SRM 3 – The Solar System Exploration Strategic Roadmap

TABLE OF CONTENTS

I. Introduction

The solar system—our Sun's system of planets, moons, and smaller debris—is humankind's cosmic backyard. Small by factors of millions compared to interstellar distances, the spaces between the planets are daunting but surmountable stepping stones toward the human dream of interstellar flight. And it is within this cosmic backyard that the immediate clues to our own origin—that of life, and of the Earth as a persistently habitable world—are to be found. We wonder, as we look up at our neighboring planets on a dark, moonless night, whether life is to be found on these worlds, either viable communities of simple organisms or remains that have been dead for geologically-long periods of time. If so, then perhaps the universe beyond our backyard is teeming with life, from the simple to the complex. If, instead, we find our planetary neighbors to be sterile testaments to a delicate fine-tuning of conditions necessary for initiating and sustaining life, then we must ask ourselves whether we are alone in a vast, impersonal cosmos.

It is for these reasons that we explore the solar system with robotic emissaries: to flex our technological muscle by crossing vast distances and operating in exotic and extreme environments; to understand how the planets came to be and what triggered different evolutionary paths among worlds; to trace the early history of our own planet Earth and how it came to be habitable; to search for evidence of extinct or extant life and life's precursory chemistry on and within neighboring planetary bodies. Mars is an important target of these endeavors but not the only one; were the red deserts and canyons of that world to be our only goal, humanity's explorations beyond Earth would be greatly impoverished. Likewise the Moon, despite its importance as a signpost of the first billion years of Earth's history, is no more than a stepping-stone to a surprising array of vastly different and more complex planetary worlds that lie beyond. We must explore the solar system in its vastness and variety; we must commit as the Earth's most advanced spacefaring nation to extending humankind's reach across an almost daunting array of different worlds. We must *explore!*

The United States has committed itself to the continued exploration of the solar system through the President's "Moon, Mars and Beyond" initiative. As a result of this initiative, it is an agency goal to

> "Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore the moons of Jupiter, asteroids, and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources."

But how do we construct an economically rational and technologically achievable ordering of planetary targets and exploration? The approach suggested in this roadmap begins with a set of five "scientific objectives":

1. Learn how the sun's family of planets and minor bodies originated

2. Determine how the solar system evolved to its current diverse state including the origin and evolution of the Earth's biosphere
3. Explore the space environment to discover potential hazards and search for resources that would enable permanent human presence
4. Understand the processes that determine the fate of the solar system and life within it
5. Determine if there is or ever has been life elsewhere in the solar system

The five objectives can be understood as addressing, in different ways, the fundamental goal of understanding *how our solar system became, and planetary systems in general become, habitable—and how they maintain that ability to nurture life.* How do planets that can support life arise, and what is the probability that any given system will have a habitable planet? Scientific objective 1 addresses the goal through a deeper understanding of the mechanisms by which our solar system formed, and whether our own system is a typical or unusual outcome of the general process of planetary system formation. Scientific objective 2 seeks to quantify how the planets and the space environment surrounding them evolved to the state we see today, and how this evolution affected the capability of particular planetary environments to nurture life. Scientific objective 3 addresses habitability through the present day space environment, the hazards that it presents in the near-future to Earthly life, and the potential opportunities it provides through resources to support the spread of humankind throughout the solar system. Scientific objective 4 stimulates exploration of planetary neighbors whose current environments are uninhabitable, and whose evolutionary history in arriving there might presage aspects of the future evolution of our own, currently habitable, home world. Finally, the search for life or evidence of past life elsewhere in the solar system is embodied in scientific objective 5—a mandate to understand whether Earth is and has always been the only habitable planet in our solar system.

Habitability, then, is the key word that drives the strategy in the program of exploration laid out here. But the question of habitability must be parsed, from a practical standpoint, into two threads that lead more directly to a prioritization of targets and exploration objectives. The first thread is that of habitability in planetary environments: how have specific planetary environments evolved with time, when and in what way were they habitable, and does life exist there now? The second thread is habitability associated with planetary system architecture: what determines the arrangements of planetary systems, what roles do the positions and masses of giant planets play in the formation of habitable planets and moons and the delivery to them of the chemical ingredients of life, and how have our own giant planets shaped the evolution of the impact hazard population in our own system? Both threads speak to the fundamental issue of how planetary systems become habitable by exploring our own solar system from two complimentary perspectives—comparative exploration of worlds, and exploration of planetary architecture. Both threads connect to other strategic roadmaps through the exploration of Mars as a once habitable world, and the exploration of the Moon as a preserved record of the earliest evolution of the Earth and its impact environment. And both connect to the compelling question, encapsulated in a third roadmap, of the potential variety and habitability of planetary systems around other stars.

Both threads require a mixture of small-, medium-, and large-class missions. The small ($300-500M) missions, carried out through the Discovery Program, are PI-led missions that allow fast response to address a specific set of high value scientific questions at targets that may be less technically challenging. For this reason, Discovery will pay a crucial role, as described below, in the exploration of small bodies—asteroids, comets—that provide key clues to the chemistry of solar system formation, impact hazards through time, and the shaping of the architecture of our own planetary system.

Medium-class ($500-800M) missions in solar system exploration, New Frontiers, are PI-led but respond to strategic targets specified in the Roadmap and other planning documents. New Frontiers missions will enable aspects of the exploration of a range of objects, from Venus to giant planets, but will be limited in scope in terms of the complexity of operational capabilities at these bodies. Hence, they too will play key roles in solar system exploration but cannot achieve all of the measurement and exploration objectives necessary to answer the basic questions that motivate robotic exploration of the planets.

"Flagship-class" ($800 to 1400M or $1400 to $2800M) missions will be needed in order to reach and explore difficult but high priority targets. These critically important targets could help establish the limits of habitability, not just for our solar system, but for planetary systems in general. In particular, they potentially provide an opportunity to identify prebiotic organic molecules or even extant life beyond Earth, should it exist, in our own solar system. The targets of flagship missions include the surface of Venus, the lower atmosphere and surface of Titan, the surface and subsurface of Europa, the deep atmosphere of Neptune and the surface of its moon Triton, and the surface of a comet nucleus in the form of cryogenically preserved samples.

The next section discusses the program of missions and supporting research and technology development that will be necessary to answer the scientific questions posed above.

II. Science Implementation

Contributions of Flagship-class Missions

Venus, so similar in size to Earth and our closest planetary neighbor, is a nightmarish world of vast basaltic volcanic flows lying under a carbon dioxide atmosphere whose pressure is 90 times the pressure at sea level on Earth. The surface temperature of Venus, over 460 Celsius, is above the melting point of lead and well above the temperature beyond which water cannot exist as a liquid, no matter what the pressure. Such extreme conditions are surprising even though Venus is 30% closer to the Sun than is the Earth; its globe circling sulfuric cloud layer reflects so much sunlight that the Venusian lower atmosphere actually receives less sunlight than does the Earth's surface. But the massive carbon dioxide atmosphere creates enormous greenhouse warming, and the resulting complete lack of water in the crust and on the surface not only rules out life but also profoundly affects the geology of this otherwise near-twin of Earth. How long Venus has been in this state is unclear—its basaltic veneer might have formed within the second half of the age of the solar system, and the isotopic enrichment of heavy hydrogen in the atmosphere's trace amount of water points to potentially large amounts of water earlier in Venusian history. The disorganized pattern of rolling highlands and lowlands are a stark contrast to the Earth's granitic continents and balsaltic ocean basins, suggesting that plate tectonics failed on Venus eons ago, or never began.

But the ancient Sun of 4 billion years ago was 30% fainter than it is today, and early Venus might not have experienced much more solar heating than does the Earth today. Did Venus lose its water and form a massive carbon dioxide atmosphere late in its history, or right at the start? To know the answer to this question is to understand whether the 0.7-AU region around a Sun-like star (Earth sits at 1 AU, or 150 million kilometers, from the Sun) forms part of the long-term habitable zone or is just too close. Together with a fuller understanding of the evolution of the Martian climate, we can then address whether the habitable zone around a solar-type star is narrow, perhaps extending only 0.1 AU inward and outward of 1 AU, or might extend inward and outward a significantly larger distance, with obvious implications for Terrestrial Planet Finder's search for extra-solar habitable worlds. And to know the answer is also the key to better understanding how far in the future our own planet will yield up its life-giving oceans to a relentlessly-brightening Sun and become a Dante-esque hell like Venus.

Venus' atmosphere will not tell us this story by itself. We must send mobile vehicles to the highlands of Venus, possibly with drills, to find ancient crust that has a granitic or andesitic signature—the signs of persistent plate tectonics and the action of liquid water on crustal formation. Should we find such crust—an indication that Venus was at one time more like the Earth—we might then plan a later and more ambitious effort to bring samples back to Earth to perform more detailed and delicate chemical and petrologic studies possible only in terrestrial laboratories. The surface exploration of Venus, and ultimately possible sample returns, are flagship-class missions.

The exploration of Venus is a dual attack on the question of habitability from the point of view of planetary architecture (how wide is the long-term habitable zone?) and habitable worlds (by what processes did Venus lose its early habitability, and to what extent was this purely a question of proximity to the Sun versus small differences in intrinsic properties relative to Earth. In conjunction with the study of Mars, the triad of atmosphere-endowed terrestrial planets will then be fully explored.

But a triad of a different kind awaits our robotic explorers in the outer solar system: three moons with varying atmosphere and ocean environments that parallel in an odd way the differences among Venus, Earth and Mars. Europa, Titan and Triton orbit Jupiter, Saturn and Neptune at distances of 5, 10 and 30 AU, respectively, from the Sun. Europa, tidally heated by Jupiter, is a warm rocky body possessed of an icy shell that is melted to some extent. That is, a global ocean of liquid water exists under an ice crust of indeterminate thickness. Yet the extent to which this subsurface ocean is endowed with organic molecules, the stuff of life, is unknown; the icy surface of Europa shows little evidence for carbon-bearing compounds, but few would survive for long exposed in vacuum to the high-radiation Jovian environment.

Titan has a Europa-sized rock core wrapped in a massive mantle of water ice, making it larger than its Jovian cousin. Resident in the colder environment of the Saturn system, Titan has a massive nitrogen-methane atmosphere with a thermal structure much like Earth's but with much lower temperatures (-180 Celsius at the surface), and abundant organics in the atmosphere and apparently (from early Cassini-Huygens results) on the surface. Neptune's moon Triton is less massive than Titan in the same proportion as Mars is to the Earth. It too has a nitrogen-methane atmosphere, but being so far from the Sun the atmosphere is mostly frozen out on the surface and moves seasonally from pole-to-pole, as does that of Mars. The Earth-Mars analogy carries through nicely with Titan and Triton; the former has methane rain and rivers of methane and perhaps ethane, while the latter is in deep freeze but shows evidence of a much warmer (perhaps tidally-driven) earlier history. Yet the origin of Triton almost certainly lies in the Kuiper Belt, like that of Pluto, and so the nitrogen-methane atmospheres of Titan and Triton could have very different origins.

To explore these three worlds is to address primarily habitability in planetary environments, but also (through the origins of the methane and nitrogen atmospheres of Titan versus Triton) planetary architecture. We seek to discover life in the subsurface oceans of Europa, but we must first know how deep we must drill and where to do so; are there places where tidal stresses open fissures and expose the water oceans to space? To address these issues requires sending a spacecraft to orbit Europa and map its crustal thickness and surface geology for as long as the intense Jovian radiation can be withstood, but at least a month. With or without a surface lander or penetrator on the same carrier, this requires a Flagship-class mission.

Cassini-Huygens has revealed Titan to be a world with processes much like those on Earth, but operating under different (colder) conditions and hence on different materials. Volcanism does not involve melting rock into lava on Titan; here water mixed with antifreeze (perhaps ammonia) produces buoyant "cryolavas" of viscous water that flow across the surface. Atmospheric jetstreams transition to variable and gentler surface winds that blow dark material across the surface and appear to form dunes of organic powders. Impact craters are few. Rainfall-driven streams seem to intermingle with intricate springs in the hills of the Huygens landing site; liquid methane and ethane evaporated into the warm Huygens probe to reveal their subsurface presence, and may have carved the springs and streams, as well as rounding the pebbles of uncertain composition at the landing site. Hints of benzene and cyanogen in the surface materials bespeak the presence of the products of methane and nitrogen chemistry.

Recent work hints at a prebiotic Earth atmosphere containing not just nitrogen and carbon dioxide, but significant amounts of methane and hydrogen as well. The present Titan environment may be compositionally much more akin to that of the pre-biotic Earth than was thought at the time Cassini-Huygens was launched. And the absence of stable liquid water may be a blessing for pre-biotic studies rather than a curse; without life gaining dominance on Titan, the surface may preserve the products of occasional encounters between organics and volcanically- or impact-generated liquid water. What happens when organic deposits on Titan encounter flows of water and ammonia? Are amino acids and other pre-biotic molecules created? How far toward life has organic chemistry proceeded on Titan's surface over eons of time, protected from destructive UV radiation? Could exotic life forms that utilize liquid hydrocarbons as primary solvents exist on Titan today? Is the chillingly familiar yet alien scene revealed by Huygens only a sampling of Stygian panoramas that await us on Titan? To address these questions we must return to this complex world with a mobile platform, perhaps taking advantage of the benignly dense atmosphere, to course over the surface and sample where interesting geology has occurred or large deposits of organics are present. To do so requires a flagship-class mission.

Exploration of Triton completes the study of the triad. Just as Cassini will reveal whether Titan has a significant amount of liquid water in its interior, a future mission to Triton will do the same. Such an experiment, as well as closer analysis of the weirdly melted crust of this frigid moon first imaged by Voyager 2 in 1989, will be part of a mission to explore the Neptune system. Neptune itself is a smaller "giant planet," often called an ice giant, with much less hydrogen and helium than Jupiter or Saturn It poses a number of important questions regarding how giant planets form and just what truncates the formation of multiple giant planets in a planetary system. Residing on the edge of our planetary system, Neptune may hold deep in its interior chemical clues to the nature of the rocky and icy debris that formed the giant planets. Because the proportion of rock and ice relative to hydrogen is much larger for Neptune than for Jupiter, the "signal" associated with the abundances of oxygen, carbon, nitrogen and noble gases more strongly reflects the origin of the solid material. Were the planetesimals primitive, hardly altered from the parent molecular cloud, or were they heavily processed in the outer disk? To what extent are ice giants like Uranus and Neptune the norm in other planetary systems, versus gas giants like Jupiter and Saturn or terrestrial planets like Earth? Neptune may provide a connection to a class of worlds around other stars just barely detectable with current technology, and whose commonality we do not yet understand. A flagship mission to Neptune would deploy deep probes in its atmosphere for comparison to elemental abundances in Jupiter, revealed in part by Galileo, but completed with New Frontier-class probes. It would make multiple flybys of, or orbit, Triton, exploring that world while it establishes the role our outermost giant planet played in shaping the leftover debris of planet formation we call the Kuiper Belt.

Comets are samples of rocky and icy bodies from the outer solar system that survived perturbations by the giant planets, being neither thrown in to the Sun nor ejected from the solar system. They supplied some fraction of the Earth's water and organic inventory, but their importance in making the Earth habitable in this regard remains uncertain. They are part of a population of impactors, along with debris in the asteroid belt and elsewhere that first frustrated the formation of life on Earth, but then perhaps stimulated the formation of new organisms over time through ecosystem-emptying catastrophic impacts (such as the Chicxulub impact that may have extinguished the dinosaurs 65 million years ago). Placing comets as primitive bodies in the framework of the planetesimals that formed the planets themselves requires understanding their relationship to asteroids and meteorites, a process to be completed by a New Frontiers class sample return from a comet nucleus. But to understand how comets relate to material in the cold, dark molecular clouds out of which planetary systems like our own may have formed, requires preserving and analyzing the most delicate ices and organics present in cometary nuclei. Such preserved samples could contain the most primitive precursors to life that we could obtain—organic molecules resident in ices that have been preserved far from the Sun for much of the age of the solar system. To return such a sample would require a Flagship mission.

The exploration of the solar system to understand why we exist as living, conscious beings, the extent to which we share the cosmos with others, and the long term fate of life on Earth, is a risky and challenging endeavor. Having laid out the science rationale for the program and the principal targets of the most ambitious, Flagship, missions, we next map out a Roadmap strategy that—in its combination of small, medium and large missions, together with decision points that determine the direction of exploration from one decade to the next—will bring humankind to a much deeper understanding of its place in the cosmos.

Contributions of New Frontiers (medium-class) Missions

As noted above, the New Frontiers Program comprises Principal Investigator-led medium-class missions addressing specific strategic scientific investigations that do not require flagship-class missions. The recent National Research Council (NRC) Report, “New Frontiers in the Solar System—An Integrated Exploration Strategy,” identified several high priority targets for this mission class. The goals of one of these, a Kuiper Belt-Pluto Explorer, are addressed in part by the first New Frontiers mission called New Horizons. New Horizons would make the first reconnaissance of Pluto and Charon - a "double planet" and the last planet in our solar system to be visited by spacecraft. Then, as part of an extended mission, New Horizons would visit one or more objects in the Kuiper Belt region beyond Neptune. Study of Kuiper Belt Objects (KBOs) including Pluto will provide important insights into the physical nature of these planetary building blocks and allow us to survey the organic matter and volatiles that they contain. Objects such as these, diverted into the inner solar system by the gravitational influence of giant planets, may have provided the volatiles and organics needed to create habitable environments on the terrestrial planets.

The second New Frontiers mission will address the goals of one of two other high priority investigations identified by the NRC. The Lunar South Pole-Aitken Basin Sample Return mission was given priority by the NRC in part because of the importance of tying down the Moon’s early impact chronology. Radioactive age dating of returned samples from this ancient impact basin could change our understanding of the timing and intensity of the late heavy bombardment suffered by both the early Earth the Moon. The emergence of life of Earth may have been stymied by the late heavy bombardment, so a better understanding of its chronology could provide important constraints on the timescales for the development of Earth’s first life. The Jupiter Polar orbiter with Probes was identified by the NRC as a high priority investigation to determine if Jupiter has a core, to measure its water abundance (and hence its O/H ratio, which is uncertain by an order of magnitude), to measure the deep winds down to the 100-bar level, and to explore the magnetosphere, particularly to understand how Jupiter's magnetic field is generated. Such a mission would contribute greatly to our understanding of how Jupiter formed, and hence to advancing knowledge about the second habitability thread, i.e., how planetary system architectures affect habitability.

The other two highest priority investigations identified by the NRC for the New Frontiers Program were the Venus In Situ Explorer (VISE) and a Comet Surface Sample Return. VISE is envisaged as a balloon mission that would study Venus' atmospheric composition in detail and descend briefly to the surface to acquire samples that could be analyzed at altitude where the temperature is less extreme. The VISE scientific measurements would help to constrain models of the Venus greenhouse history and stability as well as the geologic history of the planet including its extensive resurfacing. VISE would also pave the way for the flagship-class mission to the Venus surface and for a possible subsequent sample return from Earth's hellish neighbor.

A Comet Surface Sample Return mission, particularly if targeted to an active area, would provide the first direct evidence on how cometary activity is driven, e.g., whether water is very close to the surface. Such a mission would also provide the first real data on how small bodies form and what they are made of at the molecular level. It would provide information on how the particles in a cometary nucleus are bound together. For example, is there an organic glue? Finally, it would provide direct information on physical and compositional heterogeneity at both microscopic and macroscopic scales.

These are the missions identified by the NRC as the highest priority in the medium New Frontiers class. Missions similar to these are anticipated to be solicited in upcoming New Frontiers Program competitions. It is likely that other high priority medium-class missions beyond these will be identified in future studies and may be the subject of competitions in the more distant future.

Contributions of Discovery (small-class) Missions

The Discovery Program of small ($300-500M) PI-led missions was begun in the early 1990s. It provides opportunities for relatively rapid flight missions to respond to new discoveries. Ten full missions and three Missions of Opportunity (investigations flown on a non-NASA spacecraft) have been selected in the past decade. The Discovery Program has not been constrained to address specific strategic objectives, but is open to proposals for scientific investigations that address any area embraced by NASA's solar system exploration program and the search for planetary systems around other stars. It thereby provides an excellent means for tapping the creativity of the planetary science community.

The Discovery Program has thus far included missions to planets (Mars Pathfinder and the Messenger mission to Mercury), the Moon (Lunar Prospector), comets and asteroids (the Near-Earth Asteroid Rendezvous mission, the Comet Nucleus Tour mission which was lost, Deep Impact, Stardust, and Dawn), the Genesis mission to return samples of the solar wind, and the Kepler mission to detect Earth-size planets in the habitable zones around distant stars. Details on these past and current missions can be found on the Discovery Program web site at http://discovery.nasa.gov/index.html

In the future, the Discovery Program will continue to provide competitive opportunities for focused investigations that address the scientific objectives described in this roadmap. Although the specific contributions of future Discovery missions cannot be predicted, the many past and current accomplishments show that Discovery missions will continue to be an extremely important part of solar system exploration for the foreseeable future.

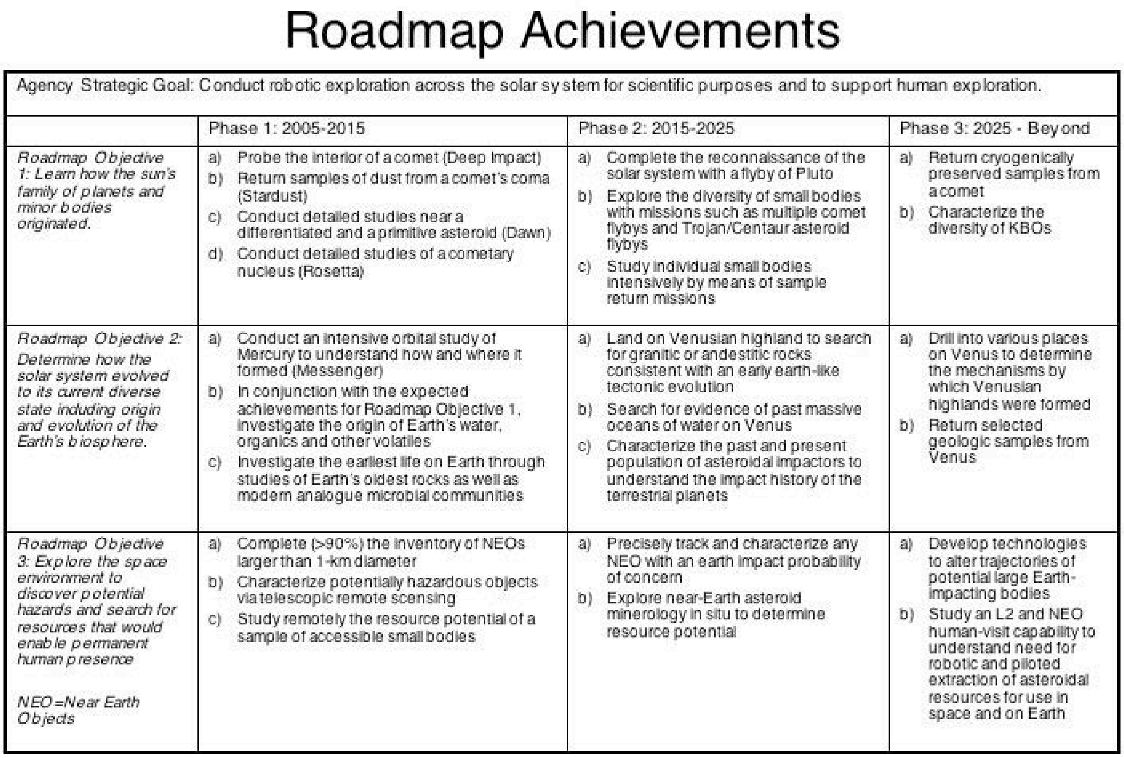
Contributions of the Research and Analysis Program

The Research and Analysis (R&A) programs comprise competitive grant awards to researchers in a wide range of disciplines and inter-disciplinary fields germane to solar system exploration including cosmochemistry, planetary geology and geophysics, planetary astronomy, planetary atmospheres, and astrobiology. In combination with mission-specific Data Analysis (DA) programs, the R&A Program provides to the science community the resources necessary to convert information returned by space missions into knowledge and understanding. It also supports laboratory, theoretical, telescopic, and field investigations that contribute to understanding the results of missions or other aspects of exploring the solar system. Further, the R&A Program makes possible new and better instruments to fly on future missions and helps complete the cycle by which the knowledge derived from flight missions is used to formulate new questions about the solar system and new mission concepts to address those questions.

The following two tables summarize the scientific achievements that are anticipated over the 3 decades encompassed by this roadmap from the combination of all flight missions and the R&A program.

The role of the R&A program is well laid out in the decadal survey of the NRC-NAS on solar system exploration, to which the reader is referred for specific examples.

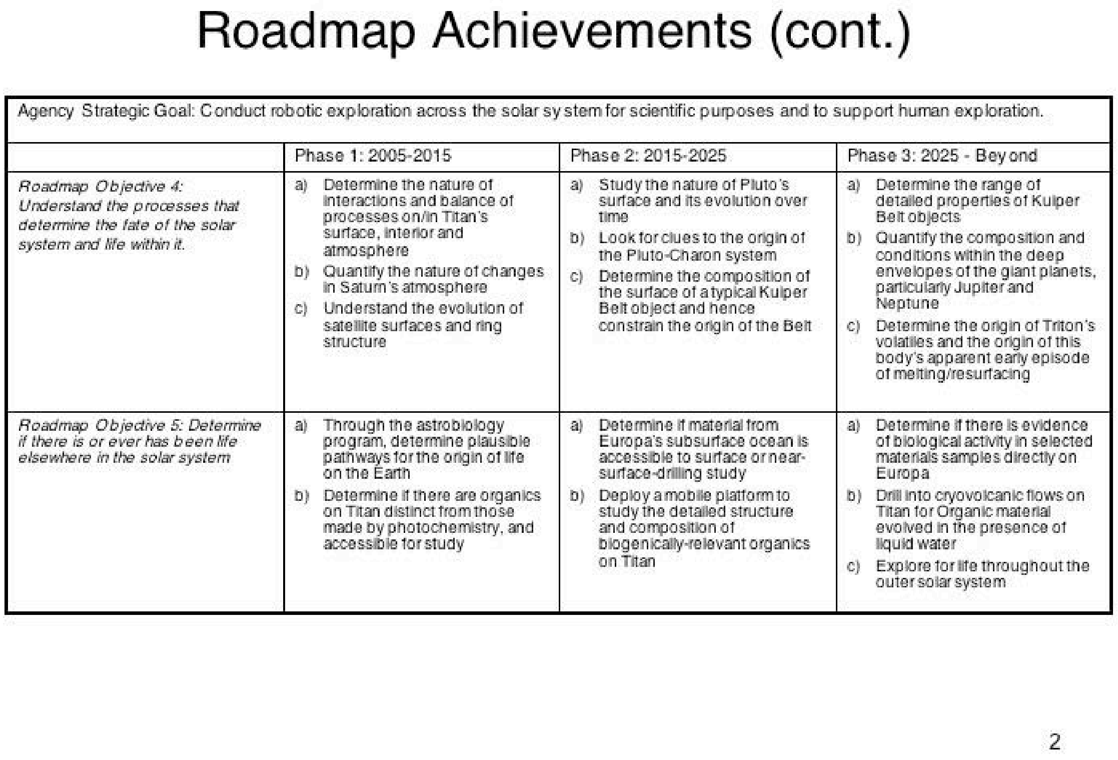
Table 1



Roadmap Achievements

Agency Strategic Goal: Conduct robotic exploration across the solar system for scientific purposes and to support human exploration.			
	Phase 1: 2005-2015	Phase 2: 2015-2025	Phase 3: 2025 - Beyond
Roadmap Objective 1: Learn how the sun's family of planets and minor bodies originated.	a) Probe the interior of a comet (Deep Impact) b) Return samples of dust from a comet's coma (Stardust) c) Conduct detailed studies near a differentiated and a primitive asteroid (Dawn) d) Conduct detailed studies of a cometary nucleus (Rosetta)	a) Complete the reconnaissance of the solar system with a flyby of Pluto b) Explore the diversity of small bodies with missions such as multiple comet flybys and Trojan/Centaur asteroid flybys c) Study individual small bodies intensively by means of sample return missions	a) Return cryogenically preserved samples from a comet b) Characterize the diversity of KBOs
Roadmap Objective 2: Determine how the solar system evolved to its current diverse state including origin and evolution of the Earth's biosphere.	a) Conduct an intensive orbital study of Mercury to understand how and where it formed (Messenger) b) In conjunction with the expected achievements for Roadmap Objective 1, investigate the origin of Earth's water, organics and other volatiles c) Investigate the earliest life on Earth through studies of Earth's oldest rocks as well as modern analogue microbial communities	a) Land on Venusian highland to search for granitic or andestitic rocks consistent with an early earth-like tectonic evolution b) Search for evidence of past massive oceans of water on Venus c) Characterize the past and present population of asteroidal impactors to understand the impact history of the terrestrial planets	a) Drill into various places on Venus to determine the mechanisms by which Venusian highlands were formed b) Return selected geologic samples from Venus
Roadmap Objective 3: Explore the space environment to discover potential hazards and search for resources that would enable permanent human presence *NEO=Near Earth Objects*	a) Complete (>90%) the inventory of NEOs larger than 1-km diameter b) Characterize potentially hazardous objects via telescopic remote scensing c) Study remotely the resource potential of a sample of accessible small bodies	a) Precisely track and characterize any NEO with an earth impact probability of concern b) Explore near-Earth asteroid minerology in situ to determine resource potential	a) Develop technologies to alter trajectories of potential large Earth-impacting bodies b) Study an L2 and NEO human-visit capability to understand need for robotic and piloted extraction of asteroidal resources for use in space and on Earth

Table 2



Roadmap Achievements (cont.)

Agency Strategic Goal: Conduct robotic exploration across the solar system for scientific purposes and to support human exploration.			
	Phase 1: 2005-2015	Phase 2: 2015-2025	Phase 3: 2025 - Beyond
Roadmap Objective 4: Understand the processes that determine the fate of the solar system and life within it.	a) Determine the nature of interactions and balance of processes on/in Titan's surface, interior and atmosphere b) Quantify the nature of changes in Saturn's atmosphere c) Understand the evolution of satellite surfaces and ring structure	a) Study the nature of Pluto's surface and its evolution over time b) Look for clues to the origin of the Pluto-Charon system c) Determine the composition of the surface of a typical Kuiper Belt object and hence constrain the origin of the Belt	a) Determine the range of detailed properties of Kuiper Belt objects b) Quantify the composition and conditions within the deep envelopes of the giant planets, particularly Jupiter and Neptune c) Determine the origin of Triton's volatiles and the origin of this body's apparent early episode of melting/resurfacing
Roadmap Objective 5: Determine if there is or ever has been life elsewhere in the solar system	a) Through the astrobiology program, determine plausible pathways for the origin of life on the Earth b) Determine if there are organics on Titan distinct from those made by photochemistry, and accessible for study	a) Determine if material from Europa's subsurface ocean is accessible to surface or near-surface-drilling study b) Deploy a mobile platform to study the detailed structure and composition of biogenically-relevant organics on Titan	a) Determine if there is evidence of biological activity in selected materials samples directly on Europa b) Drill into cryovolcanic flows on Titan for Organic material evolved in the presence of liquid water c) Explore for life throughout the outer solar system

Contributions of the Technology Development Program

As we ask more challenging questions about the solar system, we require greater technological capability to develop missions capable of addressing those questions. This is particularly true for flagship-class missions, the most difficult missions discussed in this roadmap.

Two areas of technology development have been identified as of the highest priority to enable the flagship mission concepts discussed here. These are radioisotope power sources and technologies for "extreme environments" including those characterized by high radiation, high and low temperature, extreme pressure, and the high heating rates encountered by atmospheric entry probes. In addition, technologies for ultra-high bandwidth and ultra-high pressure (for deep atmospheric entry probes) communications warrant careful assessment, as do technologies for autonomous systems, in situ science instruments, nanotechnology, and advanced modeling. These and other areas of technology development, including advanced propulsion to shorten trip time to distant destinations in the outer solar system, are discussed in more detail below.

Contributions of the Education and Public Outreach Program

"For more than half a century, the United States has led the world in scientific discovery and innovation... However, in today's rapidly evolving competitive world, the United States can no longer take its supremacy for granted. Nations from Europe to Eastern Asia are on a fast track to pass the United States in scientific excellence and technological innovation."

— Task Force on the Future of American Innovation

In the United States of America in 2005, the need for a technologically-literate—or at least a technologically-appreciative—public has grown as new technologies have entered virtually all aspects of public life, to grocery shopping to pumping gas. Recent studies* show the US lagging behind our counterparts in science, technology, engineering, and math (STEM) education, along with other benchmarks of technical innovation. Outsourcing of US jobs at all levels, including high-level science and technology fields, has become a topic of increasing debate. The implications for the future of the nation are profound.

NASA's exploration of space, and of the Solar System in particular, has motivated and inspired young people of all backgrounds to pursue STEM fields. Much as the Apollo moon landings spurred a generation to become science and technology enthusiasts, so too have recent discoveries in our Solar System, and of planets around other stars, captured the imagination of a new generation. By emphasizing STEM aspects of space exploration, NASA engages young minds and entices them to continue along educational pathways, providing a wealth of opportunities later in life, to both their benefit and to the benefit of the nation.

NASA has long had active programs of education and public outreach (EPO) in Solar System Exploration (SSE). An EPO program is more than classroom visits by astronauts and astronomers, press releases and photo ops, key chains and coffee mugs. It incorporates all elements across the EPO spectrum, reaching into classrooms, homes, and public institutions across our nation. Ongoing Space Science EPO programs demonstrate that many activities are significantly strengthened when embedded within the Science Mission Directorate. Direct engagement of NASA science programs (missions, R&A programs), scientists, and engineers yields more exciting and richer education experiences. Successful SSE activities have created collaborative programs that include both active scientists and EPO professionals, ensuring effective integration of science results in the educational realm. NASA shares its "hot" research results through press conferences, available to all through its web site. Mandating a fraction of mission funds for EPO has ensured its visibility and created a culture of EPO appreciation, especially among younger scientists and engineers.

NASA should continue to engage the public with Solar System exploration. Strategic focus for future NASA SSE-EPO efforts should nurture and expand successful programs, and re-align or re-energize programs that have not achieved full potential. The resulting strong SSE EPO program will: create and cultivate a technologically-literate 21st century workforce; create and cultivate an EPO-literate NASA workforce; stimulate scientists in their research endeavors; motivate students from diverse backgrounds to pursue STEM careers; provide teachers with materials and programs to inspire and educate their students; explain what NASA does; and return to the taxpayers—who fund NASA's work—the fruits of their investment.

* "*The Knowledge Economy: Is the United States Losing Its Competitive Edge? Benchmarks of our Innovation Future*," released February 2005 by the *Task Force on the Future of American Innovation* (available at http://www.futureofinnovation.org/).

III. “The Roadmap”

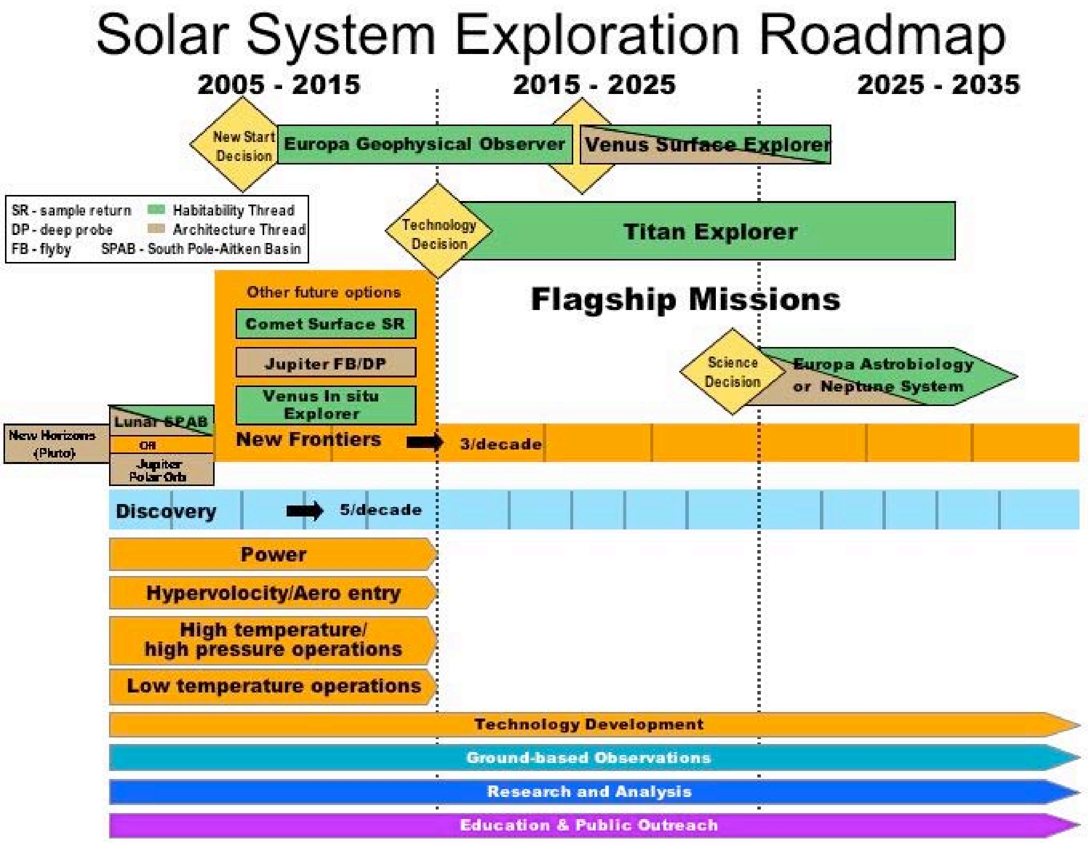


Figure 1

The SSE Strategic Roadmap is shown in Figure 1. The format shows the various program elements across three decades. The various flight programs are color coded to reflect which of the overarching science threads, i.e., Habitability and/or Planetary System Architecture, they principally address. The flight programs include the Discovery Program, New Frontiers Program, and larger flagship missions as discussed in Section II. Underlying these flight programs are the essential supporting programs: Technology Development and Research & Analysis. Ground-based Observations, a component of R&A, is illustrated to emphasize its importance in certain research areas such as studies of Kuiper Belt and Near-Earth Objects. As discussed above and in more detail below, the Technology Development Program is crucial for providing the technical capability to enable key decisions based on scientific discoveries. Education & Public Outreach is illustrated to emphasize its importance as a principal channel through which solar system exploration provides returns to the nation.

There are four key decision points (shown as yellow diamonds) in the Solar System Roadmap as illustrated in Figure 1. These decision points all involve the start of flagship missions. The Discovery and New Frontiers Programs will face critical decision points at every selection. However, the openly competed nature of these programs prevent us from assuming their outcomes beyond the missions already selected. It is clear however, that as a significant part of the portfolio of missions, they will influence decisions beyond the span of their investigations.

Decisions at any point, and particularly at the key decision points, will be influenced by the confluence of 3 major factors: scientific priorities and knowledge, technological and capability readiness, and programmatic considerations. What we learn from earlier missions will undoubtedly influence not only the destinations, but the architecture of the investigations, the approaches, and what we do once we arrive at later target destinations.

Examples of considerations that can enter into the decision making process are provided in Table 3:

Table 3: Examples of Scientific, Technology and Programmatic Considerations in the Decision Making Process

Scientific	**Impact**
Do comets have complex layered structures?	Emphasis on sample return strategy
Are cometary and meteoric particles the same?	Emphasis on sample return strategy
Strong differences between comets?	Multiple comet flyby mission(s)
NEO's with significant probability of Earth impact?	Hazard mitigation and emphasis
Strong differences among asteroid surfaces?	Multiple asteroid flyby mission(s)
Evidence of non-basaltic geochemistry on Venus?	Driller/mobile platform lander
Continents, plate tectonics on Venus?	Sample return strategy
Subsurface ocean at accessible depths on Europa?	Lander/drill strategy
Diverse organic deposits on Titan?	Mobile platform/organics explorer
Atmospheric and surface evolution on Triton?	Return missions with landers(?)
Strong diversity among Kuiper Belt objects?	Multiple KBO strategy
Organics found in Europan ocean?	Life search strategy for Europa
Life processes found on Europa or Titan?	Large scale bio laboratory
Technological	**Impact**
Cryogenic sampling and storage	Cryo Sample Return
Nuclear electric propulsion	KBO/Asteroid belt survey, Icy Moon tour, Triton
Aerocapture	Titan exploration, Triton orbiter
Extreme environment technology (cold)	Titan long duration mission
Extreme environment technology (hot, high pressure)	Venus long duration surface exploration

Aerial vehicle technology	Titan regional exploration
Surface mobility	Europa, Titan, Venus
High radiation environment	Europa long duration
Ultrahigh pressure communication/survival technology	Deep giant planets probes
High thrust/payload rockets	Venus, Titan sample return, NEO mitigation
Nuclear fission or other high power technology	Deep outer solar system exploration
High bandwidth communication	Outer solar system exploration, high data rate throughout
Programmatic	**Impact**
Human presence beyond cislunar space	Asteroid resource exploration, hazard mitigation
Emphasis on life and its origins	Europa, Mars Titan, comets
Emphasis on Earth evolution	Venus, Moon, Mars, asteroids

The first key decision point occurs in the 2006/2007 timeframe for the start of the Europa Geophysical Orbiter. The stunning discovery of a young icy surface, perhaps covering an ocean with a potentially habitable environment in Europa, made this mission one of the highest priorities for a new start flagship mission in the NRC decadal survey. The technology and capabilities are ripe for a new start. The Vision for Space Exploration, supported by the objectives of the Solar System Exploration roadmap and its emphasis on habitability, clearly reinforce this recommendation. This mission offers an opportunity for significant international collaboration.

The second decision point will occur in the 2012/13 timeframe to decide upon the phasing and start of one of the two flagship missions envisioned for the second decade. The Cassini/Huygens findings, and a preliminary assessment of technology readiness leads to a Titan Explorer ahead of a Venus Surface Explorer at this time, but other discoveries and advances in technology may require that the phasing be revisited. Both missions offer an opportunity for significant international collaboration.

The third decision point will occur in the 2018/19 timeframe for the start of the flagship mission not chosen at the second decision point. As presently envisioned, it will be a new start for a Venus Surface Explorer.

The fourth decision point, between a number of compelling scientific investigation options, will occur in the 2023/24 timeframe for the start of a large (~$3B) flagship mission. The decision will be heavily dependent upon technology and capability investments, and the scientific knowledge and priorities at the time. The principal options are discussed below in the “Third Decade” section.

A basic assumption in developing this Roadmap was that the total program content must fit within the present projected budget for solar system exploration, or approximately $900 million per year by 2010, adjusted for inflation thereafter. The flight mission model of 5 small or Discovery class, 3 medium or New Frontiers class, and 1 or 2 (depending on scope) Flagship class missions per decade, in addition to research and analysis and the technology investment base is (as a first order approximation) consistent with this assumption. Many elements of the budget plan however are preliminary and will require further study with the help of the science and engineering communities to develop viable and affordable mission concepts.

A more detailed decade-by-decade discussion of the roadmap follows.

First Decade: 2005-2015 For the first decade of the SSE Strategic Roadmap we expect to start approximately five new Discovery missions. This rate of a new start every 24 months will sustain the present level of Discovery program activity that includes five projects in various phases of implementation: Genesis, Stardust, Deep Impact, Kepler, and Dawn. In the New Frontiers Program we expect to start approximately three new missions by 2015. This rate of a new start approximately every 36 months will sustain the present level of program activity including the New Horizons mission to Pluto/Charon,. One Flagship mission is identified for this decade with a new start in the 2006/07 timeframe, a Europa Geophysical Observer.

The primary objectives of the **Europa Geophysical Observer** (EGPO) mission will be to determine the existence of a subsurface water ocean and to characterize the composition and physical properties of the overlying ice. These mission objectives flow down from the fifth Roadmap Objective: Determine if there is or ever has been life elsewhere in the solar system. This is a 6-year mission launched late in the first decade and completed around 2020. It is envisioned as a single Europa Orbiter spacecraft that may include a two-year tour within the Jupiter system using several gravity-assist maneuvers at the Galilean satellites to reduce the orbit capture requirements at Europa. The planned EGPO payload consists of a sounding radar and other remote sensing instruments. The primary mission science phase in Europa orbit is currently constrained to 30 days due to the harsh radiation environment expected to yield an integrated ionizing dose of 50 Mrad in this short orbital time span. To enable this lifetime, further development of radiation hard electronic components is needed especially for power electronics and non-volatile memory. If sufficient mission mass margin exists, however, this additional technology development can be traded against shielding mass. Sterilization of the spacecraft will also be a requirement to comply with expected planetary protection requirements for Europa.

The SSE Technology Program for the first decade emphasizes four strategic investments:

- Power
- Hypervelocity Aerodynamic Entry
- High Temperature/High Pressure Operations
- Low Temperature Operations

On-going power technology development is required to enable most new outer solar system missions that must rely on nuclear-base power systems; extended primary battery capabilities are also needed for atmospheric probes. Hypervelocity Aerodynamic Entry technologies are needed to reestablish giant planet entry capability, especially for Jupiter probes. High temperature/high pressure technologies are needed for Venus missions and for giant planet deep entry probes (typically >100 bar penetration). Low temperature capabilities are needed for future outer planet satellite atmosphere/surface missions, the first of which is expected to be to Titan. While these technologies are clearly enabling to the proposed SSE Roadmap strategy in the second decade, other are also needed, e.g., planetary protection, deep space communication, and in-space transportation. These needs are discussed in detail below. Technology investment needs should be reviewed at least every 2-3 years to ensure that needed technology readiness levels are met in a timely manner to support the on-going roadmap mission developments.

Second Decade: 2015-2025 Discovery and New Frontiers missions are planned to continue at the same flight rates during this decade. The New Frontiers AO mission set, however, will be updated with new priority missions, as the original set recommended by the National Research Council (NRC) Decadal Survey is completed. Examples of possible additions, as suggested by the 2003 NRC Decadal Survey include: Geophysical Network Science, Asteroid Rover/Sample Return, Galilean Moon Observers, and Trojan/Centaur Reconnaisance Flybys. Two smaller flagship missions are proposed as new starts for this second decade, a Titan Explorer and a Venus Surface Explorer.

A **Titan Explorer** is proposed for a new start at the beginning of the decade. Scientifically, this mission would build upon the observations of Cassini and Huygens. In addition to aerial imagery below the haze of a much larger amount of terrain than was possible with the Huygens Probe, and exploration of lower atmosphere winds, clouds and precipitation, in situ measurements of ices and organic materials at the surface to assess pre-biotic/proto-biotic chemistry will be conducted. The goal is to characterize those materials but also to contribute definitive observations concerning the origin of the diverse landforms identified in Huygens visual images and Cassini radar data. A single aerial platform with repeated access to the surface for in situ sampling is envisioned. Because of cost limitations, communications will either be direct to earth or through Cassini if it is still operating; a companion orbiter is not affordable. The mission concept is an 8-year mission, including an indirect Earth gravity-assist and direct entry into Titan's atmosphere with at least several months lifetime at Titan. Results from Titan are expected by 2030. Certain aspects of the extreme environment make in situ exploration much more challenging than the in situ exploration of Mars. The very cold temperatures (less than 100K) at Titan present challenges for materials mechanisms and electronics. However, other aspects of the environment – specifically the high atmospheric density at the surface (4.5 times terrestrial) and the very low surface winds - enable the use of a mobile buoyant platform that can move with much less energy use and with much less risk of becoming immobilized than a surface vehicle; sampling is done in a fashion analogous to the acquisition of a sea floor sample by a submersible. Visual imaging and on board machine vision implemented from a range of altitudes will play a key role in scientific exploration and navigation. The precision of targeting and the degree of mobility control are both subjects for a trade study.

A **Venus Surface Explorer** (VSE) is proposed for a new start in the second half of the decade. This mission is sequenced after the Titan Explorer for several reasons. The later start date permits an opportunity for the selection of a New Frontiers Venus *In Situ* Explorer as a precursor mission (currently in the NF AO mission set), and also provides additional time anticipated to develop high-temperature electronics/power technologies needed at the surface of Venus. VSE would take the next step in exploration of the Venus surface beyond the epic radar reconnaissance of the Magellan spacecraft and the presumed *In situ* Explorer. This mission would perform extensive measurements at the Venus surface including a search for granitic and sedimentary rocks and other vestiges of a period in the history of Venus when Venus may have been water-rich. Equipped with visual imaging and a targeted set of geochemical sensors, the VSE will use the methods of mobile scientific exploration that were so effectively validated by the Mars Exploration rover. Hence, it would include a surface rover with limited capability (100s meters). The entire project, from new start to end-of-mission, could be accomplished in 6-7 years, including a surface stay time of days or weeks. The extreme temperatures (almost 500C) at the Venus surface present challenges for materials mechanisms and electronics. The surface conditions may also be potentially hazardous due to extremely rough terrain limiting sample accessibility. The technology challenges drive previous decade technology investments and predicate this mission's new start with a strategic technology decision point early in the decade.

The Technology Program for the second decade is expected to include continuation of some elements of the first decade investments.

Third Decade: 2025-2035 Science opportunities are expected to continue both for the Discovery and New Frontiers program lines through the third decade approximately at their planned flight rates. For flagship missions however, two strategic conditions become apparent: 1) the science objectives become more challenging requiring more costly missions (<$3B), and 2) mission choices become less clear, being driven by the results of previous missions which are not yet known. Hence, there is a strategic science decision point at the beginning of this decade to address the next step in Flagship missions. Many options exist embracing both smaller and larger Flagship missions, but with the anticipation that implementation of a single larger Flagship mission in this decade may be compelling. Foremost among these candidates are a Europa Astrobiology Lander, a Neptune System Mission, Comet Cryo-nucleus sample return, or a Venus Sample Return.

The **Europa Astrobiology Lander** would focus on the investigation of chemical and biological properties of surface/subsurface materials associated with life. Selection of this Flagship mission would be driven by the results of the Europa Geophysical Observer undertaken in the first decade. It would have a large payload of scientific instruments and would be equipped to make a precision landing on the surface of Europa to avoid hazardous terrains. It would also have the ability to acquire samples from well beneath the contaminated surface layer. Long life in the high radiation environment, and planetary protection will therefore be major issues that need to be addressed with appropriate investments in relevant technologies.

The **Neptune System Mission** would be an "all-in-one" exploration package. It would include orbital remote sensing, deep atmosphere Neptune probes, and a Triton Lander. The spacecraft could be launched on a fast trajectory toward Neptune using aerocapture technology to enter Neptune orbit, or perform the transit with nuclear electric propulsion benefiting from ample power once at Neptune. Subsequently, a two-year tour of the

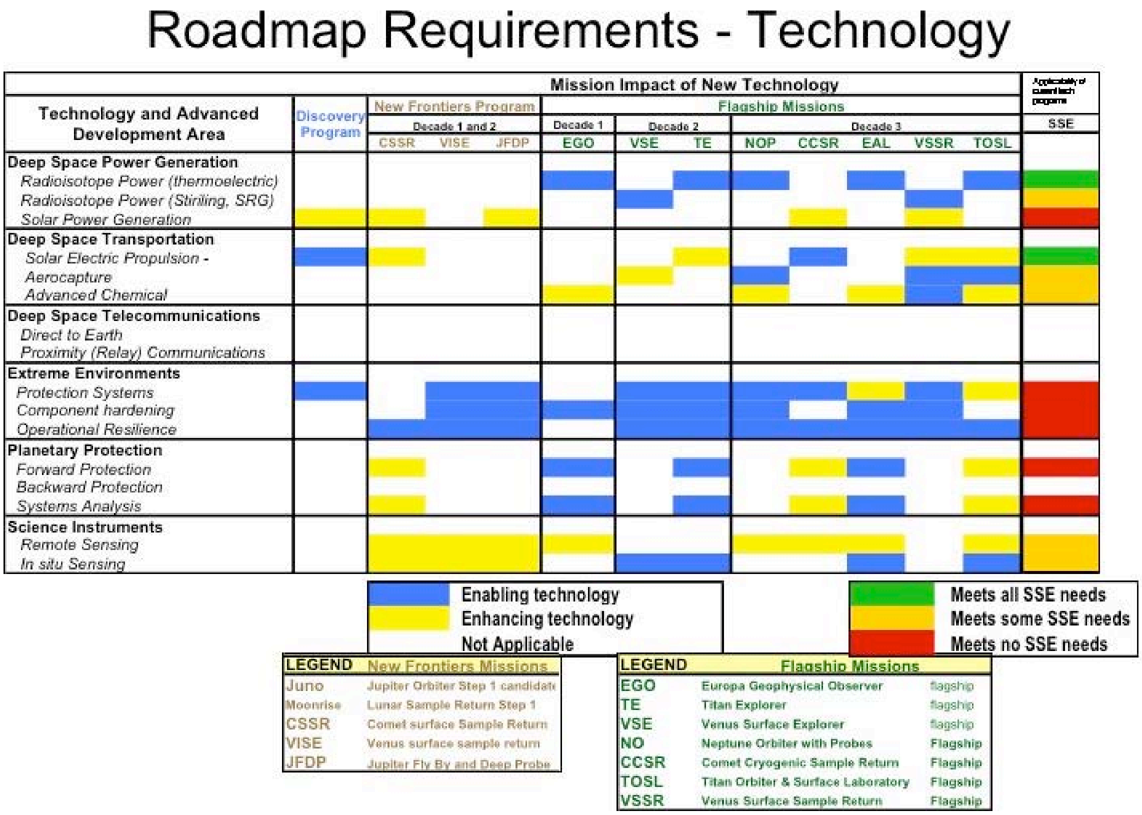
Neptune system involving multiple gravity assists at Triton has been shown to provide comprehensive high resolution imaging coverage of Triton. A limited lifetime lander on Triton could be targeted to site based on real-time Triton imaging to sample the composition and physical properties of frozen volatiles on the satellite's surface. Overall mission time from launch would be 10-12 years. If aerocapture at Nepture is employed, a second generation aerocapture technology employing high L/D aeroshells would be needed with the necessary control authority to account for uncertainties in the entry corridor and the properties of the Neptune atmosphere. This advanced technology can be used for aerocapture at any planet. However, it is only Neptune for which it is enabling. Conversely, if low-thrust propulsion is chosen, Prometheus class capabilities would be needed. Hypervelocity entry technology is needed for the Neptune probes but well within the capabilities enveloped by Jupiter probes.

The **Comet Cryogenic Nucleus Sample Return** would involve landing on and collecting a sample of the delicates ices and organics that exist on a cold and relatively fresh comet. The intent is to preserve this material in its average ambient state on the comet nucleus so that isotopic and nuclear spin ratios can be preserved along with the physical-chemical state of the sample. This requires rendezvous with a relatively fresh comet, which could require very large delta-VZ, and preserving the sample cryogenically through its return to the Earth. The propulsion and power requirements these levy on the mission make it a Flagship class endeavor. Advanced propulsion, sample collection, refrigeration (hence power) technologies are required for this mission.

A **Venus Sample Return** is a very difficult mission that would certainly follow a successful Mars Sample Return and an effective Venus Surface Explorer mission. The implementation challenge lies not so much with Venus environmental issues (although they are not trivial) as it does with the mission energetics. There would need to be a buoyant ascent stage to collect the sample either from the surface or from another vehicle (deployed to the surface and back into the atmosphere) and then carried to an altitude from which atmospheric density is low enough for launch to be feasible. At this point the propulsion needed is equivalent to a inner planet mission starting at the earth's surface. Needless to say, even with a very small sample return payload the buoyant stage would only be capable of reaching Venus orbit, where another Earth Return Vehicle would have to be waiting to rendezvous with the ascent stage, to transfer the sample for a return flight to earth. Sample recovery at Earth would be similar to Mars sample return with a direct entry to a suitable recovery site (e.g., UTTR) expected. Advanced airborne systems and high-energy rocket propulsion are key capabilities needed for this mission.

Finally, even though this is the last decade of the Roadmap, a continuing technology program aggressively developing new enabling capabilities is advocated. Not only are there many strategic SSE missions to be performed, but synergistic technology needs with a active human exploration program in this period are to be anticipated.

IV. Critical Inter-Roadmap Dependencies



Roadmap Requirements - Technology

Technology and Advanced Development Area	Mission Impact of New Technology												Applicability of current tech programs
	Discovery Program	New Frontiers Program			Flagship Missions								
		Decade 1 and 2			Decade 1	Decade 2		Decade 3					SSE
		CSSR	VISE	JFDP	EGO	VSE	TE	NOP	CCSR	EAL	VSSR	TOSL	
Deep Space Power Generation													
Radioisotope Power (thermoelectric)					🟦		🟦	🟦		🟦		🟦	🟩
Radioisotope Power (Stirling, SRG)						🟦					🟦		🟧
Solar Power Generation	🟨	🟨		🟨					🟨		🟨		🟥
Deep Space Transportation													
Solar Electric Propulsion -	🟦	🟨					🟨		🟦		🟨	🟨	🟩
Aerocapture						🟨		🟦			🟦	🟦	🟧
Advanced Chemical					🟨			🟨		🟨	🟦	🟨	🟧
Deep Space Telecommunications													
Direct to Earth													
Proximity (Relay) Communications													
Extreme Environments													
Protection Systems	🟦		🟦	🟦		🟦	🟦	🟦	🟦	🟨	🟦	🟨	🟥
Component hardening			🟦	🟦	🟦	🟦	🟦	🟦		🟦	🟦		🟥
Operational Resilience		🟦	🟦	🟦		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟥
Planetary Protection													
Forward Protection		🟨			🟦		🟦		🟨	🟦		🟨	🟥
Backward Protection													
Systems Analysis		🟨			🟦		🟦		🟨	🟦		🟨	🟥
Science Instruments													
Remote Sensing		🟨	🟨	🟨	🟨			🟨	🟨	🟨		🟨	🟧
In situ Sensing		🟨	🟨	🟨		🟦	🟦			🟦		🟦	🟧

🟦 Enabling technology
🟨 Enhancing technology
Not Applicable

🟩 Meets all SSE needs
🟧 Meets some SSE needs
🟥 Meets no SSE needs

LEGEND	New Frontiers Missions
Juno	Jupiter Orbiter Step 1 candidat
Moonrise	Lunar Sample Return Step 1
CSSR	Comet surface Sample Return
VISE	Venus surface sample return
JFDP	Jupiter Fly By and Deep Probe

LEGEND	Flagship Missions	
EGO	Europa Geophysical Observer	flagship
TE	Titan Explorer	flagship
VSE	Venus Surface Explorer	flagship
NO	Neptune Orbiter with Probes	Flagship
CCSR	Comet Cryogenic Sample Return	Flagship
TOSL	Titan Orbiter & Surface Laboratory	Flagship
VSSR	Venus Surface Sample Return	Flagship

Figure 2

This section outlines the technologies to enable the Flagship missions in the Solar System Exploration Road Map. Where appropriate, the relevance of technology needs to potential New Frontiers and Discovery missions are also covered. Figure 2 summarizes the most important areas of technology development for solar system exploration. The right-most column indicates the adequacy of current technology investment levels for the solar system exploration program. The following sections are ordered as shown in Figure 2.

Deep Space Power

Solar System Exploration depends on existing programs in Radioisotope Power Systems included here are some of the ingredients of what we need.

Radioisotope Power – Thermoelectric conversion:

Radioisotope power generation is needed for those missions where solar photovoltaic power is not feasible and stored energy from batteries is inadequate. NASA is currently investing in the *Multi Mission Radioisotope Thermoelectric Generator (MMRTG)* that is capable of operating in space or in an atmospheric environment. This dual-purpose system, driven largely by the needs of the Mars Exploration Program, has involved performance compromises. The MMRTG will support the requirements of the *Europa Geophysical Orbiter (EGO),* if available in time, and particularly the *Titan Explorer* mission. Advanced versions of the MMRTG, incorporating improved thermoelectric converters, can provide more power from within the same physical package and could benefit EGO with a focused effort. A modular RTG, that is also envisaged, will provide a much greater range of power levels with comparable specific power and efficiency and represents the road forward. It is important for NASA to continue development in this technology,

Radioisotope Power – Stirling Radioisotopic Generator

NASAis also currently investing in a *Stirling Radioisotopic Generator (SRG),* which has comparable specific power but much greater thermal efficiency than the MMRTG. The SRG technology is needed for the *Venus Surface Explorer (VSE)* mission to provide sustained power at the high temperatures of the Venus surface. The mechanical conversion device used in the SRG enables a highly efficient heat pump that can be used to enable the use of conventional electronics on the Venus surface. The current SRG development work does not include a requirement to operate in the 500C Venus environment. The SRG program should be refocused to address the Venus high temperature need.

Solar photovoltaic Power

Solar generation will continue to play an important role in deep space missions not only for powering avionics, sensors and communications but also as an integral part of solar electric propulsion systems (see next section). Solar power can, in some circumstances, be a cost effective alternative for orbital and flyby missions to the Jupiter system and beyond. The *Juno* mission – a Jupiter Polar Orbiter currently under consideration as the second New Frontiers mission – plans to use solar power and a *Jupiter Flyby Probe (JFP)* mission – identified in this road map as a New Frontier mission opportunity could also use this technology. Fly by, rendezvous and sample return missions to small bodies in the outer solar system would be major beneficiaries of this technology. NASA is currently planning a New Millennium space validation that would validate arrays with 175W/kg – double the current state-of-practice. The potential exists for doubling the performance again over the next decade in arrays that are tolerant of operation under Low Intensity Low Temperature (LILT) conditions and high radiation environments. However, this technology is not currently being addressed within NASA.

Deep Space Transportation

The existing NASA program in In Space Propulsion technologies already contains many of the key technologies for the road map. However, the program will need to be refocused to reflect the Flagship mission priorities in this road map and to enable a more rapid insertion of technologies that can enable or enhance future Discovery missions.

Solar Electric Propulsion:

Solar Electric Propulsion enables missions requiring large in space velocity changes approaching and exceeding 10km/sec and has applications to rendezvous and sample return missions to small bodies and fast trajectories towards the outer planets. The path of development of this technology is now largely evolutionary with significant performance gains, moderate development risk and significant impact on the capabilities of new missions. Current plans include near term enhancements to the NSTAR 30cm engine used on the Dawn mission, completion of the NEXT 40cm engine which is targeted at New Frontier and Small Flagship missions, and Hall technology which is a lower cost technology benefiting Discovery missions.

Aerocapture:

Aerocapture enables rapid access to orbital missions at the outer planets. As trip times to the outer planets are reduced the mass penalty of insertion with chemical propulsion becomes prohibitive. From a purely technical point of view, Titan is the natural choice for first use of this technology because of its deep atmosphere and large scale height and modest approach velocities and can use an aerocapture system which is a derivative of a conventional symmetric Mars aeroshell. For an orbital mission at Neptune with trip times of less than ten years, aerocapture technology is enabling but will require the high lift to drag, highly asymmetric *Ellipsled* design which will require a flight validation experiment before use. Aerocapture introduces constraints and challenges to RPS-powered spacecraft packaging and design associated with the impact of being completely enclosed during long duration flight, which may require additional advances in systems such as thermal management and communications. Aerocapture for Venus missions has also shown significant mass savings in comparison to propulsive orbital insertion. Currently, the Mars Program is evaluating the benefits of aerocapture for insertion of larger orbiters and sample return rendezvous vehicles.

Advanced Chemical Propulsion:

Chemical propulsion is a comparatively mature technology but one where advances in components and propellants can still have a significant impact on NASA missions. The development of lightweight components and gel propellants can improve payload fraction in orbital missions and landed missions at airless bodies. However, the primary investments in this technology will be needed late in the second decade to enable the ascent vehicles needed for Venus Surface Sample Return.

Deep Space Communications

The NASA investments in the Deep Space Mission Systems (DSMS) include work on the trunk line from Earth to deep space and proximity communications between orbiters and landed assets. The Mars Exploration Program has been taking the lead in the proximity communications. There is an ongoing technology program to look at this, but there is also a need for infrastructure investments to either maintain or upgrade the Deep Space Network.

Extreme Environments

This topic embraces a range of technologies needed for surviving and operating in the severe environments of the inner and outer planets. These environments include the intense radiation environment near Europa, the extreme radiant and convective heating of planetary entry, the high temperatures and pressures of the Venus surface and the deep Jupiter atmosphere and the frigid temperatures of the Titan atmosphere. The technologies for surviving and operating in these environments are organized into three categories: technologies for protecting or shielding vulnerable components from the environment, components specificly designed to tolerate the environment and operational strategies that are resilient to the environment.

Protection from the Environment

Protection systems are the preferred approach for coping with the induced environment of planetary entry and for many components and systems that are needed in missions to the surface of Venus and deep in the atmospheres of outer planets.

Hypervelocity Entry

Entry into planetary environments exposes the entry capsule to severe thermal environments. The use of atmospheric drag to reduce from the hyperbolic interplanetary speed to perform scientific measurements at low speeds or to deliver payload results in the extreme aerothermal environment around the entry probe. In addition to the entry speed, entry probe shape and the atmospheric properties such as gas composition, density, temperature and pressure determine the extreme environmental conditions. Thermal Protection System (TPS) design required to protect the entry probe from this extreme condition requires tools and facilities,

Entry into Mars is benign compared to conditions that will be encountered by probes to the Outer Planets as well as Venus. When the Galileo probe entered Jupiter it experienced total heating in excess of 30,000 W/cm^2 as compared to 120 W/cm^2 of convective heating encountered by the Mars Pathfinder. The Galileo entry environment produced both radiative heating in excess of 20,000 W/cm^2 and convective heating approaching 10,000 W/cm^2 a combination that is unmatched by any other environment.

NASA has not retained the capability for hypervelocity entry into the atmospheres of the outer planets – gas and ice giants. This includes the capability to design entry probes including the Thermal Protection Systems for the outer planets and Venus. The technology investment envisaged here is intended to not only recapture this capability but will represent a significant advance enabling higher velocity entry with smaller entry vehicles with larger payload fractions than used for the Galileo probe. A substantial investment in a hydrogen-helium arc jet test facilities is needed for both development and qualification of Thermal Protection Systems (TBS). The investment to revive and develop advanced TPS will enable probe missions not only to Outer Planets but also Venus missions, aerocapture missions to Neptune as well as Sample Return missions,

Extreme Pressures and Temperatures

This probe must also descend much deeper on Jupiter /Neptune/Saturn than Galileo and communicate from those depths. Investments in the analysis tools for predicting the behavior of probes during descent and for extended operation on the surface of Venus are needed. New structural and thermal control materials will improve the fraction of these vehicles available for payloads. The benefits of new technologies will increase with the depth and duration of vehicles operation.

Thermal Control

Protection systems for tolerating both very hot and very cold environments are needed. For short duration missions, passive approaches may be adequate. For longer duration missions an active approach for adding or removing heat is needed. For long duration protection of payloads on the surface of Venus, a heat engine is needed to "refrigerate" the thermal controlled avionics and sensor module. Only small heat loads can be handled so heat leaks and dissipation must be minimized. Very little work has been done on this technology. An aggressive early program of systems analysis will be needed to define the best approach and determine realistic performance goals for this technology.

Components tolerant of the Environment

For certain components, it may be impractical to provide protection for the environment. In these cases, it is necessary to develop components that can tolerate the environment.

Radiation Hard Electronics

Operations in the near-Europa space environment, exposes hardware to the severe Jovian radiation environment. Shielding can mitigate these effects but at the expense of useful payload. Both the cumulative dose and the prompt effects of the radiation are of concern to the performance of spacecraft systems and science instruments. For the *Europa Geophysical Orbiter*, with a design lifetime of one month, there is a compelling need for advanced development of power electronics and non volatile memory (NVM) systems. This can leverage prior work performed in the Europa Orbiter and Jupiter Icy Moon Orbiter (JIMO) projects and continuity with the early work is highly desirable. For the *Europa Astrobiology Laboratory,* which is a mission in the third decade, the required lifetime is many months or even years and an investment in basic technology and innovative approaches to radiation protection will be needed.

Electronics – high temperatures

Passive thermal control can only permit operation on the surface of Venus for time periods measured in hours to tens of hours. For extended lifetime missions, active thermal control and high temperature electrons are complementary approaches.
Not all electronic components can or should be implemented in high temperature component. Communications and power electronics have the most payoff. Digital electronics, which have low power dissipation, are best implemented in conventional electronics by using active thermal control.

Both semiconductor and vacuum tube approaches have been developed to the 300C range but operation at 500C represents a unique NASA need. There is currently no NASA program in this technology and an early start in this area is needed to ensure availability for Venus Surface Explorer and Venus Surface Sample Return as well as the potential for experiments and validation on earlier missions.

Sample Acquisition Mechanisms

Actuators that can operate at very high temperature and very low temperatures are the thrust here. Also there must be understanding of the mechanical properties of natural materials such as ice and rock over a comparably broad range of temperatures. Permanent magnetic materials and soft magnetic materials are required that retain their magnetic properties at high temperatures.

Systems technologies resilient in severe environments

In order not only to survive but successfully operate in severe environments, a number of systems technologies are needed.

Descent and Landing

Future solar system exploration missions must land on airless objects of widely divergent gravitational fields, contend with extreme relief and to descend land and in some cases ascend under conditions of active plumes from the surface posing major technological challenges. In contrast, landing on the planets with dense atmospheres (Venus and Titan) represent comparatively straightforward engineering: for both objects, descent vehicles designed primarily as atmospheric probes Pioneer (Venus) and Huygens (Titan) have survived landings on these objects.

The *Comet Surface Sample Return (CSSR)* mission requires the capability to rendezvous, descend and ascend from these low gravity objects using terrain relative navigation to ensure the recovery of samples from the required targets. The *Comet Nuclear Cryogenic Sample Return (CNCSR)* mission will require still greater precision and the ability to anchor to the object to facilitate deep sampling. The *Europa Astrobiology Laboratory* mission will required similar precision but because it has a substantial gravitational acceleration, terrain relative navigation must be performed at high rates and must be tolerant to spurious radiation effects.

Mobility – aerial and surface

Mobility is required to provide close up imaging and chemical and mineralogical sampling at many different sites for both the Venus Surface Explorer (VSE) and Titan Explorer (TE) missions. These vehicles must tolerate highly irregular terrains, deposits of low bearing strengths and on Titan potentially sticky or liquid surfaces. Wheeled vehicles derived from the Mars Exploration Rover and Mars Science Laboratory represent one approach to mobility. However, the dense atmospheres of Titan and Venus also enable buoyant vehicles that are much less susceptible to being immobilized by surface obstacles or surfaces with low bearing strengths. They can also travel over much greater distances with less energy consumption.

A proof of principle has been achieved for thin metal bellows balloons that can operate at Venus temperature and polymer-based films and fabrics that can retain their flexibility and resilience at Titan surface temperatures. High temperature actuators for these extreme conditions are also under development. However, NASA does not currently invest in mobility for extreme environments and a sustained effort in both basic technology and advanced development is needed to get ready for these missions. Test facilities will be required for validating the performance of mobile vehicles in both extremely hot and extremely cold environments.

Autonomous Operations

Operation in these environments will not only require tolerance of the extreme environments but the ability to autonomously respond to hazards. These vehicles may be out of contact with a ground operator during some mission phases for days or even weeks. Some autonomous operations can draw on the experience in operating the Mars rovers where commands are typically issued on a daily cycle. There are also unique challenges for future solar system exploration missions. The autonomous operations needed for proximity operations of sample return missions from small bodies and those of aerial platforms monitoring and acquiring samples from the surfaces of Titan and Venus have no counterpart in the Mars Exploration Program.

Planetary Protection and Contamination Control

For the exploration of Europa and Titan, both objects of biological interest, it will be necessary to undertake a planetary protection program to ensure that they are not contaminated with earth derived biological materials. In addition, measures must be taken to ensure that samples collected by on board instruments on landed spacecraft do not experience contamination by the spacecraft itself or other materials brought from Earth.

While the experience in the Mars Exploration Program is pertinent, Europa presents particular challenges including handling forward biological contamination by an orbiting spacecraft or lander and chemical contamination associated with Titan systems. Significant investments will be needed to handle the challenges of the icy environment of Europa in forward contaminations control, dry heat sterilization and systems analysis.

Science Instruments

Investigating the priority targets that have been identified in the Solar System Exploration roadmap will require both remote sensing and in situ sensing instruments. For outer planet missions payload mass is at a premium. When these are also in situ missions, each kilogram of payload is precious. In this context, miniaturization of instruments will be extremely important.

There are on going technology and instrument development programs for instruments. The Planetary Instrument Definition and Development Program (PIDDP) focuses on the demonstration of new instrument concepts for solar system exploration missions. NASA should continue investment in these instrument development programs.

Capability Interdependencies with other Roadmaps and Organizations

Mars Robotic and Human Exploration Program

The Mars Focused and Base programs invest in technologies that are complementary to the existing solar systems exploration technology program. There is a strong focus on Entry Descent and Landing, Surface Mobility and instruments for in situ science.

Proximity Telecommunications developed for Mars has some applications to Solar System Exploration although may in situ missions will lack an orbital relay and will have to rely on a direct communications link to the Earth.

Planetary Protection and Contamination control technology developed for Mars exploration are relevant to the needs for Europa and Titan exploration. However, Europa and Titan exploration have unique needs.

Lunar Exploration Program

Investments are more narrowly focused on the needs of lunar exploration. Primary benefits are likely to come from investments in power and propulsion.

Other Agencies and Organizations

Notable areas where non NASA efforts are important are in Solar Power generation where DARPA is funding work on advanced solar arrays and in extreme environments where what relevant work exists in high temperature electronics for example is generally implemented outside NASA.

Technology Gaps

The most significant gap is in Technologies for Severe Environments. Another gap area where there are virtually no effective programs is systems technologies for planetary protection.

Strategic Interdependencies with other Roadmaps

Lunar Robotics and Human Exploration

The Solar System Exploration research is closely linked with the Lunar program. To understand the record of solar system processes preserved in the lunar surface materials it is important to analyze Lunar Samples and perform Lunar field studies. The moon is critical in understanding the process under which the solar system developed.

Mars Robotic and Human Exploration

Understanding Mars from both a historical and current perspective will be part of understanding the full story of the development of the entire Solar System. This includes understanding the current state and evolution of the atmosphere, the surface and interior of Mars as part of understanding the development of the Solar System. Determining the nature of any habitable environments on Mars and if life exists or has ever existed on Mars, is key to the study of solar system evolution.

Earth-Like Planets and Habitable Environments

Studying the Giant Planets in our Solar System and understanding how they effect Habitability is key for understanding how life evolved and what role the giant planets may have played. Also, studying extrasolar planetary systems and understanding how they become habitable is a parallel model to help understand the evolution of life.

Exploration Transportation

Exploration of the outer Solar System will necessarily require longer transit times and as more sophisticated science data is gathered, instruments will be required which have larger launch mass and volume. Therefore the solar system exploration research will ultimately need Heavy lift launch for high mass robotic mission; Precision entry/decent and landing; In space propulsion; In space automated rendezvous and docking (depending on design of launch and transfer vehicles); Pre-deployed surface/orbit assets (fuel, power, instruments, etc); Surface ascent/sample return to earth.

Sun-Solar System Connection

Solar System Exploration is closely linked with Sun-Solar System Connection to specify and predict space weather at solar system destinations and along interplanetary routes. This would include measuring and understanding planetary atmospheric state for ascent, aerobraking, aerocapture, descent and landing. This also includes understanding the ionospheric state for communications and navigation and energetic radiation morphology and, spectral content for reliability of electronics and materials. This strategic link also includes Solar and Galactic Radiation environment prediction, detection, warning, upper atmospheric characteristics (e.g. Titan, Neptune) for aerocapture and Magnetoshperic science.

Aeronautical Technologies

It is envisioned that in the future Atmospheric vehicles will be needed as part of the capability for planetary surface or near surface mobility.

Nuclear Systems

Radioisotope Power Sources are critical for missions at extreme distances or extreme environments. It is important for providing propulsion to/from the outer solar system and in communications and in providing power for planetary surface investigations.

V. Conclusion

The President's Vision for U.S. Space Exploration observes that "Today, humanity has the potential to seek answers to the most fundamental questions posed about the existence of life beyond Earth." This Roadmap illustrates that habitability, by definition a precursor to the existence of life, is an overarching concept that unites the endeavor to explore our solar system and understand its mysteries. Pursuing the objectives discussed in this Roadmap will not only inform us about the potential for life or prebiological activity in this solar system, it will provide "ground truth" for interpreting the growing body of information concerning planetary systems around other stars. Our journey into the solar system will also be a journey to our roots as living creatures. In reaching toward the base of the tree of life, we express our highest aspirations.

Appendix: Goals of Solar System Science: The Solar System Exploration Subcommittee White Paper

The Solar System Exploration Subcommittee prepared a white paper as its contribution to the Solar System roadmap process. The purpose of the white paper is to provide a narrative exposition, in detail, of the science goals and objectives of solar system exploration consistent with the Academy Decadal Survey, but updated to the end of 2004.

The white paper was organized around four goals. The Solar System Exploration Strategic Roadmap Committee rearranged the material in the white paper to conform to the "Five Roadmap Objectives" structure of the Roadmap. The content was otherwise unchanged or modified only editorially. This modified version of the white paper is included here to provide the reader more detail on the science rationale and detailed goals/objectives of the exploration of the solar system. The text is fully consistent with, and expands upon, the goals described in the introduction to the roadmap.

Note regarding hierarchy: The Roadmap recognizes five Objectives. In this Appendix those Objectives are called Goals. Following each Goal in the Appendix hierarchically are Objectives and Investigations. We regret the potential confusion incurred by using the term "Objective" for different hierarchical levels in the Roadmap and in the Appendix, but other solutions to this conundrum would have introduced confusion of their own.

Goal 1: Learn how the sun's family of planets and minor bodies originated

We are in a time of major changes to our understanding of how solar systems form and evolve. Detections of very different planetary systems orbiting other stars, and of young protoplanetary disks, are giving us new insights into the processes that operated in the earliest history of our own solar system. Our solar system was born about 4.6 billion years ago when a cloud of gas and dust collapsed to form a nascent Sun surrounded by an accretion disk. Subsequently, material in this disk condensed and coalesced to form solid aggregates that became the building blocks of the planets and their moons, the asteroids and comets. Many of the characteristics of our solar system, and the bodies within it, were established during the first billion years of its history. This is also the period when life emerged on Earth and possibly elsewhere in the solar system. A record of these early events is still preserved in the physical and chemical makeup of primordial solar system materials, such as the oldest rocks on the Earth, Moon and Mars, in primitive asteroidal meteorites, comets, and in the Sun itself. New determinations of the elemental composition of the Sun's photosphere are changing the paradigm for its interior structure and composition, and may have profound implications for the composition of the Sun's protoplanetary nebula. Similarly, high-precision measurements of abundances of key elements and compounds in the atmospheres of our giant planets and extrasolar giant planets will lead to further revolutionary changes in our understanding of planetary formation and evolution.

Objective 1.1: Understand conditions in the solar accretion disk and processes marking the initial stages of planet formation.

Investigation 1.1a: Chemical and isotopic compositions of primitive meteorites and their components.

Primitive meteorites are time capsules that preserve information about the chemical and physical processes that operated at microscopic to planetary scales in the early solar system. Reading this information requires understanding the origin of chemical and isotopic signatures in these meteorites and their components. Although it is now clear that the solar nebula was not homogeneous, the details of the processes responsible for the known heterogeneities, including their spatial and temporal dependencies, are still poorly understood. Elemental heterogeneities among different classes of primitive meteorites may point to large-scale chemical gradients within the solar nebula and to different conditions in the inner and outer solar system (Benz, Kallenbach and Lugmair 2000). Isotopic heterogeneities in different primitive meteorites and their components, such as refractory inclusions and other less refractory components such as chondrules, may stem from processes such as incomplete homogenization of pre-existing presolar components or the decay of short-lived radioactive isotopes that were present when the solar system formed (Zinner 2003). Therefore, understanding the origin of elemental and isotopic heterogeneities is important for elucidating the earliest processes and their time scales in the early solar system.

Primitive meteorites also harbor genuine stardust, which was present in the molecular cloud from which the solar system formed (Bernatowicz and Zinner 1997). These "presolar grains" formed in the winds and ejecta of dying stars such as red giants and supernovae, and survived a number of potentially destructive processes before being incorporated into the parent asteroids of primitive meteorites. What was the mineralogy of the dust grains originally present in the molecular cloud? What was the chemical and isotopic make-up of these grains? What processes altered or destroyed presolar grains within the solar nebula and on parent bodies? Answers to such questions will help us to gain an understanding of the initial conditions in the solar nebula and the raw materials that contributed to all matter in our solar system. It is also desirable to know if any organic compounds were inherited from the interstellar medium, and the extent to which any of such compounds were chemically processed within the solar nebula (Fegley 1999, Irvine et al. 2000). This is likely to have a bearing on the important issues related to the origin and inventory of prebiotic organic materials in the solar system.

Investigation 1.1b: Physical, chemical and isotopic characteristics of Kuiper Belt objects and comets.

In the outermost reaches of our solar system, icy bodies probably grew very slowly. The largest bodies found in the Kuiper Belt at 40 AU today are Pluto and its moon

Charon, although a number of other bodies have been discovered recently that are nearly as large. One of the new objects – Sedna – is the first known example of a body orbiting between the Kuiper Belt and the Oort cloud of comets. Kuiper Belt objects (KBOs) are of particular interest because their dynamical properties, physical state and chemical composition reflect the conditions prevailing at the beginning of the solar system. The sizes and reflectivities of the major KBOs will soon be determined by a combination of optical and infrared imaging. At present, ground-based telescopes can probe the chemical composition of only the very largest KBOs through spectroscopy. In the near future, however, the New Horizons mission will produce high-resolution chemical maps of the surfaces of Pluto and Charon and at least one other KBO, which will help to determine their interior structures. This research will be complemented by observations of debris disks orbiting other stars using the Spitzer telescope. These observations will allow us to study the dust generated by collisions between objects in the outer regions of extrasolar planetary systems, providing new insights into the composition and evolution of KBOs in our own solar system.

On the other hand, a host of smaller bodies, the short period comets, has been scattered from the Kuiper Belt, and on occasion these objects enter the inner solar system. As these comets travel closer to the Sun they begin to vaporize, generating beautiful comae, which can be examined to determine the chemical composition of the cometary nuclei themselves. Comets are sufficiently small and cold that they should provide a window not only to the formation of the solar system but also to the earlier stages of cosmic evolution in the interstellar medium before the Sun was born. The data gleaned from telescopic observations can be greatly expanded for a few comets by robotic missions, and especially by sample return. The first such sample return mission, Stardust, will soon provide us with examples of cometary dust, and the Deep Impact mission will yield the first glimpse of the deeper structure and inner volatile content of a comet. Ultimately, however, in order to answer the critical questions surrounding the origin and evolution of icy bodies in the solar system – What are comets and KBOs made of? Does their physical state and chemical composition tell us about how and where they were formed? Are comets a significant source of the Earth's oceans and its early organic inventory? – it will be necessary to return an intact sample from the surface of a comet.

Investigation 1.1c: Theoretical modeling and experimental investigations of the processes in the initial stages of planet formation.

The formation of planets involves a number of steps with different physical and chemical processes occurring at each stage. For the rocky planets, early stages involved interactions between dust grains and diffuse, turbulent gas in a microgravity environment (Cuzzi and Hogan 2003, Youdin and Chiang 2004). Later stages involved high-speed collisions between large solid bodies and gravitational interactions during near misses (Chambers and Cassen 2002). Giant planets such as Jupiter are mostly composed of gas, but a large solid core may have been necessary to trigger their formation (Wüchterl et al., 2000; Inaba et al. 2003). Such cores would have formed in the same way as the rocky planets. The ice-rich planets Uranus and Neptune may be similar to the cores of the hydrogen-rich planets Jupiter and Saturn, suggesting that the Sun's primordial gas nebula had largely dispersed when Uranus and Neptune formed. The discovery of extrasolar planets is providing a wealth of opportunities and challenges for our understanding of planet formation. More than a hundred Jupiter-mass planets have now been detected in orbit around other stars (http://cfa-www.harvard.edu/planets/), and the Kepler Discovery mission promises to greatly expand this number. It is already clear from the new discoveries that there is a correlation between the likelihood of finding a planet orbiting a star and the star's chemical composition (Fischer and Valenti 2003). One interpretation of a paucity of Jupiters orbiting low-metallicity stars is that cores of the necessary size cannot form around such stars (Hubbard, 2004). It has also been suggested that nebular metallicity determines the extent to which giant planets migrate within their system, and this affects how easily these planets can be detected (Sigurdsson et al. 2003).

Gravitational interactions between growing planets and the Sun's protoplanetary nebula played a big role in determining the current configuration of the planetary system (Tanaka et al. 2002). Theoretical simulations of these processes and of planetary migration caused by interactions with the nebula will help us to understand the present and past architecture of our solar system and extrasolar planetary systems. However, theoretical models need to be based on observations and experimental data.

Appropriate interpretation of observations of emissions from dust grains as well as modeling of the protoplanetary disk processes is based on radiative transfer models that require input from experimental measurements of the optical properties of dust grains. Moreover, the dust grains in the disk are generally charged, and the grain charge influences the grain dynamics, grain-grain and grain-gas interactions, grain coagulation and evolution. Experimental investigations of grain charging processes by photoemission, collisions with gas phase electrons, and by triboelectric and contact charging processes are needed to provide more realistic information to understand and model the processes involved. In addition, experimental investigations of the growth and sticking efficiencies of dust grains by studying condensation processes of volatile gases on dust grains will provide valuable information for studies of the growth of dust grains in the early stages (Supulver et al. 1997). Thus, studying dust grain sticking and collisions in a turbulent, low pressure gas and in microgravity will provide an important foundation for our understanding of the early stages of planetary growth and essential ground truth for computational models of planet formation.

Objective 1.2: Learn about the earliest processes occurring on the surfaces and interiors of planets and minor bodies.

Investigation 1.2a: Studies of ancient rocks on the Earth, Moon, Mars and asteroids.

Events that occurred early in the solar system have left their imprint on the terrestrial planets and asteroids. Unfortunately, most rocks older than 3.5 billion years on the Earth have been eradicated by impacts, weathering, tectonics, biological activity and other processes. Nevertheless, there are a few localities where rocks and minerals preserve a record of the first billion years of Earth's history. Petrologic, chemical and isotopic investigations of these rare materials can help us to understand the environment on the early Earth and the processes that shaped it.

Unlike the Earth, the Moon retains a substantial record of its early history. Recent computational models have shown that the Moon could have formed by an energetic impact of a Mars-sized body into the early Earth (Canup and Asphaug 2001). Confirmation and refinement of this theory will require detailed examination of samples from the Moon. Rocks returned by the Apollo and Luna missions and lunar meteorites are helping to shed light on the Moon's early history, but these rocks sample only a small fraction of the lunar surface, and more will be needed in future Additional samples will help constrain the impact rate in the Earth-Moon system during the first billion years of solar system history. This has important implications for the environment on the early Earth and the emergence of life. The South Pole-Aitken basin on the Moon is one of the largest impact structures in solar system. The impact was sufficiently energetic to expose materials from the deep crust and possibly the upper mantle. The discovery of this basin provides an opportunity to sample materials unlike those that are currently available and obtain a precise age for the basin-forming event.

The ancient highlands of Mars also preserve a record of the earliest processes occurring on that planet. Remote analyses by spacecraft and detailed studies in state-of-the-art laboratories on Earth of returned samples of ancient Mars rocks will be invaluable towards a better understanding the earliest conditions and processes occurring on the terrestrial planets.

Some meteorites from asteroidal bodies are among the oldest known materials found in the inner solar system. These rocks contain a record of processes such as aqueous alteration, differentiation and core formation that occurred at a very early stage on their parent bodies. As such, investigations of their physical characteristics, chemical composition and mineralogy through spacecraft and returned samples will be important in understanding the earliest processes occurring on such bodies and in clarifying such long-standing questions as the relationship between asteroids and meteorites.

Investigation 1.2b: Interior structure and chemical-isotopic compositions of the deep atmospheres of the giant planets and comparison with characteristics of exoplanets.

In our solar system, most of the planetary mass is contained in the four giant planets, Jupiter, Saturn, Uranus, and Neptune. However, we still know little about the composition and structure of these bodies. How much water do they contain? What is the cloud-layer structure in the gas-giant planets? How massive are their deep cores and if such cores indeed exist, how and when did they form? Information on the isotopic compositions of key elements such as carbon, nitrogen, oxygen, and the noble gases is an essential diagnostic tool for understanding giant-planet formation and evolution in our solar system and in other planetary systems. A comprehensive understanding of the formation and evolution of giant planets around other stars requires better observational data for chemical and physical properties that only can be provided by spacecraft.

The highly successful Galileo probe mission gave us our first look at Jupiter's atmospheric chemistry, but the results left us with some mysteries (Atreya et al. 2003). For example, the probe did not provide measurements of the water content - a key tracer of Jupiter's formation - of the deep atmosphere and measured less water in the upper atmosphere than models had predicted. The Cassini Saturn orbiter and Huygens Titan probe will provide remote-sensing (for Saturn's atmosphere and rings) and *in situ* compositional data (for Titan), which will strongly constrain theories for the origin and evolution of these bodies. An extended orbiter mission will be critical for more complete coverage of Titan's surface and atmosphere, as well as for better constraints on Saturn's interior structure. Definitive measurement of the abundances of noble gases in Saturn's atmosphere still requires an entry probe mission.

> We now have our first measurements of atmospheric compositions in giant exoplanets. Interpretation of these measurements is difficult given their dependence on many poorly understood processes such as cloud formation, deep convection and local "weather", and effects of irradiation from the parent star. The same processes are at work in the atmospheres of our own giant planets. Some hot giant exoplanets may even have observable silicate clouds analogous to those thought to be buried deep in the atmospheres of our own giant planets, together with more easily observable water vapor (Lodders, 2004). Definitive measurement of Jupiter's deep water abundance is needed to understand the formation processes for giant planets, and will be needed for comparison with planned exoplanet measurements (Hubbard et al., 2002).

Therefore, reliable *in-situ* measurements of the abundances of key elements and compounds are required for *all* of the outer planets to build a solid base for understanding giant planet formation in our solar system and in planetary systems of other stars. We need to probe Jupiter's atmosphere again, preferably at locations that have varying meteorology, as well as to deeper levels, preferably to about 100 bars. Similarly, it is essential to make comparable measurements in the atmospheres of our other three giant planets.

Objective 1.3: Learn what the Solar System tells us about the development and evolution of extrasolar planetary systems and vice versa.

Understanding how the Solar System evolved to its current state provides the context and ground-truth for understanding planet formation and evolution processes, and therefore for understanding the diversity of possible extrasolar planetary systems. Theoretical models for the origin of the planets and satellites in our solar system provide important constraints on the possibility of similar systems elsewhere, including those with potentially with habitable planets.

Jovian planets, including the more than 100 extrasolar planets detected to date, are believed to form through either a protracted accumulation of ice-rock cores followed by gas accretion, or through an extremely rapid gravitationally induced collapse. Determining the internal structure, composition, and thermal state of Jupiter and Saturn provides key constraints on these processes and on the overall nature of giant planet structure and evolution. Such models provide a crucial foundation for understanding extrasolar planets. In addition, interactions between the planet's magnetic field and surrounding plasma, particularly at Jupiter, may shed light on processes important for angular momentum and mass loss from protostars.

The close proximity of many extrasolar planets to their parent stars seems to necessitate that they migrated inward significantly, and a possible cause of such migration is the gravitational interaction between planets and their precursor nebular disks. The concept that angular momentum exchange occurs as orbiting objects interact with a disk of material was first understood in the context of planetary rings, where signatures of such processes are directly observable. Studying the interaction of satellites and rings thus shapes our understanding of planet migration processes, which in turn may affect the degree to which extrasolar systems could harbor terrestrial-like planets. The large regular satellites of the outer gaseous planets provide additional and accessible test cases for models of both planet accretion and migration because, like planets, these satellites are believed to have formed within disks of gas and solids. Other dynamical processes whose effects are observable in the Solar System, including resonant and tidal interactions and gravitational scattering, are also believed to be important potential shapers of extrasolar systems.

Models of the formation of rocky planets provide the basis to assess theoretically the potential for extrasolar terrestrial planet systems. Formation models may rely on the properties and temporal evolution of a circumstellar gas of nebula and the formation accompanying jovian planets. Likewise, studies of the factors that influence habitability in our solar system help to constrain the general astronomical conditions related to the formation of Earth-like planets elsewhere.

Understanding the formation and ongoing dynamical and collisional evolution of the asteroid and Kuiper belts is relevant to understanding dust and debris disks around other stars, and what their structure may imply for the possible presence of embedded planets.

Investigation 1.3a: Observations and modeling of the architecture of and gravitational interactions among Solar System bodies at scales from planets to dust.

Investigation 1.3b: Comparative studies of the internal states, orbital histories, and magnetospheric interactions of the outer gaseous planets and their satellites to constrain their origin and evolution.

Investigation 1.3c: Studies of planet and satellite formation (including accretion, volatile delivery, and dynamics), especially as pertinent to planetary habitability.

Decadal Survey mapping:
12. What Does the Solar System Tell Us About the Development and Evolution of Extrasolar Planetary Systems and Vice Versa?

Goal 2: Determine how the solar system evolved to its current diverse state including the origin and evolution of the Earth's biosphere

Objective 2.1: Understand why the terrestrial planets differ so dramatically in their evolution.

The terrestrial planetary bodies share many similarities, but solar system exploration has revealed that they are also fundamentally different in many other ways. The Moon, Mercury, and Mars stabilized their crusts and lithospheres early in planetary evolution and became "one-plate" planets. In contrast, Earth evolved into a dynamic, multi-plate planet that is constantly renewing itself through atmospheric erosion and recycling of the lithosphere into the interior. Venus shows no active plate tectonics and may have been catastrophically resurfaced within the last billion years.

Terrestrial planet atmospheres also show major differences, with Venus and Mars both being CO_2-dominated, but with orders-of-magnitude different surface pressures. On Earth, liquid water provides a substantial thermal buffer to sudden changes in the climate; nevertheless, ample evidence indicates that the climate has varied considerably with time. Climate can be altered by changes in global volcanism, solar output, celestial mechanics, and the effects of pollutants made by humans. Atmospheric constituents have been removed over time by the solar wind. The interactions among these influences are so complex that they are not fully understood, yet they are fundamental to understanding atmospheric evolution and planetary habitability.

Our neighboring planets Venus and Mars provide compelling examples of atmospheric evolution along very different paths from that of Earth. The thin CO_2 atmosphere of Mars represents an extreme in which temperatures are low and a significant fraction of the "atmosphere" lies buried as ice within the regolith and upper crust. It is critical to understand climate change at Mars and its potential causes and effects. The influence of a planet's dynamical history, notably its obliquity and orbital eccentricity, on climate and habitability are important to understanding the differences between Earth and its neighboring terrestrial planets.

The surfaces of the Moon and Mercury are superficially similar but differ in detail, for example with Mercury showing only indirect evidence for volcanism. Moreover, their interiors are quite different, with Mercury having a very large iron core and the Moon a very small one. Fundamental questions remain regarding the current state and the evolution of the lunar surface and interior, and Mercury's level of internal and crustal evolution is uncertain. Both planetary bodies have tenuous exospheres with multifaceted solar wind interactions; however, he role of the magnetic field of each is very different, as Mercury has a significant magnetosphere. Both bodies show evidence for volatiles in polar cold traps.

For the Moon, seismic data would resolve the internal structure, permitting a much-improved estimate of bulk composition. Samples of rocks from major unsampled terrains, primarily the South Pole–Aitken Basin which excavated into the lower crust of the Moon, are needed to determine an accurate crustal composition and stratigraphy. For Mercury, basic information is needed on surface composition, internal structure, and distribution of mass, each of which provides important constraints on bulk major-element composition.

Investigation 2.1a: Comparative studies of climate evolution of Mars, Earth, and Venus to better evaluate the roles of planetary parameters (composition, volatile inventories, dynamical properties, and surface processes) in determining terrestrial planet habitability.

Investigation 2.1b: Comparative studies of the current state and inferred evolution of the interiors and surfaces of Mercury and the Moon.

Decadal Survey mapping:
9. Why Did the Terrestrial Planets Differ So Dramatically in Their Evolution?

Objective 2.2: What environmental factors were required for the emergence and sustenance of life?

The origin of life occurred through a set of chemical and physical processes that are likely to have occurred on numerous other planets circling sun-like stars. These processes must be understood not only in terms of the Earth, but also with regard to possible origins of life elsewhere. A clear starting point is to determine what raw materials of life can be produced by chemical evolution in interplanetary space and on planets. From recent investigations we now know that one possible source is photochemical processing that may have synthesized some of the organic compounds found in comets, interplanetary dust particles (IDPs) and carbonaceous meteorites. Presumably these can be delivered to planetary surfaces during accretion. A second major source of prebiotic organics is geochemical synthesis taking place on planetary surfaces and within their interiors; this may be relevant to meteorite parent bodies as well since alteration by liquid water is seen in some chondritic mineral phases.

Next, we must establish how organic compounds are assembled into more complex molecular systems and the processes by which complex systems evolve those basic properties that are critical to life's origins, persistence and evolution. Primary properties of life include capturing energy and nutrients from the environment, manufacturing copies of key biomolecules, and self-replication of the individual. There remains a vast gap in our understanding of how such properties first appeared in molecular systems on the early Earth, and NASA flight missions and ground-based research will be essential for answering these fundamental questions.

Changes in the physical and chemical environment of Earth have had a profound influence on the history of life on Earth. We must identify the dates of origin of key metabolic pathways and the divergences of the major clades in prokaryotic and early eukaryotic life, of the establishment of complex life, and its relationship to significant events in Earth's environmental history. Such information provides critical constraints on understanding the processes of biotic innovation necessary for the persistence of life. The longevity of life on this planet also appears intimately connected with biotic responses to catastrophes mediated by both endogenous and exogenous environmental factors. Although advances have been made in documenting such perturbations, less is known of the subsequent biotic responses.

This will require an integrated program of pan-spectral astronomical and orbital observations, sample return missions, laboratory studies of extraterrestrial materials, and realistic laboratory simulations of inaccessible cosmic environments, as well as a deeper understanding of key evolutionary events in the history of terrestrial life and the factors responsible for driving evolutionary change.

The basic requirements for terrestrial life include liquid water, a source of energy, a source of organic compounds, and environments favorable for the assembly of complex organic molecules into systems that can capture energy and undergo catalyzed growth processes. For life to begin there must be active mechanisms for concentrating and maintaining interacting molecular species in a microenvironment favorable for life’s emergence. From this perspective, life began as a bounded system of interacting molecules, none of which has the full property of life outside of that system.

We must also continue to study life in extreme environments. Recent studies have demonstrated that life can adapt to temperatures as high as 121°C in subsurface hydrothermal systems, and sub-zero temperatures in the eutectic phases of polar ice. However, despite 3 billion years of evolutionary history no microbial or multicellular organisms are known that involve a life cycle in environments that are permanently frozen solid, totally dry or lacking a source of energy and nutrients. These observations suggest that there are certain fundamental constraints on carbon-based life, and that these provide initial astrobiological constraints for the exploration of other planets. The challenge of defining these constraints will lead to a more refined definition of habitability and the living state, and will clarify the hurdles faced by self-assembled systems of organic molecules as they evolved toward the first life on the Earth.

Investigation 2.2a: What conditions on the early Earth fostered the emergence of life?

A primary objective of research for this investigation is to establish laboratory models of primitive planetary conditions and determine how plausible mixtures of organic compounds can undergo self-assembly processes. These systems will have the capability to capture energy and nutrients from the environment, grow through polymerization, and reproduce some of their polymeric components. We must also to continue to explore the likely nature of the environment of the early Earth and its influence on the origin and early evolution of life.

Investigation 2.2b: Where did Earth's inventory of simple organic molecules and "volatiles" (especially water) come from?

To understand how life can begin on a habitable planet such as the Earth, it is essential to understand the origin of both organic compounds and the water to form the necessary aqueous environment.

For organic compounds we need to know what was likely to have been available. Prebiotic organic synthesis also occurs by photochemical processes in interstellar clouds. Laboratory simulations have recently demonstrated that key molecules can be synthesized in interstellar ices that are incorporated into nascent solar systems, and astronomical observations and analyses of extraterrestrial materials have shown that many compounds relevant to life processes are also present in meteorites, interplanetary dust particles and comets. It is likely that substantial amounts of such organic material were delivered to the Earth during late accretion, thereby providing organic compounds that could be directly incorporated into early forms of life or serve as a feedstock for further chemical evolution. Incoming comets and asteroids are rich in organic molecules. Carbonaceous chondrites, the most volatile-rich meteorites contain several types of amino acids and comets appear to contain up to ten times more organics than carbonaceous chondrites. However large objects are subject to extreme thermodynamic stress during entry and impact and as a result interplanetary dust particles (IDPs) have long been indicated as the main vehicle for carrying organic material to planetary surfaces. However, theoretical and laboratory studies have recently suggested that non-negligible fractions of complex organics can survive the shock events associated with large impacts, and secondary organics have been synthesized in strong shock events in the laboratory (Peterson et al., 1997; Blank et al. 2001). It is becoming clear that asteroid and comet impacts played an important role in the development and evolution of the prebiotic inventory of planetary objects, including the Earth (e.g. Pierazzo & Chyba, 1999) Detailed theoretical and laboratory work is needed to determine the rate of survival and synthesis of complex organics in strong shock events, as well as the role of planetary gravity in retaining impactor material delivered in impact events.
Chemical syntheses that occur within the solid crust, hydrosphere and atmosphere are potentially important sources of organic compounds, and they continue to be an important focus of research.

A major question is the origin of the water in the Earth's crust and oceans that has sustained life and regulated climate over our planet's history. A local source of water would require reduced temperatures in the protoplanetary disk in the 1 AU region, where the Earth formed, and this seems inconsistent with the water content of various chondritic meteorite types. However, this source cannot be ruled out. Comets, at least the long-period ones, seem to have a deuterium-to-hydrogen ratio that is twice that of ocean water, and thus cannot be a primary source. Indeed, dynamical models suggest that no more than 10% of the Earth's water may have come from comets. A promising source, from the dynamical and hydrogen-isotopic point of view, is large bodies formed in the primordial asteroid belt, which is generally thought to have been orders of magnitude more massive than the remnant belt we see today. There remain many unanswered questions about how the Earth acquired its water, whether comets truly are ruled out, and how much material was from the 2-4 AU region was acquired by the Earth. Further, we seek to understand the origin of organic carbon on the Earth, much more poorly constrained. It is essential to have samples of cometary materials, and the current Stardust mission with the planned sample return will be an enormous advance in advancing our understanding of this question. As well, exploration fo the asteroid belt to directly sample the chemical and isotopic nature of possible parent bodies of the chondrites, and other meteorite types, is essential. Finally, a firm understanding of the history of water on Mars will tie together the problem of the origin of water on Earth and Mars, providing much tighter constraints for models than can be afforded by either planet alone.

Investigation 2.2c: Are (or were) these conditions found on other planets or satellites in the solar system?

Building on the foundation from the preceding investigations, we must refine our models of habitable zones around other stars to better understand the "real estate" available for the origin and persistence of life on other planets. For the period of this plan, most of these studies will be based on theoretical models and astronomical investigations covered under other roadmaps, but the will provide a necessary foundation for further research

Objective 2.3: Determine the historical relationship between Earth and its biosphere

The Earth and its biosphere have co-evolved over some 4.5 billion years, with changes in one frequently triggering changes in the other. Examples pertinent to NASA's mission of understanding the origin and early history of life and the possibility of life elsewhere include: the oxygenation of the ocean and atmosphere, the redox history of the oceans through the Archean (4.2-2.5 billion years ago) and Proterozoic, (2.5 billion to 543 million years ago) the relationship between tectonic activity and the weathering cycle and their impact on the habitability of the planet, the diversification of prokaryotic lineages, and the origin of complex multicellular life. In each of these cases research is needed to connect changes in the Earth's physical and chemical environment to changes in biotic systems, and vise versa. There is also a clear need for more sophisticated, process-based models of the interaction between changes in the physical environment and biological innovation. In addition, NASA has a clear interest in determining the effect of extra-terrestrial impact's on the Earth's biota, and more specifically, on the extent to which major biotic crises in the history of life have been driven by exogenous factors (impacts), versus endogenous factors (climate change, volcanism, etc).

Investigation 2.3a: Search for biosignatures (molecular biomarkers, fossils and chemical signatures) of key microorganisms and metabolic processes in Archean and Proterozoic rocks, and correlate them with environmental changes on the early Earth.

Biosignatures provide critical information on the origin of major clades and their constituent metabolic processes during the Archean and Proterozoic. Establishing the timing of these events and correlating them to changes in the chemistry of the oceans and atmospheres will identify whether environmental triggers are responsible for key biological innovations. Fossil biosignature analysis is still a developing field and much progress is needed for the unambiguous identification their presence in ancient rocks. However, fossils provide our only direct record of the history of life on Earth and the reliable recognition of biosignatures will be crucial establishing the timing and history of key biological innovations. In addition, we need to place key innovations within the geological context of paleoenvironmental change (e.g. in the chemistry of the oceans and atmosphere), to evaluate whether or not major evolutionary events were triggered by intrinsic environmental factors. [See also description of Fossil biomarkers below]

Investigation 2.3b: Study the environmental, ecological and developmental conditions that led to the evolution of complex, multicellular life in the Neoproterozoic and Cambrian.

Complex multicellular life arose between 1.2 billion years ago (the earliest multicellular algae) and 543 million years ago (the Cambrian radiation of animals). The pattern of evolution is increasingly well constrained, with decreasing differences between molecular clock estimates of lineage divergences and times of lineage appearance in the fossil record. Connections between geochemical changes in the oceans and atmosphere during the late Neoproterozoic (Ediacaran Period) and the diversification of multicellular life are becoming clearer. Less clear is the relative significance of environmental, ecological and developmental factors in the timing and extraordinary breadth of this event. This is an area where more theoretical models of ecological niche construction and the interactions between ecology, development and the physical environment may prove quite valuable.□

Investigation 2.3c: Examine the response of the Earth's biological and geochemical systems to extraterrestrial events, particularly asteroid and cometary impacts and explore the use of the lunar cratering and geochemical crustal records to provide constraints on the Hadean Earth that have been destroyed on Earth.

At least one and possibly more of the six great mass extinctions in the history of life have been associated with impacts of extra-terrestrial objects; other known impacts had no evident biotic effects in the fossil record. The relative importance of endogenous and exogenous influences on the history of life is an important area of research. In the absence of a geologic record for the Hadean Earth, future missions to investigate the lunar cratering and geochemical records coupled with better modeling of impacts and their environmental effects will provide an opportunity to explore the likely influence of Hadean impact events on the emerging biosphere.

Goal 3: Explore The Space Environment To Discover Potential Hazards and Search for Resources that would enable permanent human presence

Our planet Earth moves through interplanetary space and is bombarded by a continuum of energetic particles, cosmic rays, dust, and occasionally larger objects, all of which are hazards to human life. These hazards become even more severe for future human and robotic explorers that will move beyond the shielding provided by Earth's atmosphere and magnetic field, and into space environments that may be vastly different than on Earth. Here we catalogue these hazards to human and robotic explorers, and discuss vital resources needed to sustain life beyond Earth

Once a source of life-giving organics and water, cosmic impacts have the potential to wreak widespread destruction or even to extinguish much of life on Earth. Although the impact flux has declined greatly since the early days of the solar system, these events still occur regularly on planetary timescales. This sobering conclusion stems from the convergence of many lines of study, from geology to astronomy to paleontology. Evidence continues to mount that the so-called Cretaceous-Tertiary mass extinction event 65 million years ago was caused by the impact of an extraterrestrial body about 10 kilometers in diameter. It has also become apparent that even much smaller objects, which impact Earth much more frequently, are capable of doing serious damage to modern industrialized society. Classified satellites detect approximately 1 impact per month into the Earth's atmosphere (Brown et al. 2002). To understand the impact threat posed by asteroids and comets, as well as the feasibility of potential mitigation strategies, we must assess not only the number of potentially hazardous bodies and the frequency of both small and large impacts, but also the physical characteristics of the objects themselves

Objective 3.1: Determine the inventory and dynamics of bodies that may pose a hazard to Earth.

Investigation 3.1a: Updating the inventory of small bodies

The interplanetary space between the major bodies in our solar system is far from empty. Considerable progress has been made in discovering and cataloguing near-Earth asteroids (NEAs) that could potentially pose a threat to Earth and as a direct result of increased knowledge of the discovered population, estimates of the total population of potentially hazardous near-Earth asteroids have become increasingly accurate. Based on this evolved understanding of the population and the threat that it represents about 52% of the potentially hazardous near-Earth asteroids larger than 1 kilometer have now been catalogued. It is estimated that approximately 10,000 asteroids of diameter greater than 140 meters still exist in orbits that directly represent a collision hazard to Earth. Such objects have orbits that could bring them to within 0.05 AU of the Earth and are termed Potentially Hazardous Asteroids (PHAs). Of those, approximately 220+/-40 have diameters of 1 kilometer or larger, with 115 of these having been discovered to date (Stuart, J. S. and R. P. Binzel 2004). An impactor at the smaller end of this size range could wipe out a city or an entire coastal region; at the upper end of this range it could cause global devastation. NASA has played a key role in the discovery of these objects in response to a stated goal of discovering and cataloging 90% of all Near-Earth Asteroids (NEAs) with diameters larger than 1 km by 2008. However, based on the evolved understanding of the asteroid population and the threat that it represents, it is appropriate to modify this goal to better focus resources on the truly threatening population of objects. These changes are as follows:

1) The discovery and cataloging goal focuses specifically on the objects in orbits that represent a direct collision threat to Earth. These are the PHAs rather than the broad NEA category. Only about 20% of NEAs are actually PHAs.

2) The goal has been modified to directly address resolving the largest risk for the amount of resources invested. As such the goal is stated as "discover and catalog the population of potentially hazardous asteroids sufficient to resolve 90% of the risk from the impact of sub-kilometer asteroids". This will also resolve essentially all of the residual collision risk for the 1 km and larger asteroids. This goal indicates the development of a catalog of

PHAs 90% complete for asteroids larger than 140 meters diameter, which is achievable by the application of currently available technology (ref SDT report).

3) The long-period comets represent less than 1% of the total collision risk and therefore are not an important component of the stated goal. However, any such objects on a collision course likely will be discovered with only a few weeks to months of warning time by systems built to accomplish asteroid search.

This represents a unique contribution to the protection of our home planet that is synergistic with our objectives of understanding key solar system processes.

Investigation 3.1b: Understanding the impact process on different planetary settings

Impact cratering is a common geologic process in the solar system (Melosh, 1989). On Earth, craters in water-saturated sediments are larger than their energy-equivalents in dry soils, which in turn are larger than their energy-equivalents in crystalline rocks. Features of Martian craters have been used to indicate presence of water in the subsurface. Craters on the icy moons of Jupiter have morphologies that are quite different from those on rocky surfaces. To date there have been no direct observations of the formation of planetary impact craters in recorded history. While NASA's Deep Impact mission will provide a unique chance to witness a hypervelocity impact, a comprehensive understanding of the impact cratering process requires the combination of planetary geologic and geophysical observations and experimental and theoretical studies. Terrestrial impact structures are in the unique position of providing ground truth information on the impact cratering process. Their investigation can provide crucial information on the cratering process, in particular the importance of target composition and the amount and nature of deformation outward from the crater (Herrick and Pierazzo, 2003). Because of its arid environment and close proximity to the Earth, the Moon has been a valuable natural laboratory for studying planetary impact processes at 1 AU. New data from the science and exploration programs will add significant new constraints to our understanding of the Earth-Moon environment.

A critical component of the impact process is the response of materials to the wide range of temperatures and pressures associated with impact cratering. Specific material properties govern the response of materials to stress, resulting in different behaviors of different materials for nominally the same impact conditions. Gravity is another poorly explored parameter that can affect impact cratering, especially for very low gravity bodies, such as asteroids and comets. As a result, there are clear differences among craters on different planetary surfaces, especially in the outer solar system. To understand the role of impact cratering on the various planetary surfaces of the solar system the science community is in need of experimental data that can characterize the response of different materials in the impact process. This includes shock data relative to the exotic materials making up the surfaces of outer solar system bodies, such as different ices at very low temperatures, as well as mixed materials with very different characteristics, such as water ice and silicate rocks on the surface of Mars. These data can provide precious information for the development of accurate material models that still represent one of the major problems associated with theoretical modeling of impact cratering. Data on low gravity impacts are needed to understand impact cratering where usual scaling laws may not work. Measuring the surface and interior composition and structural properties of comets and asteroids will enable modeling of the effects of impacts and the development of credible mitigation strategies. It will also be important to understand the impact processes under low-gravity conditions, such as will be possible to study with the Deep Impact mission.

Investigation 3.1c: Impacts and Exogenous Delivery/Production of Organics

Incoming comets and asteroids are rich in organic molecules. Carbonaceous chondrites, the most volatile-rich meteorites, are known to contain several types of amino acids. Comets appear to contain up to ten times more organics than carbonaceous chondrites. Objects larger than few kilometers in diameter are the most important contributors of extraterrestrial material to Earth (Anders, 1989). Their usefulness in delivering complex organic molecules to a planetary surface is weakened by the extreme thermodynamic conditions occurring during an impact event. As a result, interplanetary dust particles (IDPs) have long been indicated as the main vehicle for carrying organic material to planetary surfaces. However, theoretical and laboratory studies have recently suggested that non-negligible fractions of complex organics can survive the shock events associated with large impacts, and secondary organics have been synthesized in strong shock events in the laboratory (Peterson et al., 1997; Blank et al. 2001). It is becoming clear that asteroid and comet impacts played an important role in the development and evolution of the prebiotic inventory of planetary objects, including the Earth (e.g. Pierazzo & Chyba, 1999). However, our knowledge of the potential effects of shock-loading on the modification of organic material is still sparse. Detailed theoretical and laboratory work is needed to determine the rate of survival and synthesis of complex organics in strong shock events, as well as the role of planetary gravity in retaining impactor material delivered in impact events.

Investigation 3.1d: Impacts and Extinctions

Collisions of large asteroids and comets with the Earth's surface are rare events that punctuate the geologic record. While the existence of large impact structures on Earth is undisputed, their effects on the biosphere are still not well understood. Based on statistics, the number of major mass extinctions characterizing the evolution of the Earth's biosphere is close to the number of expected large impact events (e.g., Rampino and Haggerty, 1996). On the other hand, hard evidence points to the well-studied end-Cretaceous (K/T) mass extinction (65 Myr ago) as the only one that clearly coincides with a major impact event, although mechanisms linking the impact event with the mass extinction are still debated (e.g., Toon et al., 1997). Attention has recently focused on the possibility of another mass extinction-impact event coincidence, at the Permian/Triassic boundary (P/T) around 250 million years ago (Becker et al., Science, 2002?). The investigation of the Earth's record for the evidence of an impact at the end of the Permian is still in its infancy, and any conclusion of a temporal coincidence with the mass extinction requires a major interdisciplinary investigation effort from the scientific community (*e.g.,* Becker *et al.*, 2004). The examination of the Earth's geologic record coupled to the investigation of the effects of large impacts on the biosphere can provide important insights on the consequences of large impacts on Earth and into the processes by which life adapts and evolves. This in turn can help us learn about the role that impacts may have played in affecting the habitability of other planetary bodies of our solar system and beyond.

Objective 3.2: Characterize the Hazards from Radiation in Space and at Other Planets to Improve Forecasting and Mitigation Capabilities

One of the most serious issues facing the future human and robotic exploration of the Moon, Mars and beyond is the radiation hazard posed by solar energetic particles, galactic cosmic rays, and the radiation environments on other planets that are not now well characterized. On Earth, radiation from space is predominantly shielded by Earth's magnetic fields, but as spacecraft move into high altitude orbits, through the magnetosphere and beyond, they are exposed to a variety of serious radiation hazards. The radiation environment places a fundamental limit on human space flight. Over the past 20 years, on average, one to two satellites per year experience a premature partial or total mission loss due to radiation damage to electrical components. Shielding on spacecraft provides some protection from radiation, but for very high-energy radiation (>100MeV), shielding makes matters worse by producing secondary, penetrating particles, such as neutrons and nuclear fragments, that increase the hazard. Large solar energetic particle events can deliver lethal doses to astronauts over short periods of time. For example, the 1989 September event would have delivered a lifetime dose to astronauts in less than 12 hours. The event lasted for many days.

There are three primary categories of radiation hazard from space that dictate specific strategies for mitigation:

1. Galactic Cosmic Rays (GCRs) are an ever-present background radiation in space that is difficult to shield against. Astronauts would accumulate a career limit due to GCRs in roughly 3 years. We need to understand the current limits imposed by GCRs on mission transit time, shielding levels, or develop new techniques to shield against them.

2. Large solar energetic particle events are extremely dangerous to astronauts. To mitigate the hazard due to solar events, we must develop the ability to predict when and where they will occur.

3. There are unique radiation environments at each planet or satellite. At Earth, we have thoroughly characterized locations of the radiation belts, which allows us to mitigate the hazard they pose by transiting them rapidly. For future human and robotic exploration of other planets and satellites, it is essential to characterize the planetary radiation environments so that appropriate mitigation strategies and adequate shielding are designed.

Development and research of new materials and innovative approaches to shielding will be important to help mitigate the risks posed by all radiation hazards.

Investigation 3.2a: Develop an End-to-End Predictability of Solar Storms to be able to deal with lethal transient phenomena

There were Apollo lunar landings in April and December, 1972. Had the great storm of August 4, 1972 happened 4 months earlier or later, astronauts in the lunar module would have been exposed to a high radiation dose, causing acute radiation sickness and possibly death. Solar energetic particles are accelerated either on the Sun through stochastic processes or reconnection in strong magnetic field regions, and through acceleration at strong shocks set up by the formation of coronal mass ejections (CMEs) that plow through the solar wind. These events have a range of intensities, maximum energies, and frequency of occurance from the almost ubiquitous seed population at 10's of keV, up to very intense infrequent events with energies up to and even beyond GeV. The infrequent but very high-energy events are the most dangerous.

The frequency of occurrence and intensity of solar energetic particle events (SEPs) vary strongly with solar activity. When the Sun is extremely active, energetic particle events are more frequent and intense. Near solar minimum, energetic particle events are less frequent, but still pose a significant hazard. The onset of SEP events is prompt and potential alert systems must take the need for immediate actions into account. The composition of flares is also highly variable with heavy elements (Fe) often being enriched by large factors, which significantly increases the radiation dose. An important activity of solar and heliospheric physics is to develop the capability to predict when, where and how intense solar energetic particle events will be. The spiral shape of the interplanetary magnetic field guides particles away from the radial direction. This poses difficulties for developing alert capabilities from direct solar observations, since the relevant solar activity is most often hidden behind the limb of the Sun. The development of end-to-end predictive capabilities for solar energetic particles requires detailed knowledge of the nature and evolution of solar and heliospheric magnetic fields, the generation and influence of magnetohydrodynamic turbulence, and the formation and evolution of shocks from the Sun throughout the inner heliosphere. For short duration space travel, adequate shielding may mitigate the hazard posed by most of the low to moderate intensity solar particle events, but the largest events will remain a critical risk, even with well-shielded spacecraft.

Investigation 3.2b: Understanding Limits to human space flight imposed by Galactic Cosmic Rays

Highly energetic GCRs (100 MeV-10GeV) are always present in space, continually bombarding Earth's atmosphere, producing secondary particles and radiation through cascading high-energy collisions. The outer heliosphere shields us from the majority of GCRs. A small fraction of GCRs penetrate into the heliosphere and propagate toward the Sun and planets. Coronal mass ejections and other large magnetic disturbances are frequent during solar maximum, which minimizes the flow of GCRs during this period. GCRs pose a common health hazard even at low-Earth orbit, where only the lowest energy GCRs are shielded by the Earth's magnetic field. However, during space travel, GCRs are almost impossible to shield [Wilson et al., 1991] since they produce secondary radiation in shielding and other material that is even more hazardous than the primary GCRs. On long duration missions, such as to Mars, GCR radiation is the primary health hazard to astronauts who would accumulate a lifetime does in less than 1.5 years [NAS, 1973, 1997; Cucinotta et al, 2001]. We need to understand the limits imposed by GCRs on the duration of manned missions, or the levels of shielding that must be applied to mitigate the GCR hazard.

What we know about the dominant shielding of GCRs in the inner heliosheath is very limited and based mostly on models and theory. Large changes in the Local Intersetllar Medium have dramatic effects on the heliosphere and the radiation environment of the solar system. Such large changes have certainly occurred in the past and will occur again in the future. Isotopes produced in Earth's atmosphere through interactions with cosmic ray protons have been recorded in Antarctic ice. The ice records show two prominent peaks 35,000 and 60,000 years ago, when the radioisotope production rate was about twice the current value for about 1500 and 2000 years, respectively [Raisbeck et al., 1987]. We do not currently have the observational knowledge required to understand how the local interstellar medium interacts with the heliosphere; observations of that global interaction are essential for understanding the radiation environment that must be traversed by astronauts for long missions to distant destinations, such as Mars.

Investigation 3.2c: Characterizing the radiation environment at other planets and satellites

There are unique radiation environments and radiation belts at the Earth and in other planetary systems. In Earth's magnetosphere, the radiation environment is fairly well known. The hazards posed by the radiation belts can be mitigated because their locations and altitudes are well known and the transit time through them can be minimized. Radiation environments are remarkably different at each planet. For example, Jupiter is, second to the Sun, the strongest source of highly penetrating electrons in the solar system, which can severely damage electronic spacecraft subsystems if adequate shielding is not designed. On the surface of the Moon and Mars, neutrons produced from solar energetic particles and GCRs are one of the most destructive radiation hazards to astronauts. The radiation environment of other planetary systems must be charted and thoroughly understood before manned missions can be executed.

Large-scale ejections by the Sun form shocks as they propagate through the solar wind. These ejections cause large variations in the radiation environments at Earth and other planets by impacting and disturbing their magnetospheres, ionospheres and atmospheres. The types of disturbances released by the Sun are a strong function of solar activity. Near solar maximum, when the number of sunspots is at its highest level, the Sun's magnetic fields are in a continual state of massive reorganization. This causes the frequent eruption of solar matter and energy, coronal mass ejections (CMEs), that disrupt the global structure of the solar wind, cause major geomagnetic storms, and magnetospheric or ionospheric storms at other planets and satellites. Near solar minimum, when there are fewer sunspots, there are disruptions in the solar wind that recur with each 27-day solar rotation due to the interaction between fast and slow solar wind streams. These interactions lead to large spiral-shaped structures that co-rotate with the Sun, co-rotating interaction regions (CIRs), which cause recurrent geomagnetic activity at Earth. Because CIRs strengthen beyond Earth, they cause stronger ionospheric and magnetospheric disturbances at Mars and Jupiter. Understanding the effects of CMEs and CIRs on planetary atmospheres, magnetospheres and ionospheres will be essential for defining the varaibilities in the radiation environments at planets throughout the solar system.

Objective 3.3: Inventory and characterize planetary resources that can sustain and protect humans as they explore the Solar System

Permanent human habitation of space requires knowledge of the resources available from the Moon, Mars, and asteroids, and access to those resources. Assessing space resources requires missions that (1) determine the global distribution of materials (mineralogy and elemental abundances) with sufficient detail to understand geologic context (origin), (2) land on planetary bodies and characterize the surface and subsurface environments, (3) carry resource extraction test beds and pilot plants to develop engineering capability to use extraterrestrial resources; and (4) gain an understanding of the bulk densities of asteroids to ascertain which are solid bodies and which might be rubble piles (this is important from both the planetary defense point of view and the issue of asteroid resources). The combined data returned will be of immense long-term value to both science and resource exploration. There are four areas of investigation:

Investigation 3.3a: Determine the nature of water resources in lunar polar regions, on Mars, and the locations of water-bearing near-Earth asteroids and the most efficient ways to extract oxygen from non-polar lunar regolith.

Water may be the fuel that allows humans ready access to the Solar System. It is essential for life support, of course, but it is particularly useful as its constituents hydrogen and oxygen for use a rocket fuel. Water is found throughout the Solar System, but we do not have a systematic knowledge of its occurrence on specific bodies.

The Moon. Lunar Prospector data show conclusively that lunar polar regions are enriched in hydrogen. We do not know the precise form of the hydrogen (H, H_2O[ice], H_2O[bound], CH_4, organic compounds, etc.), its distribution in the regolith, or its precise location (permanently shadowed craters or over a broader region). To understand the concentration mechanisms, sources of hydrogen, and composition and total inventory of the deposits, requires dedicated mission(s). Such mission(s) would characterize the locations of the hydrogen deposits from orbit and, equally important, make detailed *in situ* measurements of representative deposits. Sub-surface sampling is expected to be important and should reach a depth of at least a meter (ideally to the base of the regolith, several meters). As an independent approach, it has long been known that oxygen can also be extracted from the lunar regolith, particularly from ilmenite and FeO-rich glass such as pyroclastic glass. Landed experiments are needed to test and refine such extraction techniques on the Moon.

Asteroids and Martian moons. Water is abundant in some asteroids, bound in phyllosilicate minerals. CI carbonaceous chondrites, which are believed to come from asteroids, contain about 10 wt% water. Prospecting for water requires missions that characterize the composition and physical properties of a number of specific asteroids that might be accessible for resources. We must identify water-rich near-earth asteroids and characterize their surface properties in sufficient detail to design and develop extraction systems.

Mars. A unifying theme of the Mars Exploration Program is to understand the distribution and history of water. Water is also essential for permanent settlements on Mars. Mars Odyssey neutron and gamma ray spectrometers have shown conclusively that abundant water exists in polar regions within the upper meter of the surface, and modest amounts are present in equatorial regions, probably bound in hydrous minerals. However, we do not have a detailed understanding of water on Mars, e.g., variations laterally or with depth, depth to liquid water, or purity of the water. Understanding water on Mars, along with hydrous mineralogy of the soil and surface rocks, will involve a continued series of orbital, flying, roving, and drilling measurements.

Investigation 3.3b: Determine the Inventory of rare metals

We will soon experience a shortage of rare metals needed for industrial processes (e.g., platinum. Some asteroids are "known" to be rich in these desirable and valuable metals. A large percentage of an impactor on the Moon would not be vaporized in certain lower velocity collisions, thus it may be possible to prospect for precious metal concentrations on the Moon which representing the remains of metal-rich asteroids. While a meteoritic component has long been recognized in lunar fines, these arguments speculate that large areal concentrations of ores can exist on the Moon and that these ore bodies could be mined for resources.

Investigation 3.3c: Use of local resources for primary shielding

It will be essential to shield astronauts from cosmic and solar radiation, especially during solar flare events. Current understanding indicates that more than two meters [check number] of lunar or asteroidal regolith should provide adequate shielding, although further research will be needed to both establish the radiation environments to which astronauts will be exposed (Objective 2) and explore new and innovative shielding techniques and approaches.

Efficient methods must be developed and tested that move large amounts of regolith to construct shielded habitats. Asteroids and the Moon present very different problems for using regolith, however, because physical properties may be different. Measurements of geotechnical properties of asteroid surface materials and development of excavation techniques at very low gravity are needed.

Investigation 3.3d: Assess potential long-term resources

Permanent settlements will require use of materials from the Moon, Mars, and asteroids (because this is less expensive than bringing materials out of Earth's gravitational potential) to build and maintain the infrastructure and generate products for export. Prospecting for these resources and devising mining and processing techniques are crucial steps in human activities in space. More importantly, some space resources, such as producing solar energy on the Moon, are expected to make the transition to be used for the benefit of people on Earth while opening new economic markets that might drive the human exploration of space.

Initial lunar resource utilization will focus on the most concentrated deposits of materials of immediate interest (e.g., highest titanium, phosphorous, or zirconium concentrations [note: explain why these materials specifically]) and development of efficient techniques to extract those resources and manufacture products from them. Although our understanding of the potential value of specific resources is in its infancy, a thorough inventory of raw materials is the baseline information that is essential for extended planning. This requires a combination of orbital exploration that provides mineral and elemental concentrations in detailed geologic context and coordinated landed (roving) investigations of surface composition and physical properties with tests of extraction technologies. Asteroids are diverse and their surfaces poorly explored (although individual asteroids may be homogeneous; see Objective 1). The distribution of potential useful materials (e.g., iron metal, organic compounds) on asteroids needs to be determined through orbital and landed measurements. Techniques to process materials in low gravity must also be developed and tested.

Goal 4: Understand the processes that determine the fate of the soalr system and life within it.

Objective 4.1: Learn how the processes that shape planetary bodies operate and interact, through multidisciplinary comparative studies.

Improved understanding of planetary formation and evolution, and of how habitable environments arise, can be gained through a detailed knowledge of the individual processes that affect planetary bodies. Distinct processes are at work in the very diverse settings of planetary interiors, surfaces, atmospheres, magnetospheres, and in the ring systems of the jovian planets. The dominant process at any given location can operate in relative isolation, but more commonly a suite of processes is at work on planetary bodies. The history of the interactions that affect planetary bodies may be very dynamic in nature, with diverse intermediate states that depend on the time scales of the processes at work. Physical processes describe the essential mechanisms by which the many components on or around a planetary surface can interact and evolve. Many examples of relevant processes could be cited; here we list some illustrative examples for the broad range of settings associated with understanding planetary bodies.

This complex array of interrelated processes must be better understood if we are to correctly identify both the past history and the potential future evolution of diverse planetary bodies. As more is learned about individual and multiple processes active in various settings, it becomes increasingly important to evaluate how processes work together. For example, the dynamics of planetary interiors translates to observable magnetic fields, which in turn directly influence particle interactions around each body. Multidisciplinary comparative investigations of planetary bodies should eventually lead to an integrated understanding of what planetary processes are required to provide a full accounting of how complex planetary bodies evolve.

Investigation 4.1a: Studies of the interiors of planetary bodies.

Interior phenomena include diverse processes such as chemical differentiation, core formation and segregation, mantle dynamics and convection, and heat sources and heat transfer. In the jovian planets, understanding deep interior structure can constrain planet formation. For both rocky and icy worlds, interior evolution is intimately linked to surface and atmospheric evolution, and to habitability. Interior processes operating in icy worlds determine whether habitable oceans might exist within.

Investigation 4.1b: Studies of the surfaces of planetary bodies.

Surface phenomena are affected by processes such as impact cratering, tectonism, volcanism, hydrology, glaciation, and aeolian (wind-surface) interaction. Any particular planetary surface can involve several of these processes, all acting at varying time scales and intensities. Impact cratering may be particularly important to understanding life processes because large impacts can cause major extinctions, intermediate impacts can pose a serious threat to localized life communities, and even relatively small meteoroids might be carriers of organic materials between planets.

Investigation 4.1c: Studies of the atmospheres of planetary bodies.

Atmospheric phenomena include such diverse processes as volatile evolution and loss rate from the planetary body, chemical interactions between the atmosphere and surface materials, particle interactions between the magnetosphere and the upper atmosphere, meteorology, weather and climate.

Investigation 4.1d: Studies of magnetospheric interactions.

Magnetospheres involve electromagnetic processes between particles and fields at many scales, producing interactions with planetary atmospheres and surfaces. Magnetospheric interactions can affect heating, chemistry and loss of atmospheres, and space weathering of surfaces.

Investigation 4.1e: Studies of planetary rings.

Planetary rings involve both constructional and destructional interactions among particles ranging in size from dust to boulders, complex gravitational interactions with neighboring satellites, and magnetospheric interactions. They may provide present-day examples of mechanisms associated with the original accretion of the Solar System.

Decadal Survey mapping:
11. How Do the Processes That Shape the Contemporary Character of Planetary Bodies Operate and Interact?

Goal 5: Determine if there is or ever has been life elsewhere in the solar system

Objective 5.1: Determine if life exists or ever existed on other planetary bodies

As presently understood, the basic requirements for life include liquid water, environments favorable for the assembly of complex organic molecules and metabolically useful energy sources. Because so little is known about the detailed distribution of these requirements within our solar system, exploration logically begins by determining the nature and distribution of potentially habitable environments (i.e., those meeting the basic requirements for life). Earth-based analog studies and theoretical investigations, all informed by data from solar system missions, are crucial activities for helping refine exploration strategies and scientific priorities for future astrobiological missions in the solar system. Research in such widely divergent areas as solar system and planetary evolution, origin of life studies, extremophile biology and microbial paleontology have been instrumental in helping inform NASA about where and how to begin looking for habitable environments, pre-biotic chemistry and life elsewhere in the solar system.

The Viking landers, Pathfinder and now the Spirit and Opportunity rovers provided our initial steps to answering questions of habitability and life. Viking searched (unsuccessfully) for organic compounds in Martian surface samples, and Spirit and Opportunity have returned positive evidence that Mars once had standing bodies of liquid water on its surface. The latter results are enormously encouraging and will inspire future robotic and ultimately human investigations of Mars.

Important next steps in Mars exploration are to: 1) using high spatial and spectral resolution infrared mapping from orbit discover additional deposits of aqueous minerals and sediments on the surface of Mars to guide future surface missions; 2) undertake surface robotic missions to carry out definitive mineralogical, geochemical (including isotopic) and organic analyses of Martian surface materials at high priority sites; 3) probe Martian polar ice deposits to determine whether any organic or even biochemical molecules have been cryopreserved there; 4) investigate the deep subsurface of Mars from orbit and by surface drilling to search for subsurface groundwater; 5) obtain a more thorough understanding of the potential for forward and back-contamination of Mars; 6) carry out the first in situ life detection experiments on the surface of Mars at locations proven to be potentially habitable environments; 7) undertake sample returns from high priority sites to provide definitive life detection studies in Earth-based labs. Significant missions in development involved in this issue include the Mars Science Laboratory, Phoenix and follow-on programs within the Mars exploration program.

Life can be described as a chemical system that links a common property of organic molecules - the ability to undergo spontaneous chemical transformation - with the uncommon property of synthesizing a copy of that system. Biosignatures arise from this fundamental process in a number of ways.

Simplest to understand is that life, even microscopic life, leaves morphological traces of itself in the form of cellular or body fossils. There is presently considerable controversy around the question of the earliest terrestrial microfossils, so continuing research on this topic is very important. Such investigations will guide us as we look for microfossils in the first Mars sample returns expected in the 2010 - 2020 period.

Another type of biosignature derives from the fact that some organic compounds produced by the life process are very stable and can be detected as "molecular fossils”, even in very old rocks. Examples from the Archean fossil record on Earth include hopanes and terpenes preserved in ancient sediments.

Other chemical biosignatures are based on the fact that living systems choose between carbon isotopes when metabolizing single carbon species, such as carbon dioxide. This results in a characteristically "light" ratio of C^{13}/C^{12} compared to inorganic minerals, such as calcium carbonate. Similar patterns occur for sulfur and nitrogen isotopes.

On a global scale, life can move an entire planetary environment away from chemical equilibrium. In the case of the modern Earth, the presence of molecular oxygen arising from oxygenic photosynthesis is a clear indication of the existence of surface life. Oxygens coexistence with methane reflects a dynamic equilibrium mediated by life. The recent observation of methane in the Martian atmosphere is potential example of this type of process elsewhere in our Solar System, and should be given high priority for further investigation.

High resolution images of the surface of Europa, obtained by the Galileo mission fly-bys, have revealed a complexly fractured and largely uncratered surface, where blocks of water ice crust appear to have foundered, tilted and become frozen in the leads between diverging plates of ice. Ice mounds appear to have formed where “volcanic” eruptions of water or ice were sustained at one place for some time. These features suggest the possibility of a kind of “cryo-tectonic” cycle driven by tidal flexing and internal frictional heating, which could maintain a zone of liquid water or a fluid ice-brine mixture beneath the crust up to three times the volume of the Earth’s oceans. The movements of the ice crust would be sustained by density-driven, upward flows of warm water, or ice-brine mixtures from beneath the crust. Where the crust was breached, water or brines erupted and froze out at the surface. This hypothesis is consistent with magnetometer measurements obtained from orbit at Europa (as well as the other icy Galilean satellites, Ganymede and Callisto), which require the presence of conducting brines beneath the surface of these moons. In addition, spectral mapping of the surface of Europa from orbit shows the presence of magnesium salts, supporting the presence of interstitial brines. Additional orbital measurements of Europa’s surface are needed to determine the mineralogical and organic composition of the surface ice and to probe the interior for evidence of a subsurface ocean. In addition, landed robotic missions directed to sites of recent up-flows, are needed to explore for evidence of pre-biotic organic chemistry, potential energy sources for life and biosignatures preserved within surface and subsurface ices.

Titan is a planet-sized moon of Saturn with a dense atmosphere of nitrogen and methane. Over geologic time photochemistry has converted methane and nitrogen into a diverse suite of hydrocarbon and nitrile products, which sediment out onto the surface. We do not know whether these hydrocarbons and nitriles remain on the surface as solids and liquids, or have been gardened into the crust by impact and other geologic processes. Regardless, exposure of any of this material to transient liquid water or ammonia-water would be extremely interesting from the astrobiological viewpoint because synthesis of monomeric, or even polymeric, building blocks of life might be possible. Impacts or internal processes on Titan are capable of creating localized, transient bodies of liquid water or water-ammonia. Determination of the existence and distribution of surface organics on Titan, and evidence for past geologic activity consistent with the melting of the water ice (or ammonia-water) crust, are goals that can be met with the ongoing Cassini explorations during its four year prime mission, though an additional 2-3 years to allow for more Titan flybys would ensure mapping of much of the surface of this diverse world. If merited by Cassini and Huygens probe studies, a follow-on mission to sample organic deposits on Titan's surface could permit the search for and detection of amino acids, peptides, purines/pyrimidines, and other molecules of prebiotic or protobiological interest. Were such to be found on Titan, the notion that life forms wherever salubrious conditions are found would be greatly bolstered.

Investigation 5.1a: Develop reliable, universal methods for the in situ detection and characterization of pre-biotic organic chemistry and biosignatures present in surface and subsurface rocks, soils and ices, over a broad range of conditions that are representative of the extreme environments that exist on other planetary bodies in our Solar System.

Developing methods for the reliable identification of biological and chemical biomarkers is criticially important for this objective. Although considerable progress has been made in recent years, clarification of the nature, preservation potential and interpretation of potential biomarkers is urgently needed. Such methods are needed on Mars, Titan, comets and possibly meteorite parent bodies.

Investigation 5.1b: Explore Mars for potentially habitable environments (past or present) using orbital and surface missions.

Search for surface and subsurface reservoirs of water (in all of its forms), energy sources, mineralogical indicators of past aqueous environments, pre-biotic organic chemistry and biosignatures of fossil or extant life. Use orbital and in situ investigations to create a context for multiple targeted sample returns. This will require support for technology developments needed to pursue both broadly based orbital and in situ surface robotic exploration to search for biosignatures present in surface or subsurface environments.

Investigation 5.1c: Conduct orbital remote sensing of Jupiter's icy moons to test alternative models for the presence of subsurface brines.

Map surface geomorphology and composition at high spatial and spectral resolution in preparation for surface missions that will explore pre-targeted sites for pre-biotic organic chemistry, energy sources and biosignatures preserved in surface/subsurface ices and brines.

Investigation 5.1d: Explore the atmosphere and surface of Titan for environments conducive to complex pre-biotic synthesis and life.

Determine the nature of pre-biotic organic chemistry, energy sources and aqueous environments present and explore for biosignatures in surface materials**.**

References:

Atreya, S.K., Mahaffy, P.R., Niemann, H.B., Wong, M.H., and Owen, T.C. (2003) *Planet. Space Sci.,* 51, 105.

Anders E. (1989) Pre-biotic organic matter from comets and asteroids. *Nature* **342**, 255-257.

Becker L., Poreda R.J., Basu, A.R., Pope K.O., Harrison T.M., Nicholson C., Iasky R. (2004) *Bedout: A possible end-Permian impact crater offshore of northwestern Australia*, Science express, 13 May 2004, DOI: 10.1126/science.1093925.

Beer, J. A. Bilnov, G. Bonani, H. J. Hofmann, and R. C. Finkel, Use of Be-10 in polar ice to trace the 11-year cycle of solar activity, Nature 347, 164, 1990.

Benz, W., Kallenbach, R. and Lugmair, G.W. (Eds.) (2000) *From Dust to Terrestrial Planets*, Space Science Reviews, 92, No. 1-2, 422 pp.

Bernatowicz, T. and Zinner, E. (Eds.) (1997), *The astrophysical implications of the laboratory study of presolar materials,* Amer. Institute of Physics Conf. Proc. Vol. 402, pp.

Blank, J.G., Miller, G.H.,1 Ahrens, M.J. and Winans, R.E. (2001), Experimental Shock Chemistry of Aqueous Amino Acid Solutions and the Cometary Delivery of Prebiotic Compounds. *Origins Life Evol. Biosph.* **31**, 15-51.

Brown, P.; Spalding, R. E.; ReVelle, D. O.; Tagliaferri, E.; Worden, S. P.: The flux of small near-Earth objects colliding with the Earth, Nature 420, 294-296 (2002).

Canup, R.M. and Asphaug, E. (2001) *Nature,* 412, 708-712.

Chambers, J.E. and Cassen, P. (2002) *Meteoritics and Planet. Sci.,* 37, 1523-1540.

Cucinotta, F.A., Manuel, F.K., Jones, J., Izsard, G., Murray, J., Djojenegoro, and Wear, M., Space Radiation and Cataracts in Astronauts. *Radiat. Res.* **156**, 460-466 2001.

Cucinotta, F.A., P. B. Saganti, J. W. Wilson, and L. C. Simonsen, Model predictions and visualization of the particle flux on the surface of Mars, pp. 17, Houston, TX, 2002.

Cuzzi, J.N. and Hogan, R.C. (2003) *Icarus,* 164, 127-138.

Fegley, B. (1999) *Space Sci. Rev*., 90, 239-252.

Fischer, D.A. and Valenti, J.A. (2003) In *Scientific Frontiers in Research on Extrasolar Planets*, ASP Conference Series, Vol 294, D. Deming and S. Seager (Eds.). (San Francisco: ASP) ISBN: 1-58381-141-9, 2003, pp. 117-128

Florinski, V., G. P. Zank and N. V. Pogorelov, Galactic cosmic ray transport in the global heliosphere, J. Geophys. Res., 108, 1228, doi:10.0129/2002JA009695, 2003.

Herrick R. and Pierazzo E. (2003) Results of the Workshop on Impact Cratering: Bridging the Gap Between Modeling and Observations, Lunar and Planetary Institute Contribution No. 1162 (Houston, TX).

Hoppe, P. and Zinner, E. (2000) Presolar dust grains from meteorites and their sources. *JGR* **105,** 10371-10386.

Hubbard, W. B. (2004) *Nature,* 431, 32-33.

Hubbard, W.B., Burrows, A., and Lunine, J.I. (2002) *Annual Rev. Astronomy and Astrophys.,* 40, 103-136,

Inaba, S.; Wetherill, G.W., and Ikoma, M. (2003) *Icarus,* 166, 46-62

Irvine, W.M., Schloerb, F.P., Crovisier, J., Fegley, B., and Mumma, M.J. (2000) In *Protostars and Planets IV*, V. Mannings, A. P. Boss & S. S. Russell (Eds.), pp. 1159-1200, University of Arizona Press.

Lodders, K. (2004) *Astrophys. J.*, 611, 587-597.

Melosh H.J. (1989) *Impact cratering: A Geologic Process,* Oxford Univ. Press, New York, New York.

National Academy of Sciences Space Science Board, HZE Particle Effects in *Manned Space Flight*, National Academy of Sciences U.S.A. Washington D.C., 1973.

National Academy of Sciences, NAS. National Academy of Sciences Space Science Board, Report of the Task Group on the Biological Effects of Space Radiation. Radiation Hazards to Crews on Interplanetary Mission National Academy of Sciences, Washington, D.C., 1997.

Pierazzo, E., and Chyba, C.F. (1999a), Amino Acid Survival in Large Cometary Impacts. *Meteoritics Planet. Sci.* **34**, 909-918.

Peterson, E., Hörz, F. and Chang, S. (1997), Modification of amino acids at shock pressures of 3.5 to 32 GPa. *Geochim. Cosmochim. Acta* **61**, 3937-3950.

Raisbeck, G. M., F. Yiou, D. Bourles, C. Lorius, J. Jouzel, and N. I. Barkov, Evidence for two intervals of enhanced 10Be deposition in Antarctic ice during the last glacial period, Nature, 326, 273-277, 1987.

Rampino M.R. and Haggerty B.M. (1996) Impact crises and mass extinctions: A working hypothesis, in G. Ryder and D. Fastovsky and S. Gartner, Eds., *The Cretaceous--Tertiary event and other catastrophes in Earth history*, Geol. Soc. Am. Special Paper, 11-30.

Report of the Near-Earth Object Science Definition Team (2003), NASA., Stokes, et al.

Sigurdsson, S., Richer, H.B., Hansen, B.M., Stairs, I.H., and Thorsett, S.E. (2003) *Science,* 301, 193-196

Stuart, J. S. and R. P. Binzel (2004), Icarus 170, 295-311

Supulver, K.D., Bridges, F.G., Tiscareno, S., Lievore J., and Lin, D.N.C. (1997) *Icarus,* 129, 539-554.

Tanaka, H., Takeuchi, T. and Ward, W.R. (2002) *Astrophys. J.,* 565, 1257-1274

Toon O.B., Zahnle K., Morrison D., Turco R., Covey C., 1997. Environmental perturbations caused by the impacts of asteroids and comets. *Rev. Geophys.*, **35***,* 41–78.

Wilson, J. W., L. W. Townsend, W. Schimmerling, G. S. Khandelwal, F. Khan, J. E. Nealy, F. A. Cucinotta, L. C. Simonsen, J. W. Norbury, Transport methods and interactions for space radiations, NASA-RP1257, 1991.

Wilson, J. W., J. Miller, A. Konradi, and F

Wüchterl, G., Guillot, T., and Lissauer, J. J. (2000) In *Protostars and Planets IV,* V. Mannings, A. P. Boss, and S. S. Russell (Eds.), pp. 1081-1109, Univ. of Arizona Press.

Youdin, A.N. and Chiang, E.I. (2004) *Astrophys. J.,* 601, 1109-1119.

Zinner E. (2003) *Science,* 300, 265-267.

Zonner, E. (1998). Trends in the study of presolar dust grains from primitive meteorites (Leonard Medal Address) *Meteoritics and Planetary Science* **33**, 549-564.