these "ice giant" planets comes from the brief flybys of Voyager 2. So the ice giants are one of the great remaining unknowns in the solar system: the only class of planet that has never been explored in detail. The proposed program will fill this gap in our knowledge by initiating a mission to orbit Uranus and put a probe into the planet's atmosphere. It is exploration in the truest sense, with the same potential for new discoveries as Galileo at Jupiter and Cassini at Saturn.

The program described in this report also vigorously continues NASA's two programs of competed planetary missions: New Frontiers and Discovery. It includes seven candidate New Frontiers missions from which NASA will select two for flight in the coming decade. These New Frontiers candidates cover a vast sweep of exciting planetary science questions: The surface composition of Venus, the internal structure of the Moon, the composition of the lunar mantle, the nature of Trojan asteroids, the composition of comet nuclei, the geophysics of Jupiter's volcanic moon Io, and the structure and detailed composition of Saturn's atmosphere. And continuation of the highly successful Discovery program, which involves regular competitive selections, will provide a steady stream of scientific discoveries from small missions that draw on the full creativity of the science community.

Space exploration has become a worldwide venture, and international collaboration has the potential to enrich the program in ways that benefit all participants. The program therefore relies more strongly than ever before on international participation, presenting many opportunities for collaboration with other nations. Most notably, the ambitious and complex Mars Sample Return campaign is critically dependent on a long-term and enabling collaboration with the European Space Agency (ESA).

In order to assemble this program, four criteria were used to select and prioritize missions. The first and most important was science return per dollar. Science return was judged with respect to the key scientific questions identified by the planetary science community; costs were estimated via a careful and conservative procedure that is described in detail in the body of this report. The second was programmatic balance—striving to achieve an appropriate balance among mission targets across the solar system and an appropriate mix of small, medium, and large missions. The other two were technological readiness and availability of trajectory opportunities within the 2013-2022 time period.

In order to help develop its recommendations, the committee commissioned technical studies of many candidate missions that were selected for study on the basis of white papers submitted by the scientific community. A subset of these was chosen on the basis of the four prioritization criteria listed above for independent assessments of technical feasibility, as well as conservative estimates of costs. From these, the committee finalized a set of recommended missions intended to achieve the highest priority science identified by the community within the budget resources projected to be available. It consists of a balanced mix of small Discovery missions, medium-sized New Frontiers missions, and large "Flagship" missions, enabling both a steady stream of new discoveries and the capability to address major challenges. The mission recommendations assume full funding of all missions that are currently in development, and continuation of missions that are currently in flight, subject to approval via the appropriate review process.

SMALL MISSIONS

Missions for NASA's Discovery program lie outside the bounds of a decadal strategic plan, so this report makes no specific Discovery flight mission recommendations. The committee stresses, however, that the Discovery program has made important and fundamental contributions to planetary exploration, and can continue to do so in the coming decade. Because there is still so much compelling science that can be addressed by Discovery missions, the committee recommends continuation of the Discovery program at its current level, adjusted for inflation, with a cost cap per mission that is also adjusted for inflation from the current value (i.e., to about $500 million in fiscal year (FY) 2015). And in order for the science community to plan Discovery missions effectively, the committee recommends a regular, predictable, and preferably rapid (≤24 month) cadence for Discovery AO releases and mission selections.

An important small mission that lies outside the Discovery program is the proposed joint ESA/NASA Mars Trace Gas Orbiter that would launch in 2016. The committee supports flight of this mission as long as the currently negotiated division of responsibilities and costs with ESA is preserved.

MEDIUM MISSIONS

The current cost cap for NASA's competed New Frontiers missions, inflated to FY2015 dollars, is $1.05 billion, including launch vehicle costs. The committee recommends changing this cap to $1.0 billion FY2015, *excluding* launch vehicle costs. This change represents a modest increase in the effective cost cap and will allow a scientifically rich and diverse set of New Frontiers missions to be carried out, and will help protect the science content of the program against increases and volatility in launch vehicle costs.

Two New Frontiers missions have been selected by NASA to date, and a third selection is underway now. The committee recommends that NASA select two New Frontiers missions in the decade 2013-2022. These are referred to here as New Frontiers Mission 4 and New Frontiers Mission 5.

New Frontiers Mission 4 should be selected from among the following five candidates:

- Comet Surface Sample Return,
- Lunar South Pole-Aitken Basin Sample Return,
- Saturn Probe,
- Trojan Tour and Rendezvous, and
- Venus In Situ Explorer.

No relative priorities are assigned to these five candidates; instead, the selection among them should be made on the basis of competitive peer review.

If the third New Frontiers mission selected by NASA addresses the goals of one of these mission candidates, the corresponding candidate should be removed from the above list of five, reducing the number from which NASA should make the New Frontiers Mission 4 selection to four.

For the New Frontiers Mission 5 selection, the following missions should be added to the list of remaining candidates:

- Io Observer,
- Lunar Geophysical Network.

Again, no relative priorities are assigned to any of these mission candidates.

Tables ES.1 and ES.2 summarize the recommended mission candidates and decision rules for the New Frontiers program.

LARGE MISSIONS

The highest priority large mission for the decade 2013-2022 is the Mars Astrobiology Explorer-Cacher (MAX-C), which will begin a three-mission NASA-ESA Mars Sample Return campaign extending into the decade beyond 2022. At an estimated cost of $3.5 billion as currently designed, however, MAX-C would take up a disproportionate share of the NASA's planetary budget. This high cost results in large part from the goal to deliver two large and capable rovers—a NASA sample-caching rover and the European Space Agency's ExoMars rover—using a single entry, descent, and landing (EDL) system that is derived from the Mars Science Laboratory (MSL) EDL system. Accommodation of two such large rovers would require major redesign of the MSL EDL system, with substantial associated cost growth.

The committee recommends that NASA fly MAX-C in the decade 2013-2022, but only if it can be conducted for a cost to NASA of no more than approximately $2.5 billion FY2015. If a cost of no more than about $2.5 billion FY2015 cannot be verified, the mission (and the subsequent elements of Mars Sample Return) should be deferred until a subsequent decade or cancelled.

It is likely that a significant reduction in mission scope will be needed to keep the cost of MAX-C below $2.5 billion. In order to be of benefit to NASA, the Mars exploration partnership with ESA must involve ESA participation in other missions of the Mars Sample Return campaign. The best way to maintain the partnership will be an equitable reduction in scope of both the NASA and ESA objectives for the joint MAX-C/ExoMars mission, so that both parties still benefit from it.

The second highest priority Flagship mission for the decade 2013-2022 is the Jupiter Europa Orbiter (JEO). However, its cost as currently designed is so high that both a decrease in mission scope and an increase in NASA's planetary budget are necessary to make it affordable. The projected cost of the mission as currently designed is $4.7 billion FY2015. If JEO were to be funded at this level within the currently projected NASA planetary budget it would lead to an unacceptable programmatic imbalance, eliminating too many other important missions. Therefore, while the committee recommends JEO as the second highest priority Flagship mission, close behind MAX-C, it should fly in the decade 2013-2022 only if changes to both the mission and the NASA planetary budget make it affordable without eliminating any other recommended missions. These changes are likely to involve both a reduction in mission scope and a formal budgetary new start for JEO that is accompanied by an increase in the NASA planetary budget. NASA should immediately undertake an effort to find major cost reductions for JEO, with the goal of minimizing the size of the budget increase necessary to enable the mission.

The third highest priority Flagship mission is the Uranus Orbiter and Probe mission. The committee carefully investigated missions to both ice giants, Uranus and Neptune. While both missions have high scientific merit, the conclusion was that a Uranus mission is favored for the decade 2013-2022 for practical reasons involving available trajectories, flight times, and cost. The Uranus Orbiter and Probe mission should be initiated in the decade 2013-2022 even if both MAX-C and JEO take place. But like those other two missions, it should be subjected to rigorous independent cost verification throughout its development, and descoped or canceled if costs grow significantly above the projected cost of $2.7 billion FY2015.

Table ES.3 summarizes the recommended large missions and associated decision rules.

Following the priorities and decision rules outlined above, two example programs of solar system exploration can be described for the decade 2013-2022.

The *Recommended Program* can be conducted assuming a budget increase sufficient to allow a new start for JEO. It includes the following elements (in no particular order):

- Discovery program funded at the current level adjusted for inflation;
- Mars Trace Gas Orbiter conducted jointly with ESA;
- New Frontiers Missions 4 and 5;
- MAX-C (descoped to $2.5 billion);

- Jupiter Europa Orbiter (descoped);
- Uranus Orbiter and Probe

The *Cost Constrained Program* can be conducted assuming the currently projected NASA planetary budget. It includes the following elements (in no particular order):

- Discovery program funded at the current level adjusted for inflation;
- Mars Trace Gas Orbiter conducted jointly with ESA;
- New Frontiers Mission 4 and 5;
- MAX-C (descoped to $2.5 billion);
- Uranus Orbiter and Probe

Plausible circumstances could improve the budget picture presented above. If this happened, the additions to the recommended plan should be, in priority order:

1. An increase in funding for the Discovery program,
2. Another New Frontiers mission, and
3. Either the Enceladus Orbiter mission or the Venus Climate Mission.

It is also possible that the budget picture could be less favorable than the committee has assumed. If cuts to the program are necessary, the first approach should be descoping or delaying Flagship missions. Changes to the New Frontiers or Discovery programs should be considered only if adjustments to Flagship missions cannot solve the problem. And high priority should be placed on preserving funding for research and analysis programs and for technology development.

Looking ahead to possible missions in the decade beyond 2022, it is important to make significant near-term technology investments in the Mars Sample Return Lander, Mars Sample Return Orbiter, Titan Saturn System Mission, and Neptune System Orbiter and Probe.

NASA-FUNDED SUPPORTING RESEARCH AND TECHNOLOGY DEVELOPMENT

NASA's planetary research and analysis programs are heavily oversubscribed. Consistent with the mission recommendations and costs presented above, the committee recommends 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. Also, the future of planetary science depends on a well-conceived, robust, stable technology investment program. The committee unequivocally recommends that a substantial program of planetary exploration technology development should be reconstituted and carefully protected against all incursions that would deplete its resources. This program should be consistently funded at approximately 6 to 8 percent of the total NASA Planetary Science Division budget.

NSF-FUNDED RESEARCH AND INFRASTRUCTURE

The National Science Foundation supports nearly all areas of planetary science except space missions, which it supports indirectly through laboratory research and archived data. NSF grants and support for field activities are an important source of support for planetary science in the United States, and should continue. NSF is also the largest federal funding agency for ground-based astronomy in the United States. The ground-based observational facilities supported wholly or in part by NSF are essential to planetary astronomical observations, both in support of active space missions and in studies independent of (or as follow up to) such missions. Their continued support is critical to the advancement of planetary science.

One of the future NSF-funded facilities most important to planetary science is the Large Synoptic Survey Telescope (LSST). The committee encourages the timely completion of LSST, and stresses the importance of its contributions to planetary science once telescope operations begin. Finally, the committee recommends expansion of NSF funding for the support of planetary science in existing laboratories, and the establishment of new laboratories as needs develop.

TABLE ES.1 Medium Class Missions—New Frontiers 4 (in alphabetical order)

Mission Recommendation	Scientific Objectives	Key Challenges	Decision Rules	Chapter
Comet Surface Sample Return	• Acquire and return to Earth for laboratory analysis a macroscopic (≥500 cc) comet nucleus surface sample • Characterize the surface region sampled • Preserve sample complex organics	• Sample acquisition • Mission design • System mass	N/A	4
Lunar South Pole-Aitken Basin Sample Return	Same as 2002 decadal survey	N/A	Remove if MoonRise is selected for NF-3	5
Saturn Probe	• Determine noble gas abundances and isotopic ratios of hydrogen, carbon, nitrogen, and oxygen in Saturn's atmosphere • Determine the atmospheric structure at the probe descent location	• Entry probe • Payload requirements growth	N/A	7
Trojan Tour and Rendezvous	Visit, observe, and characterize multiple Trojan asteroids	• System power • System mass	N/A	4
Venus In Situ Explorer	Same as 2002 decadal survey (and amended by 2007 NRC New Frontiers report)	N/A	Remove if SAGE is selected for NF-3	5

NOTE: N/A = Not available (not evaluated by decadal survey). The MoonRise and SAGE missions that address these scientific objectives are currently in competition for New Frontiers 3 (NF-3).

TABLE ES.2 Medium Class Missions—New Frontiers 5 (in alphabetical order)

Mission Recommendation	Scientific Objectives	Key Challenges	Decision Rules	Chapter
Comet Surface Sample Return	See Table ES.1	See Table ES.1	Remove if selected for NF-4	4
Io Observer	Determine internal structure of Io and mechanisms contributing to Io's volcanism	• Radiation • System power	Remove if selected for NF-4	8
Lunar Geophysical Network	Enhance knowledge of lunar interior	• Propulsion • Mass • Reliability • Mission operations	Remove if selected for NF-4	5
Lunar South Pole-Aitken Basin Sample Return	See Table ES.1	N/A	Remove if selected for NF-4, or if MoonRise is selected for NF-3	5
Saturn Probe	See Table ES.1	See Table ES.1	Remove if selected for NF-4	7
Trojan Tour and Rendezvous	See Table ES.1	See Table ES.1	Remove if selected for NF-4	4
Venus In Situ Explorer	See Table ES.1	N/A	Remove if selected for NF-4, or if SAGE is selected for NF-3	5

NOTE: N/A = Not available (not evaluated by decadal survey). The MoonRise and SAGE missions that address these scientific objectives are currently in competition for New Frontiers 3.

TABLE ES.3 Large Class Missions (in priority order)

Mission Recommendation	Scientific Objectives	Key Challenges	Decision Rules	Chapter
Mars Astrobiology Explorer-Cacher Descope	• Perform in situ science on Mars samples to look for evidence of ancient life or pre-biotic chemistry • Collect, document, and package samples for future collection and return to Earth	• Keeping within Mars Science Laboratory design constraints • Sample handling, encapsulation, and containerization • Increased rover traverse speed over MSL and MER	Should be flown only if it can be conducted for a cost to NASA of no more than approximately $2.5 billion (FY ’15 dollars)	6
Jupiter Europa Orbiter Descope	Explore Europa to investigate its habitability	• Radiation • Mass • Power • Instruments	Should be flown only if changes to both the mission design and the NASA planetary budget make it affordable without eliminating any other recommended missions.	8
Uranus Orbiter and Probe (no Solar Electric Propulsion stage)	• Investigate the interior structure, atmosphere, and composition of Uranus • Observe the Uranus satellite and ring systems	• Demanding entry probe mission • Long life (15.4 years) for orbiter • High magnetic cleanliness for orbiter • System mass and power	Should be initiated even if both MAX-C and JEO take place.	7