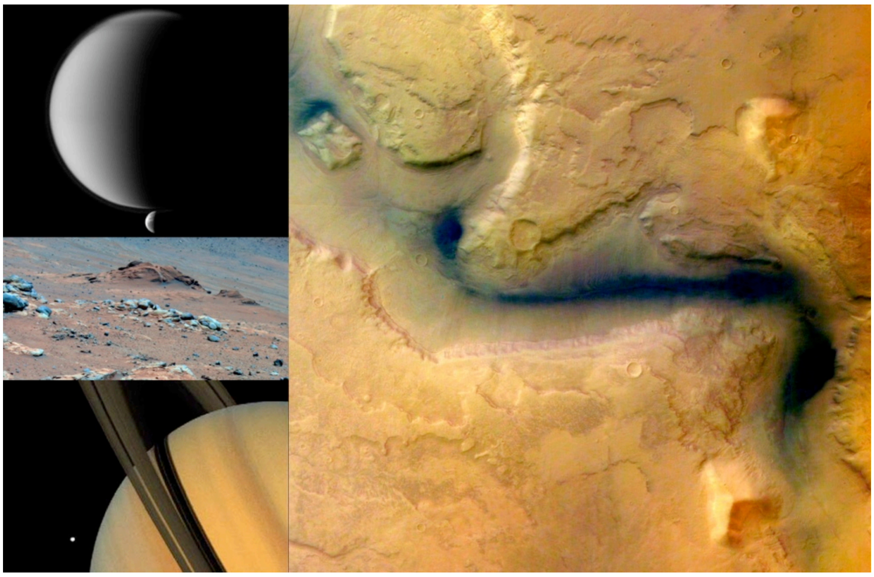
# FUTURE PLANETARY ROBOTIC EXPLORATION: THE NEED FOR INTERNATIONAL COOPERATION



**International Academy of Astronautics**

The International Academy of Astronautics (IAA), an independent nongovernmental organization recognized by the United Nations, was founded in 1960. The purposes of the IAA are to foster the development of astronautics for peaceful purposes, to recognize individuals who have distinguished themselves in areas related to astronautics, and to provide a program through which the membership can contribute to international endeavours and cooperation in the advancement of aerospace activities.



**Study on FUTURE PLANETARY ROBOTIC EXPLORATION: THE NEED FOR INTERNATIONAL COOPERATION**

**Edited by Gregg Vane, J.N. Goswami, Lev Zelenyi, Bernard Foing**

**International Academy of Astronautics**
**6 rue Galilée, Po Box 1268-16,**
**75766 Paris Cedex 16, France**
**www.iaaweb.org**

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# FUTURE PLANETARY ROBOTIC EXPLORATION: THE NEED FOR INTERNATIONAL COOPERATION

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# TABLE OF CONTENTS

# Foreword

I am pleased to welcome the present International Academy of Astronautics (IAA) study that will support discussions during the historic Heads of Space Agencies Summit on November 17, 2010 in Washington DC, USA. Prepared during a record time of one year with an unprecedented support, this study constitutes one of the four pillars of the Summit dialogue.

In addition four successful IAA conferences contributed to the input of the four studies, namely: the Academy Day in Bremen on planetary robotic exploration, the IAA conference in Riga on disaster management, IAA conference in Nagoya on climate change and the Academy Day in Prague on human spaceflight.

I would like to thanks the Study group members who have prepared this study and the Trustees of the Academy who have reviewed it. I would like to particularly thank the Summit Coordinator, Dr. Jean-Michel Contant, IAA Secretary General, who has coordinated these four studies and remarkably secured the 24 Heads of Space Agencies, as of October 1st, 2010.

I would like also to extend my thanks the Co-Chair of the Steering Committee and Summit Program Manager, Mrs. Corinne Jorgenson, President, Advancing Space and the Co-Chair of the Steering Committee, Mrs. Mary Snitch, Director, Lockheed Martin Corporation for their valuable contributions to the studies and Summit preparation.

After 50 years of existence the International Academy of Astronautics is recognized by space agencies as a unique elite body that can help advancing international cooperation. It has been observed that much current cooperation programs are aging such as the International Space Station (ISS) initiated with just a few countries. Many newcomers are joining the club of emerging space countries and more than half of the current space agencies did not exist at the beginning of ISS. The result is a need to enlarge significantly the circle of the current partners for international space cooperation.

The IAA with members from all over the world is engaged in extending the frontiers of knowledge in space exploration and also its applications to solve the day-to-day problems of humankind. Academicians have worked in unison to achieve the set goals of the Academy and it is inspiring to note the many IAA emerging activities. In view of the Summit achieving successful concrete preliminary results, many space agencies have already welcomed the Academy serving as catalyst for years to come with several subsequent implementation meetings and studies.

Gopalan Madhavan Nair
President
International Academy of Astronautics

# EXECUTIVE SUMMARY

Exploration has been a primary focus of space activities since the beginning of the space age in 1957 and before in the dreams and plans of its pioneers. Humans are, by nature, explorers in the fullest sense of the word and are continuing their effort to obtain newer insights into understanding our planetary neighbours, the stars and galaxies in the Universe and our place in the cosmos. Human exploration and robotic scientific exploration have enjoyed equal priority and support in this long-term endeavour. As we move forward in the 21st Century the driving forces for planetary exploration are (1) the search for evidence of extinct or extant life on other bodies in our solar system, and (2) the extension of human life to our nearby planetary neighbours. These ideas and aspirations have become cemented in ever ambitious international space exploration missions beyond low-earth orbit (LEO). The major space-faring nations have developed a framework for humanity's future exploration of space that is known as the *Global Exploration Strategy: The Framework for Cooperation* (2007) [http://esamultimedia.esa.int/docs/GES_Framework_final.pdf] and have developed an action plan to share the strategies and efforts of individual nations so that there is synergy in efforts and all can achieve their exploration goals more effectively. It also highlights the significant social, intellectual and economic benefits that will flow to people on Earth from the investments necessary to realise our ambitious goals, and focuses on the role exploration plays in inspiring young people to think about what they want to achieve in their lives.

## *Case for international cooperation:*

In addition to the scientific quest to increase our knowledge of the origin and evolution of the solar system, and to search for signs of life within it, a major driver related to current exploration plans is the establishment of a permanent human presence outside of low-Earth orbit (LEO). Robotic missions are essential to both these goals. New technologies and capabilities will be required for successful extension of human presence into the solar system and robotic missions will be key proving grounds for them. Many of the new technologies will benefit humanity in other areas here on Earth. A well-planned, integrated international program to leave LEO will involve utilizing the strengths and talents of all participating countries in the most efficient manner. Cooperative scientific and technical planning and implementation is expected to result in significant advancement and sharing of knowledge and increased opportunities for countries with emerging space exploration capabilities to participate at an affordable level. Given the fiscal realities all countries face, an international, cooperative approach increases the likelihood of both mission success and the necessary enduring political support and adequate level of funding to have a vibrant exploration program. In pursuing our common desire to explore, we must work together to overcome our common fiscal, political, and societal hurdles.

## *Planned robotic exploration activities:*

The destinations for planetary exploration are vast. A widely accepted and well coordinated plan that details the science to be pursued, the activities to be undertaken and the technologies required to be developed is necessary to successfully accomplish goals within a larger comprehensive program. Specific contributions from participating countries can support specific individual objectives while at the same time contributing to the larger program. The planning and coordination of a cohesive, integrated plan will define the robotic exploration mission to planets, satellites and primitive bodies such as asteroids in the inner and outer solar system that will enhance our knowledge about origin and evolution of our solar system, paving the way for long-term human exploration of these bodies. International participation will leverage the resources of all nations and maximize the return on each investment in planetary exploration.

## *Challenges and needed R&D solutions:*

Expanding human presence with robotic surrogates and humans themselves beyond LEO presents many challenges that must be overcome. For example, advances in propulsion will be one of the main thrust area to shorten the time required to reach distant destinations to ease the logistics burden and help reduce radiation hazard during human exploration. Advances in space power systems will be required for both the robotic scientific explorers and humans, to meet ever-increasing challenging objectives. Advances in scientific instrumentation will be required to unravel the scientific mysteries we seek to solve, as well as characterize the harsh environments so that suitable technologies can be developed to safeguard human exploration in such environments. The local environments of destinations may also provide resources to be used to support the human missions; our robotic precursor explorers will be challenged to find and characterize those resources. A carefully blended exploration program of robotic and human activities using new technologies will therefore be necessary to overcome the many known as well as unknown challenges.

The following pages of this background paper for the Heads of Space Agencies Summit will cover these topics:

- CHAPTER ONE: Scientific exploration of the solar system - The driving science goals for the coming decades
- CHAPTER TWO: Space weather and the characterization of the space environment - What we can learn from them related to the furtherance of our understanding of the Sun, solar activity and space plasma physics

- CHAPTER THREE: R&D investment in specific areas needed to ensure a meaningful scientific exploration program - The key enabling technologies for the future robotic scientific exploration of the coming decades
- CHAPTER FOUR: Human-mission technology validation - Ways in which our robotic scientific exploration missions could demonstrate some of the capabilities required for the subsequent phase of human presence in space, while meeting their primary objective of advancing basic scientific understanding of the solar system
- CHAPTER FIVE: The case for international cooperation in robotic and human exploration of space beyond low earth orbit, and summary of some key areas where there are opportunities for interested countries to participate at a level consistent with their country's desires and abilities.

# CHAPTER ONE: SCIENTIFIC EXPLORATION OF THE SOLAR SYSTEM

Humans have pondered our place in the universe since before the dawn of civilization. The scientific tools of the $20^{th}$ Century allowed us to answer, at least in broad terms, many of the questions we and our ancestors have asked since these early times. We now know generally that our Universe began with the Big Bang some 14 Ga years ago, and we understand broadly the events that led to the formation of the solar nebula out of which condensed our Sun and other bodies of our solar system about 4.7 Ga years ago, and of course the materials for life on Earth. One driving question remains, and it is perhaps the most profound one of all: Are we alone in the Universe, or is there life elsewhere. The quest to answer this question drives above all else our current scientific exploration of the solar system. The paths to the answer take many directions. Basic questions about the origin and evolution of planetary bodies help us understand the nature of the environments in which life as we know it could have arisen. Thus studies directed at understanding planetary geology, atmospheres, climates on those planets with atmospheres, processes that control the interaction of planetary interiors with their surfaces and with their atmospheres and with the solar wind all play a role in our drive to answer the question "are we alone?" And as our technical capabilities have matured with time, we can now begin to search directly for actual evidence of extinct or even extant life.

The details of scientific robotic exploration of the solar system are tailored to the specific bodies within the solar system. They are defined by specific goals or questions related to those bodies. In general terms, the solar system can be thought of a set of five classes of bodies,:

1. The inner planets, comprised of Mercury, Venus, and the Earth's Moon. They all share a common structure and composition similar to the Earth and therefore offer key insight into the nature of our planet and how it evolved to its current state.

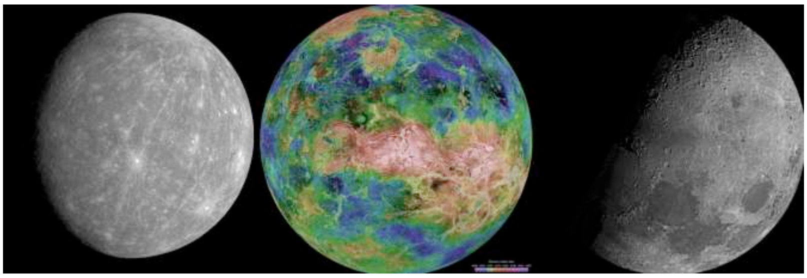
2. Mars, which because of the intensive robotic exploration conducted there over the past twenty years, is a rather special destination. We know more about Mars than any planet other than the Earth. Especially importantly, in the past decade our robotic explorers have confirmed the existence of abundant water ice beneath its surface, and indeed a surface that was itself shaped by liquid water long ago. Mars is hence a prime target for the direct search for evidence of past or current life, and for eventual human exploration and habitation.

3. Giant planets of the outer solar system: Jupiter, Saturn, Neptune and Uranus. Interesting in themselves for what they can reveal about the origin and evolution of

our solar system, they are also local analogs for the many extra-solar planets that have been detected in the past twenty years. Study of them furthers our understanding of our local neighbourhood as well as distant planetary systems.

4. Giant planet satellites. The diverse bodies that orbit the outer planets have their own special place in our quest for understanding our origins and our search for life. The icy water world of Europa, embedded in Jupiter's harsh radiation field, is a prime target. Saturn's Titan, shrouded in a methane atmosphere, is in many ways the most earth-like of the bodies in the solar system and is now known to have an abundance of abiotic organic materials. Even distant Triton, in orbit around Neptune, has been revealed to be active with ice volcanoes that spew materials into space. It joins the active moons Enceladus (at Saturn) and Io (at Jupiter) as one of the small number of bodies in the solar system known to be tectonically active today.
5. Primitive bodies include a diverse collections of objects that includes "local" near-earth objects (NEOs), comets, asteroids, space dust and much further out, the bodies of the Kuiper Belt beyond Pluto and the Oort Cloud beyond that. These objects are generally thought to be reservoirs of the primordial building blocks of our solar system.

Each class of object has its own specific set of goals for scientific exploration. Those goals will drive the nature of our exploration for decades to come. They are summarized below.



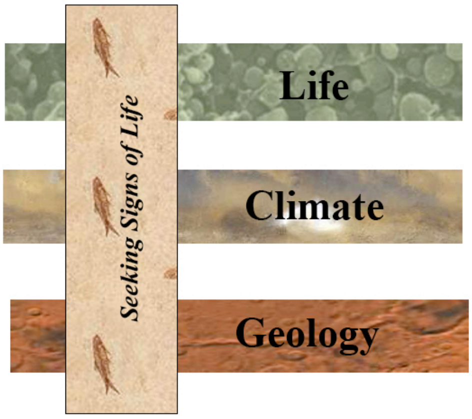
***Inner Planets Science Goals***

| | |
|---|---|
| **1.** | **Understand the origin and diversity of terrestrial planets** |
| | Bulk composition |
| | Interior evolution and differentiation |
| | Geological history of surfaces |
| **2.** | **Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life** |
| | Distribution of volatile chemical species |
| | Effects of internal planetary processes |
| | Effects of processes external to a planet |
| **3.** | **Understand the processes that control climate on the Earth-like planets** |
| | Current climate processes |
| | Climate evolution |
| | Primordial climates |

## Mars Science Goals

A durable set of themes linked first by "Follow the Water" and now by "Seeking Signs of Life".

A series of focused scientific questions emerge from a decade of discovery.

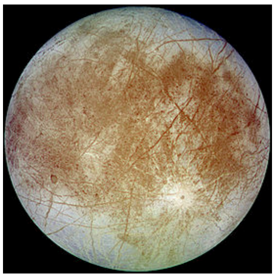
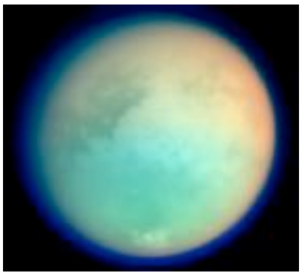
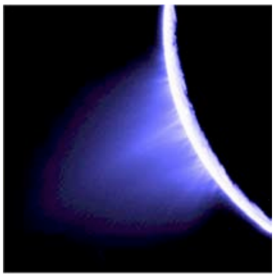



| | |
|---|---|
| **1.** | **Life** |
| | Understand the potential for life elsewhere in the Universe |
| **2.** | **Climate** |
| | Characterize the present and past climate and climate processes |
| **3.** | **Geology** |
| | Understand the geological processes affecting Mars' interior, crust, and surface |

## Giant Planets Science Goals

| | |
|---|---|
| **1.** | **Ground truth for planets around other stars** |
| | Diversity of bulk characteristics, atmospheres, evolution |
| | Planetary extrema |
| **2.** | **Tracers of interplanetary environment** |
| | Energy balance, solar wind and magnetic field interactions |
| | Planetary migration, role in creating earths |
| **3.** | **Laboratories for Earth** |
| | Properties, internal processes |
| | Influence of external processes |

## *Giant Planet Satellites Science Goals*

| | |
|---|---|
| **1.** | **How did the satellites of the outer solar system form and evolve?** |
| | What were conditions during satellite formation? |
| | What determines the abundance and composition of satellite volatiles? |
| | How are satellite thermal and orbital evolution and internal structure related? |
| | What is the diversity of geological activity and how has it changed over time? |
| **2.** | **What processes control the present-day behavior of these bodies?** |
| | How do active endogenic processes contribute to surface-interior exchange |
| | What processes control the composition and dynamics of satellite atmospheres? |
| | What exogenic processes, including atmospheric processes, modify these bodies? |
| | How do satellites influence their own magnetospheres and those of their parent planets? |
| **3.** | **What are the processes that result in habitable environments?** |
| | Where are subsurface bodies of liquid water located, and what are their characteristics? |
| | What are the sources, sinks and evolution of organic material? |
| | What energy sources are available to sustain life? |

## Primitive Bodies Science Goals


| | |
|---|---|
| 1. | **Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere** |
| | Understand presolar processes recorded in the materials of primitive bodies |
| | Study condensation, accretion, and other formative processes in the solar nebula |
| | Determine the effects and timing of secondary processes on primitive bodies |
| | Assess the nature and chronology of planetesimal differentiation |
| 2. | **Understand the role of primitive bodies as building blocks for planets and life** |
| | Determine the composition, origin and primordial distribution of volatiles and organic matter in the solar system |
| | Understand how and when planetesimals were assembled to form planets |
| | Constrain the dynamic evolution of planets by their effects on the distribution of primitive bodies |

# CHAPTER TWO: SPACE WEATHER AND THE CHARACTERIZATION OF THE SPACE ENVIRONMENT

*WHAT WE CAN LEARN FROM THEM RELATED TO THE FURTHERANCE OF OUR UNDERSTANDING OF THE SUN, SOLAR ACTIVITY AND SPACE PLASMA PHYSICS*

Study of the Sun and solar-terrestrial relations is of fundamental importance in solar system astrophysics and sustainability of life on the Earth. The Sun is a typical star among many others in the Universe. However, this is the only star that can be studied in great detail, by observing directly its expanding atmosphere, explosive emission of radiations and particles, magnetic field pervading the whole solar system and the processes taking place in these environments.

The influence of solar activity on the Earth, in other words, space weather, provoking regular perturbation in near-earth space and affecting different spheres of human activity, has become an integral part of everyday life. Observation of solar activity and its influence on the Earth and inner solar system, its short-term and long-term forecasts have become necessary for promotion of safety of human activities either on the Earth or in near earth space and in connection with the proposed manned missions to the Moon, NEOs and Mars. The importance of elaborations and research in this sphere, connected particularly with radiation security of humans during long-duration space voyages, is increasingly becoming an integral part of such projects.

However, there are many fundamental problems in space plasma physics that remain unsolved. Thus circum-terrestrial space, the solar wind and the Earth's magnetosphere become a unique laboratory which allows the conduct of research of key physical processes taking place in collisionless plasma, such as particle acceleration, conversion of magnetic energy into thermal energy of plasma (reconnection of magnetic field), generation of electromagnetic radiation and turbulence.

Space weather is the notion of changing environmental conditions in outer space. It deals with phenomena involving ambient plasma, magnetic fields, radiation and other matter in space. Changing geomagnetic conditions under solar influence can induce changes in atmospheric density causing the rapid degradation of spacecraft altitude in Low Earth Orbit. Geomagnetic storms due to increased solar activity can potentially blind sensors aboard spacecraft, or interfere with on-board electronics. Apart from these concerns for geo-space, an understanding of space environmental conditions is vital for designing shielding and life support systems for manned spacecraft.

In addition to the problems caused to spacecraft by the ultrahigh vacuum and extremes of heat and cold in space, spacecraft also have to survive very hostile environments that can severely limit space missions as well as pose threats to long duration manned mission to moon and Mars. Radiation in ultraviolet, X-ray, and gamma ray regions, energetic charged particles (ranging from kev to tev), plasmas (both high- and low-energy) emanating from the Sun and streaming into the solar system from various stellar sources in our galaxy can cause serious hazard to both spacecraft systems as well as astronauts. Space debris and meteoroids are also a growing cause for concern. Table 1 is an overview of the energy, temporal, and first-order spatial range of major radiation environments in the heliosphere of both solar and galactic origin. Physical or computational models for prediction of these environment and their time variations and related effects is a difficult task.

**Table 1. Major Radiation Environments in the Heliosphere**

| Particle Populations | Energy Range | Temporal Range | Spatial Range (First Order) |
|---|---|---|---|
| Galactic cosmic rays | 0.1–1000 GeV (the 100- to 1000-MeV fluxes constitute the largest contribution) | continuous (factor 10 variation with solar cycle) | entire heliosphere |
| Anomalous cosmic rays | <100 MeV | continuous | entire heliosphere |
| Solar energetic particles | keV–GeV | sporadic (minutes to days) | source region properties (flare/coronal mass ejection (CME) sites and evolution) and bound to CME-driven shock |
| Energetic storm particles | keV to >10 MeV | hours–day | bound to shock |
| Corotating interaction regions (CIR) | keV–MeV | few days (recurrent) | bound to CIR shock and compression region |
| Particles accelerated at planetary bow shocks | keV–MeV | continuous | bound to bow shock |
| Trapped particle populations | tens of keV to a couple of hundreds of MeV (for protons); tens of keV to several MeV (for electrons) | variations "minutes–years" | variations "height–width" |

(Source: http://www.agu.org/journals/sw/swa/news/article/print.php?id=2007SW000361)

In the case of a solar energetic particle (SEP) event, charged particles can propagate to remote sites (e.g., a space ship, a planet's environment) along the magnetic field lines emanating from the site of particle acceleration on the sun. The particle populations listed in Table 1 are all a function of solar activity, though each in their own way. For example, it is well known that the galactic cosmic ray (GCR) flux in the solar system is modulated by the helio-magnetic field. During solar maximum (when sunspot number is at its highest) the increase in the interplanetary magnetic field strength, increases the protection of the heliosphere from penetrating GCR particles. Therefore the GCR population is most intense during solar minimum. On the other hand, SEP events are more frequent during solar maximum. High-speed solar winds dominate during the declining phase of solar maximum. While the effect of these changes is relatively well documented in the circum-terrestrial environment, we only have rudimentary idea of the same in the interplanetary space.

Understanding and predicting the dangers of interplanetary travel is a difficult task which must be resolved for successful long-term exploration of Moon, NEOs and Mars. Further, these close by planetary targets are devoid of internal magnetic field and have no or very little atmospheric cover making it difficult to understand the risks to missions and crew once a spacecraft reaches its destination. Short term ionization increases due to solar radiation (ultraviolet and X-ray) in a planet's atmosphere could also cause telecommunications problems, and may pose a serious issue for well being of human space travelers at a distant planet.

A unified quantitative treatment of all other non-radiation health and technical risks arising during the mission is necessary. In particular, the minimization of the "healthy life span lost" for such a risk criterion appears to be the optimal strategy for mission designers. Presently, countermeasure against radiation risks is simply to provide shielding matter necessary to reduce mission doses to acceptable limits. Even if the levels of exposure could be predicted for a given mission scenario with some confidence, a substantial uncertainty would remain for the prediction of associated health effects. The extent to which these effects might be modified by other factors of the space environment (such as weightlessness) is essentially unknown.

Any trip to the Moon or another planet involves crossing the Earth's radiation belt in addition to being exposed to continuous GCR radiation and hitherto unpredictable sporadic solar flare events. The timing of any interplanetary space mission must take into account the phase of the solar cycle. Spacecraft shielding requirements, including space storm shelters on the spacecraft as well as radiation protection facilities on the target (such as the Moon, near-earth asteroids or a planet), must also be considered. It is therefore necessary to implement onboard forecasting capabilities. The key to understanding radiation protection requires knowledge about the space environment and particle interaction with shielding materials leading to production of secondary radiations. It is a difficult task for scientists to develop physical tools and models that can predict radiation levels in the various domains of space in order to help engineers to design suitable technologies for radiation mitigation for spacecraft and passengers. In particular, the very causes themselves consists of extremely variable individual events such as solar flares, coronal mass ejections etc. making modelling a difficult task. Detail study of space weather is a very important aspect of any long-term planetary exploration scenario and demand very serious application oriented and mission oriented approach.

Understanding local near-Earth space weather capabilities will be critical for the next generation planetary missions. The four main parameters describing any Earth-to-target (e.g., Moon/Mars) scenario are: (1) telecommunications; (2) target's position with respect to Sun and Earth; (3) estimation of SEP event hazards; and (4) target-Earth phasing to minimize travel time. Particle flux profile predictions are highly uncertain when the target is on the opposite side of the Sun with respect to the Earth. The detection of back-sided CMEs (sites of possible SEP events) when, for example, Mars is on the far side of the Sun will require space-based coronograph observations from observatories such as the International Space Station, or from satellites in orbits such as those used in the Solar Terrestrial Relations Observatory (STEREO) mission.

Protecting astronauts from radiation is a key factor for future human space exploration. There are differences between near-Earth space weather and the local space weather on targets elsewhere in our solar system. Knowledge of near-Earth space weather will serve as the template for interplanetary and helio-space weather conditions. It is therefore essential that all space agencies interested in robotics as well as manned planetary exploration initiate targeted projects aimed at understanding near earth space environment during various phases of solar activity through direct observation coupled with analytical approach and develop suitable models to predict space-weather for different level of solar activity both at near earth space, interplanetary space and at target space that will serve as input in planning and realizing fruitful planetary exploration missions.

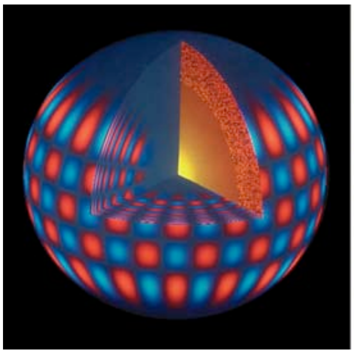
## *Lessons Learned*

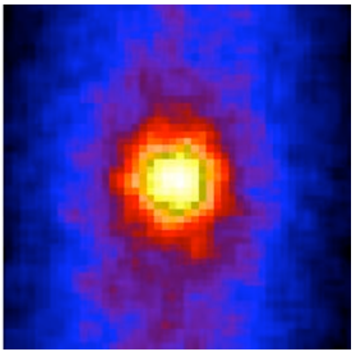
Lessons learned in the study of planetary plasma environments can be applied to our home on Earth, and vise versa, the study of our own magnetosphere and ionosphere supports the exploration of other planets. However certain aspects of space plasma physics are of particular importance for planetary exploration. Ion-neutral interactions between upper atmosphere or gas envelope and magnetospheric or solar wind plasma as well as the role of planetary magnetic field are a critical factors for formation and evolution of planetary atmospheres. Planetary magnetic dynamo operate on the same physical principles as the solar one. Surfaces of small bodies in solar system are for billions years affected by solar wind flow and solar and planetary radiations. On the other hand a billion year history of solar activity is implanted in their upper layers. Finally, safeguarding robotic planetary missions requires development of predictive and forecasting strategies for space environmental hazards. This work will aid in the optimization of habitats, spacecraft, and instrumentation, and for planning mission operation scenarios, ultimately increasing mission productivity. In connection with the forthcoming manned missions to the Moon and Mars, particularly radiation security of crews during space transfers, increases, becoming an integral part of such projects.

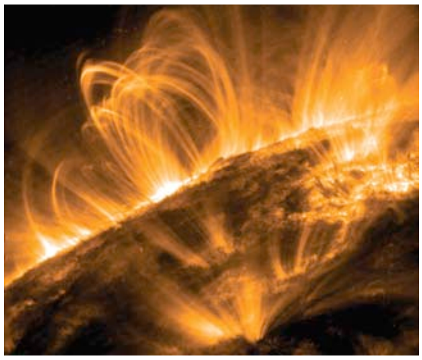
## *Areas for Study*

The pursuit of the knowledge that will be required for safe human travel beyond low Earth orbit falls broadly into five areas: solar physics; the heliosphere and its components; space environments of the earth and other solar system bodies; space weather; and finally, fundamental space plasma physics. A set of goals to motivate our scientific exploration for each area is summarized below.

### *The Sun*

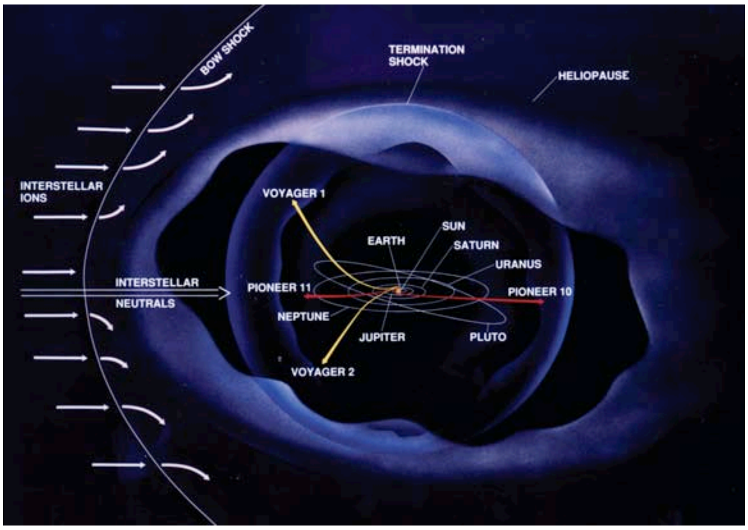






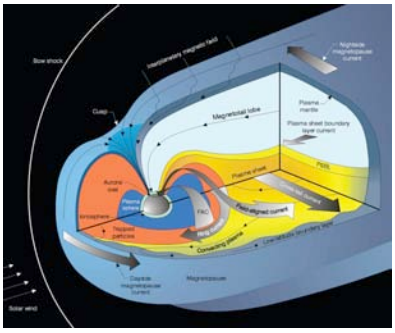
| **Solar Physics** |
|---|
| Explore and understand the activity of our star—the Sun |
| What is the fundamental nature of the solar dynamo and how does it produce the solar cycle? |
| What physical processes are responsible for heating the corona? |
| What are the basic physical mechanisms for, and characteristics of, the acceleration of the fast and slow solar wind? |
| What is the physics of explosive energy release in the solar atmosphere? How are coronal mass ejections (CME), flares, etc are initiated? How and where are solar cosmic rays accelerated? |

### *The Heliosphere*



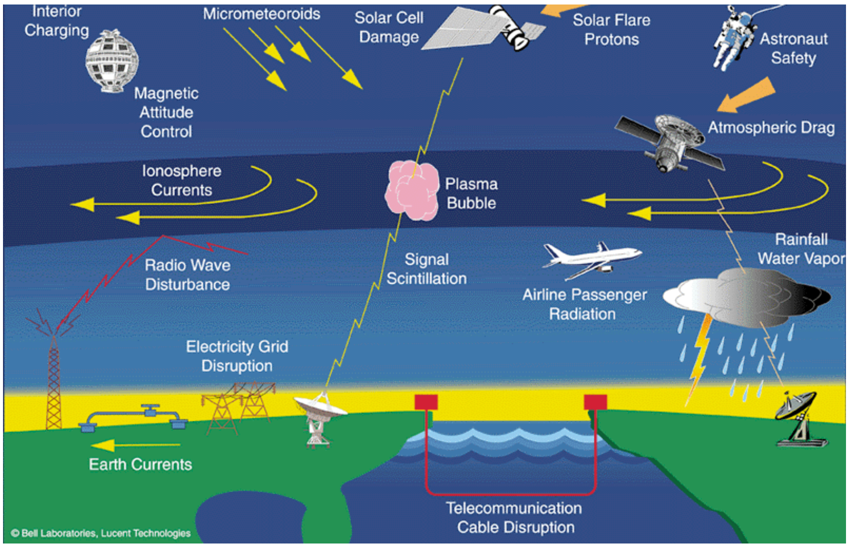

| The Heliosphere and Its Components |
|---|
| Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar plasma with the local interstellar medium. |
| How do coronal structures evolve into solar wind structures of varying speed, density, magnetic field etc ? How do CME-driven disturbances evolve in space and time as they propagate through the heliosphere? |
| How are magnetic field, plasma, neutrals, heavy ions, turbulent fluctuations, solar energetic particles, and galactic cosmic rays distributed throughout the entire heliospheric volume? |
| What is the nature of the local interstellar medium? How do the solar wind plasma and magnetic field interact with it? How and where is the boundary of the heliosphere established? |

### *Space Environments*



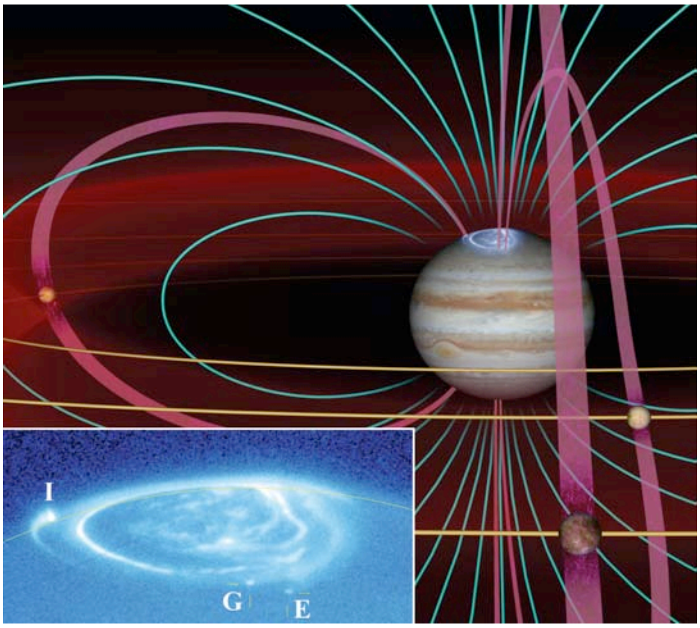
| Space Environments of Earth and Other Solar System Bodies |
|---|
| Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences. |
| How do planetary dynamos function and why do they vary so widely across the solar system? |
| How are mass and energy transferred from the heliosphere to a planetary magnetosphere?<br>How are planetary thermal plasmas accelerated and transported?<br>What are the roles of mass and energy flows in the behavior of planetary magnetospheres? |
| How solar wind and cosmic radiation affect formation and evolution of open planetary surfaces? |
| What governs the coupling of neutral and ionized species?<br>How do coupled middle and upper atmospheres respond to external drivers and to each other? |
| What is the role of solar variability and cosmic radiation in general in evolution of Earth' climate? |

## *Space Weather*




| **Space Weather** |
|---|
| Developing near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in planetary magnetospheres and ionospheres. |
| What measurements need to be made to quantify the effects of space weather? |
| Quantify variability, extremes, and boundary conditions of space weather across the solar system? |
| Develop capability to predict the origin, onset, and level of solar activity, propagation and evolution of solar disturbances, subsequent conditions in any place of solar system |
| What risks does space weather present for human spaceflight outside the protective shield of Earth's magnetosphere? |

## Fundamental Space Plasma Physics




| **Fundamental Space Plasma Physics** |
| --- |
| Understanding the basic physical processes driving solar and space plasmas. |
| What are the fundamental physical processes and topologies of magnetic reconnection? |
| What is the nature and role of turbulence in collisionless plasmas? |
| What are laws of ion-neutral interactions? |
| What are laws of creation and variability of magnetic dynamos? |

# CHAPTER THREE: R&D INVESTMENT IN SPECIFIC AREAS NEEDED TO ENSURE A MEANINGFUL EXPLORATION PROGRAM

*THE KEY ENABLING TECHNOLOGIES FOR THE FUTURE ROBOTIC SCIENTIFIC EXPLORATION OF THE COMING DECADES*

The European Space Agency (ESA), through their Cosmic Vision program, and the US National Aeronautics and Space Agency (NASA), through their Decadal Survey priorities, have agreed to work together for the coming decades on a variety of missions to Mars and the outer planets. Other countries are also providing opportunities for collaborations. During the next two decades many exciting flagship missions are being proposed that will revolutionise the understanding of our solar system, and in particular expand our knowledge of the outer planets, Mars and Venus. Future robotic scientific exploration will lead us to the Europa Jupiter system and the Titan Saturn system. We will bring samples back from Mars and examine the history of Venus. All these missions are high on the international community priority list, and all will require the development of new technologies. In addition to the flagship class missions, there are several likely candidates for NASA's New Frontiers missions, most of which will require some technology development, and similarly for ESA's Cosmic Vision missions. Missions to small bodies, and those which define highly focused scientific goals to specific bodies, such as the moon, asteroids and comets are all under consideration.

In order to identify the key enabling technologies, it is useful to organize them into the five classes of planetary bodies discussed in the chapter on Scientific Exploration. NASA has organized Assessment Groups, such as Mars Exploration Program Analysis Group (MEPAG), Outer Planets Assessment Group (OPAG), Small Bodies Assessment Group (SBAG), Lunar Exploration Analysis Group (LEAG) and Venus Exploration Analysis Group (VEXAG), which are comprised of international members as well as researchers from the US. These groups have studied the needs required by their scientific community and written white papers to indicate which technologies support their priority mission concepts. Their white papers serve as useful references for this document, which summarizes the enabling technologies and identifies the critical technological needs for the upcoming two decades.

## *Outer Planets and Their Satellites*

Beginning at the far reaches of our solar system, the richness and diversity of the outer planets (OP) and their satellites are second to none in the Solar System, but to explore the outer solar system requires advanced technology. The challenges common to all OP missions—large distances, long flight times, and stringent limitations on mass, power, and data rate—mean that all missions can benefit significantly from technical advances in a number of broad areas. Since technology development timescales are long, it is most productive to base technology requirements on the expected general characteristics of future missions. While the Flagship mission concepts are better understood, an estimate of the needs for NASA's competed small class (Discovery) and medium class (New Frontiers) missions, and also ESA's Cosmic Vision missions, can be included in constructing an effective technology plan.

Technology priorities are guided by the requirements established in mission and system studies that are focused on the highest priority science objectives. NASA has decided that it's next OP Flagship mission will be to the Jupiter System, the Europa Jupiter System Mission. The one following that would likely involve orbiting the Saturnian satellites, Titan and Enceladus. The nominal mission concept involves orbiting and *in situ* elements, as confirmed by the science panel for the 2008 Titan Saturn System Mission (TSSM) concept review. *In situ* elements are envisioned to be aerial and landed platforms with sampling capabilities. New Frontiers or small flagship missions that may be realizable in the 2013-2022 timeframe include shallow atmospheric probes of the giant planets and an advanced flyby of an ice giant and its satellites. Subsequent potential OP large-class missions include orbiting Neptune and Uranus, landing on Enceladus and Europa, and probing deep into the atmospheres of the giant planets.

The breadth of technology needed for OP exploration clearly calls for an aggressive and focused technology development strategy that aligns with the recommended mission profile, and includes technologies developed by NASA, ESA and other national space agencies, as well as acquisition of applicable technologies from other government and commercial sectors. Table 1 summarizes the technology priorities for OP exploration. This work is the culmination of a multi-institutional international effort spanning several months.

**Table 1. Technology Priorities for Outer Planet Exploration.**

| | Technology | Priority | Comments |
|---|---|---|---|
| Spacecraft Systems | **Power** | UP | Radioisotope power systems would be needed for the next Titan/Enceladus Flagship mission, requiring a sufficient supply of $^{238}$Pu. Advances in power conversion efficiencies would reduce the quantity of $^{238}$Pu needed for a given power requirement, along with a mass savings. |
| | **Transportation** | 1 | Electric propulsion would be strongly enhancing for most OP missions, including a Titan/Enceladus Flagship, and aerocapture technologies would enable a Neptune orbiter mission. These technologies provide rapid access, increased mass and/or lower mission risk. |
| | **Communications** | 1 | The science return from every mission would benefit from improvements in communications infrastructure, including Ka band and direct-to-Earth communications. *In situ* exploration with orbital assets would be greatly enhanced by improved proximity links. |
| | **Planetary protection** | 2 | New planetary protection approaches and technologies will be required to meet the anticipated requirements for *in situ* exploration to targets of interest for astrobiology. |
| *In Situ* Exploration | **Mobility and landers** | 1 | Access is critical to *in situ* exploration central to a Titan Flagship mission concept, making various types of mobility systems enabling, e.g., Montgolfière balloons for Titan. Advances in autonomous mobility technologies could also provide alternatives for various New Frontiers mission concepts. Landers required with sampling acquisition and handling for Titan lake, dune & cryovolcanic regions. |
| | **Extreme environments** | 1 | The proposed missions span a number of diverse environments; requiring technology advances in fields ranging from low T and P, to high heat flux and pressure during atmospheric entry. *In situ* sampling and instruments would benefit from technology program. |
| | **Entry systems** | 2 | New propulsive landing systems would enable operations on satellites without atmospheres. Investments required in key technologies for entry systems and planetary probes: extreme environment systems, miniaturized and low power integrated sensors, transmitters, and avionics, thermal materials, power management systems, entry/descent/landing technologies & on-board processing. |
| Instruments | ***In situ* instrument systems** | 1 | New technologies and instruments would be required for improved science return to targets of astrobiological interest, enabling the proposed Titan/Enceladus Flagship mission. The instrument technologies would require associated development in sample acquisition and handling systems. Advances in thermal management are critical. Instruments required for Atmospheric probe missions. |
| | **Components and miniaturization** | 1 | Every mission is either strongly enhanced or enabled by improvements in miniaturization and advanced component design. A Titan/Enceladus Flagship mission would be strongly enhanced by development of miniature long-lived, low power cryogenic electronics. |
| | **Remote sensing instrument systems** | 2 | All missions with orbital or extended aerial operations would be strongly enhanced by improved technologies for passive and active remote sensing and radio science. High resolution and sensitivity instruments that are low in mass and power are required for a Titan/Enceladus Flagship. |

UP Ultimate priority—Without new Pu-238, no further exploration beyond Jupiter will occur subsequent to EJSM.
1 Highest priority—New developments are required for all or most future OP missions.
2 High priority—Either the applications are more limited or NASA could effectively leverage existing work.

The recommendations to enable this exploration are:

1. Within the US, NASA should work with the relevant agencies within the US to ensure availability of Pu-238 for future outer planet missions. In particular, NASA should flight-qualify ASRG power systems.

2. NASA, ESA and other agencies need to initiate a technology program for the next Outer Planet (OP) Flagship mission after EJSM to be ready for a launch in the mid-2020s. Current planning indicates a mission to Titan and Enceladus will be the highest priority and funding is required for development of the Montgolfière balloon, the autonomy required to operate it at Titan, landing technologies required for sampling the high latitude lakes, dunes and cryo-volcanic regions and components operable in extreme environments. In addition, it is critical to initiate a program in cryogenic sample acquisition and sample handling.

3. It is necessary to expand the communication and radio science technologies required for the outer planets, especially making Ka band operational and furthering proximity and direct-to-Earth communication technologies.

4. Agencies should continue development of underlying technologies (thrusters, power and control, propulsion technologies) for solar electric propulsion, to bring these systems to flight readiness and to make the capability affordable to and within the risk postures of different mission classes.

5. Agencies should invest in aerocapture technologies and conduct a space-flight validation of aerocapture in advance of the decision points of identified missions.

6. For probes into planetary atmospheres, development of alternative thermal protection systems (TPS) materials, and periodic limited manufacturing and testing demonstrations to ensure that heritage TPS manufacturing is kept current, are required.

7. Agencies should achieve a better balance between component development, *in situ* and remote sensing (active and passive) scientific instrument definition and development, with a focus on demonstrating complete instrument *systems* and bridging the technology readiness gap from concept to flight. An OP instrument program should focus on developing and maturing low mass and low power instrument systems that have high resolution and sensitivity, raising the Technology Readiness Level (TRL) to $\geq$6.

**Table 2. Summary of Technologies required for Outer Planet Missions**

| Technology Development | Missions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Titan Orbiter *In Situ* Sampler | Neptune Orbiter | Neptune Flyby to KBO Flyby | Uranus Orbiter | Saturn Probe | Jupiter Probe | Neptune Probe | Enceladus Sample Return | Europa Lander |
| **Power** | | | | | | | | | |
| RPS | E | E | E | E | e | e | *E | E | e |
| Low intensity, low temperature solar arrays | | | | e | e | e | | | |
| **Transportation** | | | | | | | | | |
| Electric propulsion | e | E | e | e | e | | e | e | |
| Aerocapture | | E | | E | | | | | |
| **Communications** | | | | | | | | | |
| Expanded Ka capability | e | e | e | e | | | e | | e |
| Improved proximity links | e | | | | e | e | e | e | e |
| Improved UHF systems | e | | | | E | e | E | e | e |
| **Planetary protection measures** | e | | | | | | | e | e |
| **Mobility and Landers** | E | | | | | | | | e |
| **Autonomy** | e | | | | | | | E | E |
| **Extreme environments** | e | | | | e | e | e | e | E |
| **Entry systems (includes TPS)** | e | E | | e | e | E | E | E | E |
| **Planetary probe S/C technologies** | | | | | e | e | E | | |
| ***In situ* sensing of surface and atmospheres** | E | | | | e | E | E | E | E |
| **Components and miniaturization** | E | e | e | e | e | e | E | E | E |
| **Remote sensing** | e | e | e | e | e | e | e | e | e |

Legend: E = enabling, e= enhancing (reduces cost and/or risk, increases performance) Spacecraft Systems); *need RPS or radio science for carrier-relay spacecraft that delivers probe.

A new internationally focused technology effort should ensure readiness for launch of a mission to Titan and Enceladus in mid-2020s. Further, technologies that require long-term investment for missions beyond the next decade should also be developed. Table 2 shows a summary of the technologies required for specific example missions.

## *Mars*

Moving closer to home, the Mars science community has discussed a number of candidate strategic missions as important options for future Mars exploration. The intent here is to provide concise information regarding enabling technologies for the following candidate missions: a Mars Net Lander Mission, and missions associated with a Mars Sample Return (MSR) campaign of three launches including Mars Astrobiology Explorer-Cacher (MAX-C), MSR fetch rover and MSR orbiter.

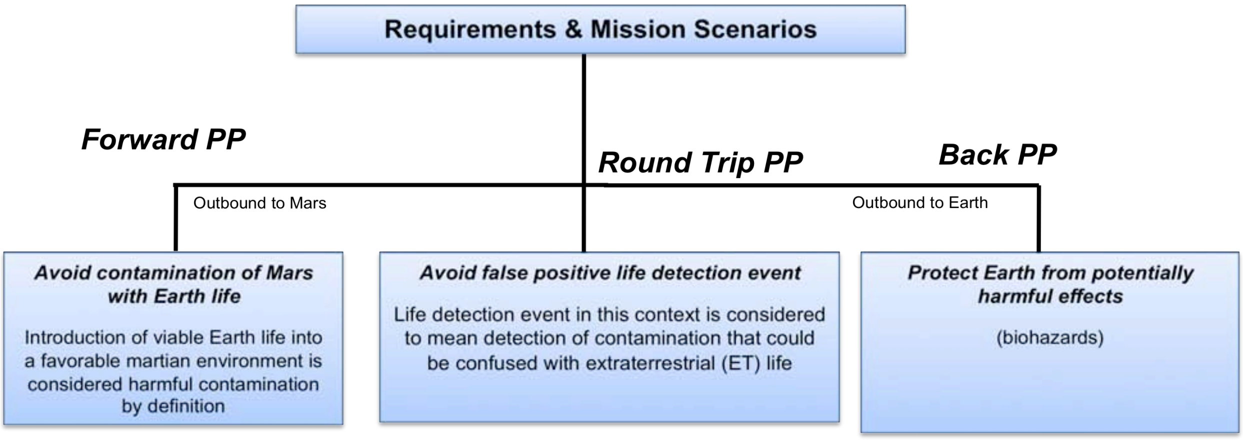
The most challenging technologies, defined as *key* technologies that require *significant* development include sample acquisition and encapsulation (MAX-C), Mars ascent vehicle (MSR Lander) and back planetary protection (MSR orbiter). Other key challenges for the elements of the Mars sample return mission are the round trip planetary protection (MAX-C), mobility capability (MAX-C and MSR fetch rover), terrain-relative descent navigation (MAX-C and MSR Lander) and rendezvous and sample capture (MSR orbiter).

**Table 3: Enabling technologies for the candidate missions**

| TGM | Net Landers | MAX-C | MSR-Lander | MSR-Orbiter |
|---|---|---|---|---|
| No new enabling technologies would be needed | Technologies depend on mission architecture and would require further study | Entry Descent & Landing: precision landing and hazard avoidance | MAV | Rendezvous and sample capture |
| | | Sample acquisition and handling | Back PP | Back PP |
| | | Rover technologies: faster traverse | Low-mass, low-power avionics for fetch rover | Earth Entry Vehicle (EEV) |
| | | Avoidance of Earth organisms in returned samples (round trip PP) | | EEV and Mars Returned Sample Handling (MRSH) |

Some of the technology challenges associated with a potential MSR campaign would be particularly difficult. These include the Mars Ascent Vehicle (MAV); sample acquisition and handling; and back planetary protection (Back PP). MAV, in particular, stands out as the development system with highest risk, pointing to the need for an early start to complete trade-study analysis, retire component technology risks, and develop and flight-test a flight-like engineering unit in a relevant environment before an MSR Lander (MSR-L) PDR. MAV target requirements are to launch a 5kg Orbiting Sample (OS) into 500+/-100 km orbit, +/-0.2deg, have the ability to launch from +/- 30$^{o}$ latitudes, provide continuous telemetry for critical event coverage during ascent and survive relevant environment for Earth-Mars Transit, EDL, and Mars surface environment for up to one Earth year on Mars. The MAV is a critical part of the MSR mission concept. Although there is extensive terrestrial experience and knowledge in rocket engineering, the US has never launched an unmanned rocket from a planetary surface. To date, no engineering MAV unit has been developed, thus the MAV as a system is at a very low TRL. Development of the MAV would require sustained funding and management over a decade or more. The component technologies would need to be at TRL 6 and ready for integration into a flight test unit 7–8 years prior to launch.

Planetary protection requirements can be subdivided into three areas as shown below.




Back planetary protection deals with the need to assure containment of all returned Martian samples, as well as flight hardware that has been exposed to Martian material, until they could be tested for possible biohazards. The potential biohazard risk has led to a requirement that samples returned from Mars by spacecraft should be treated as though potentially hazardous until proven otherwise. Back planetary protection would require new technologies for three high-level functions: break the chain of contact with Mars; preserve containment of the sample; and assess sample safety. Back planetary protection technologies would be required for the proposed MSR-L, MSR Orbiter (MSR-O), and the Sample Receiving Facility (SRF).

MSR is a restricted Earth return mission with a goal of $<10^{-6}$ chance of inadvertent release of an unsterilized >0.2 micron Mars particle. Subsystem requirements are to break-the-chain of contact with Mars, which involves delivering a “Mars contained” OS to a Containment Vessel (CV), assure the OS does not “leak” and mitigate ascent and orbiter dust. The sample container protection must provide reliable delivery to Earth entry corridor utilizing a robust Earth Entry Vehicle (EEV), assure containment at impact and maximize OS, CV, and EEV meteoroid protection. All samples must be quarantined in specialized sample handling facility and application of a test protocol to assess safety prior to release. In order to verify the probabilities, we need to update and improve models for Probabilistic Risk Analysis (PRA) to measure the capability to meet the goal.

Other key challenges are:

1. The round trip planetary protection (MAX-C) where the objective is to avoid false positive life detection. The approach to mitigating this is to clean the assemblies, provide a bio-barrier, and develop analytical tool to compute overall probability of contamination.
2. Mobility capability (MAX-C and MSR fetch rover). In this case we need to increase the average rover speed and develop lighter/smaller motor controller by using FPGAs as co-processors and developing distributed motor control.
3. Terrain-relative descent navigation (MAX-C and MSR Lander) to improve landing robustness. The approach is to use terrain-relative navigation for avoiding landing hazards by leveraging the NASA ALHAT project.
4. Rendezvous and sample capture (MSR orbiter) in order to locate, track, rendezvous, and capture OS in Mars orbit. To accomplish this we need to update the system design, develop testbeds, and perform tests and leverage Orbital Express capability.
5. In situ Instruments. The network lander concept mission might require heat flow probes and atmospheric trace gas detectors. Furthermore, depending on the mission architecture, some existing instruments would have to be ruggedized. For the MAX-C concept mission, the 2-D in situ micro-mapping instruments would need development, especially for mineralogy and organic detection.

## *Inner Planets*

Much science can be done on the surface of Venus and within its atmosphere using existing technology. For example, the pressure vessel, passive thermal control, and insulation for short–lived landers (designed for five to ten hours operation on the surface), as well as technologies for mid–altitude balloons are considered to be mature. These technologies will enable Discovery, New Frontiers and Cosmic Vision-class scientific missions. Similarly, spacecraft technologies for Venus orbiting missions are largely in hand.

However, moving beyond the science that be achieved with today's mission capabilities will require longer duration survival on the surface, access to the most rugged terrain, and surface mobility. The next step in Venus exploration therefore will require development of several key new technologies. To assess the needed technologies, NASA recently completed a Venus Flagship Mission study, which identified key technologies required to implement its Design Reference Mission. The highest priority technologies and capabilities for the Venus Design Reference Mission are: surface sample acquisition and handling; mechanical implementation of a rotating pressure vessel; a rugged–terrain landing system; and a large scale environmental test chamber to test these technologies under relevant

Venus–like conditions. Other longer–term Venus Flagship Mission options will require additional new capabilities, such as a Venus–specific Radioisotope Power System; active refrigeration; high temperature electronics; advanced thermal insulation; and high temperature motors and actuators developed for sample acquisition system. The capability to test and validate scientific measurements and to assess the survivability of all exposed sensors/instruments and lander components in Venus–like environment is critical to the mission success. This testing capability is not available and needs to be developed.

### *Primitive Bodies*

For primitive bodies such as comets and asteroids, the technologies required relate to the type of object studied and the mission scenario that enables the discoveries. For NEO Sampling, we need deployable assets (e.g., penetrators, rovers) for microgravity environments. Technologies for Main Belt asteroid and Trojan investigations center on propulsion, telecom, sensing and landing packages, proximity operations, and sampling mechanisms. The strategy for comet exploration involves a strong technology development program that can enable sampling from depth in the nucleus, improved in situ analysis, and the return of nucleus material to Earth. Improvements should be developed in spacecraft power systems, propulsion technologies, and low power, lightweight instruments, including those that probe structure of the nucleus. The exploration strategy for the Ice Dwarf Planets would hasten development of mission-enabling technology in areas similar to the outer planet technology recommendations: Electric power - Advanced Stirling Radioisotope Generators (ASRGs), $^{238}$Pu production; Navigation - long distance ranging, autonomous GN&C; Low mass flight systems and instruments and maintaining very deep space communications capabilities. Centaurs and TNOs missions require improved power systems for outer solar system trips. Nuclear power would facilitate multi-object missions. Lastly, Interplanetary Dust investigations require development of technologies for IDP collection and analysis and instruments that can monitor and accurately measure the zodiacal light.

## *In Summary*

In summary, the technologies required vary considerably with mission destination, with the critical items being development of power and propulsion systems that can take our experiments to the far reaches of the solar system; development of capabilities to ensure Mars samples can be returned to Earth safely; and in situ technologies that can enable experiments on Titan, Venus, small bodies and eventually Europa. Aerocapture and planetary probe technologies also need to be advanced in order to provide a wider range of mission concepts to the scientific community.

Although none of the community assessment groups have highlighted the need to re-develop nuclear reactors for space applications, it is clear that this is an alternative path in the event that $^{238}$Pu production is not immediately forthcoming. Small nuclear fission reactors, using $^{235}$U rather than $^{238}$Pu are feasible for many robotic missions and recent developments in thermoelectric technology should allow simpler and more mass-efficient design. Use of such a reactor could enable more capable missions and allow use of electric propulsion at extreme solar distances, which could facilitates rendezvous and orbit insertion and possibly increase delivered mass for many missions. In addition, it could obviate the need for gravity assists to outer planets and provide frequent launch opportunities. Nuclear thermal propulsion, using hydrogen as the working fluid, is also being considered for the manned mission to Mars and if we see robotic exploration as a first step toward combined human-robotic exploration then the development of high Isp, high thrust propulsion is also required.

At this point in time, there is broad enthusiasm for international collaboration and now may be the right to time to generate a globally coherent technology plan. Such a plan would benefit all the space agencies as well as the member countries in planning their future technology investments.

# CHAPTER FOUR: HUMAN-MISSION TECHNOLOGY VALIDATION

*WAYS IN WHICH OUR ROBOTIC SCIENTIFIC EXPLORATION MISSIONS COULD DEMONSTRATE SOME OF THE CAPABILITIES REQUIRED FOR THE SUBSEQUENT PHASE OF HUMAN PRESENCE IN SPACE, WHILE MEETING THEIR PRIMARY OBJECTIVE OF ADVANCING BASIC SCIENTIFIC UNDERSTANDING OF THE SOLAR SYSTEM*

Inasmuch as human exploration of the solar system over the coming few decades will be limited to destinations such as the Moon, near-Earth objects (NEOs) and to Mars, we limit our discussion of the potential synergies between robotic and human missions to those destinations. The scientific drivers for the robotic exploration of the Moon, Mars and NEOs were summarized in Chapter One. Now we turn our attention to some examples of how our robotic scientific missions could further the goals of the human exploration program through acquisition of knowledge of the environments in which humans will have to survive and operate, and through the validation of technologies and exploration techniques of relevance to both the robotic and the human missions of the future.

## *Moon-Mars-NEO robotic exploration before humans: knowledge, reconnaissance and technology*

The robotic exploration of the Moon, asteroids and Mars can prepare for human missions with various phases: surface and sub-surface exploration; assessment of potential hazards, toxicity and biohazards; and demonstration of key capabilities (in situ resource utilization – ISRU; and entry, descent and landing - EDL). Development of major capabilities required for human exploration can also leverage off of robotic precursor exploration: Expanding Moon, Mars and inner solar system communication infrastructure; human habitation and operations validation on the Moon; site selection for robotic outposts.

A global repository and tools need to be developed for data archival, distribution, and analysis across the different missions. Space environment studies can be performed through robotic scientific missions and used to establish state of the art knowledge and needs for long term human exploration.

International collaborations should include the discussion of effective coordinate systems, standards (protocol, interface, spacecraft bus, interoperability), coordination benefits and models, information exchange and cooperation tools, development of robotic deployment of human precursors, and robotic assistants to human missions. An inventory of technology developments and a network for possible technical collaborations should be in place for all stakeholders.

Terrestrial analogue field campaigns are essential for demonstrating technologies, research goals, science, human-robotic interactions, and aspects of human operations. Analog studies in extreme environments provide a unique opportunity to foster collaboration between the Earth science and space exploration communities and engaging the public, space agencies, media, and educators. International cooperation in such activities is also a logical first step to implementing international Moon-Mars missions.

## *Robotics and human exploration of the Moon, Mars and near-Earth asteroids*

A sequence of technology, exploration and commercial missions needs to be defined on the road to long term human presence in space. A comprehensive series of lunar missions including polar orbiters and landers and network missions could be a key element of a comprehensive plan. Robotic engineering precursors for in-situ resource utilization and deployment of infrastructures at selected landing sites are pre-requisite for preparing for human-tended operations.

Martian surface network missions in coordination with orbital assets are essential for the study of Mars interior, atmospheric dynamics and climate, as noted earlier. Exploration of the Martian moons Phobos and Deimos, and using them as a gateway for Mars exploration should to be considered. This could lead to a Mars global robotic ensemble or colony that could support not only scientific exploration but also prepare for human Mars exploration.

A similar approach for deploying surface elements on a diversity of selected NEOs and main belt asteroids to study the diversity of small bodies and prepare for future human missions for exploration and resource utilisation of these bodies will be an obvious candidate for coordinated international efforts.

## *International sample return missions from the Moon, asteroids and Mars*

The analytical precision and accuracy obtainable in modern Earth-based laboratories exceeds that of any in-situ instrument onboard spacecraft due in part to limited resources of power and sample preparation, and to the ability to miniaturize the required scientific instruments. Therefore many robotic lunar sample return options have been evaluated in the last decade to return samples from locations on the Moon that were not accessed by the

Apollo astronauts, and take them into terrestrial laboratories to perform a full suite of investigations such as mineralogical, lithological, geochemical and geo-chronological analyses that are not possible to conduct in-situ. We shall learn by returning samples from large impact basins about the ancient history of the Moon and its relationship to Earth during the early era of solar system formation, about the early and late heavy asteroid bombardments of the Moon.

The analysis of returned samples from Mars to terrestrial state-of-the-art laboratories can answer questions about life, climate, and geology. Human exploration of Mars is probably decades away but it will eventually lead to completion of a detailed study of the planet Mars, leading in the end to a new understanding of the evolution of the solar system and the origin and evolution of life,

Moon, Mars and NEO Sample Return Missions can advance readiness and reduce the risk for future human mission by demonstrating scaled versions of key technologies.

## *International Moon and Mars bases and deep space stations*

A recent ESA-NASA architecture study offered a unique possibility to discuss the requirements and implementation aspects of human lunar exploration missions by sharing capabilities. Scenarios have been investigated using stand-alone capabilities (Automated Lunar Cargo Landing System; Communication and Navigation Systems); development of crew transportation architecture elements such as human crew transportation to LEO including human-rated launch vehicle and crew transportation vehicle; orbital infrastructures (low orbiting lunar station); and development of dedicated lunar surface exploration elements including pressurized rovers and surface habitation modules.

A sensible long-term exploration roadmap will envision that robots and humans should explore in synergistic partnership.

An international lunar base design requires the knowledge of many different disciplines, e.g. engineers, architects, industrial designers and medical personnel. ILEWG and LEAG have worked together for a decade on concepts for a lunar base as an important milestone in their roadmap. The participants of ICEUM10/ LEAG/ Space Resources Roundtable in 2008 addressed relevant key questions (see ICEUM10 Cape Canaveral declaration 2008, and presentations online at http://sci.esa.int/iceum10) that can be extended to Mars, NEOs and other destinations:

- What technologies need to be developed now for human return to the Moon (and beyond)?

- What are the critical elements for robotic development, habitats and hazard prevention?
- What is the current state of ISRU development?
- What are logical architectures and open implementation to allow effective integration of international elements?
- What opportunities are afforded within the current architecture for commercial on-ramps and how can these be facilitated?
- What are the needs/advantages of robotic missions for advancing science and benefiting human exploration?
- What technology developments in robotic exploration are being conducted by various countries and agencies?
- How can human-robotic partnerships be used to develop and build a long-term presence on the Moon? What are the sub-surface drilling challenges on planetary surfaces and how can they be addressed?
- How can future lunar surface activities be optimised?
- What precursor lunar surface experiments are of highest priority for space settlement/ commercial development?

### *Recommendations for human /robotic exploration and Earth-Moon-Mars synergies*

As proposed by several space agencies and reports, the scientific study of the Moon, Mars and Near Earth Objects should be treated as an integral part of an overall solar system science program, including strong relations with Earth science, technologies and applications. Planetary exploration calls for the development of an integrated human/robotic science strategy. The Moon is an excellent place to develop capabilities for minimally contaminating equipment, facilities, and human support, as well as capabilities that will be required for future exploration. Robotic exploration experience gained in Lunar robotic exploration and investments made to enable it can be adapted towards robotic exploration of near-Earth destinations. They in turn can then support the preparation for human missions.

The exploration of the inner solar system in robotic/human synergy should lead to outstanding scientific discoveries, strategic partnerships, technology progress, and inspiration for the public stakeholder. Broad national engagement of all stakeholders (government, scientific community, industry, public) will be required to create a global exploration platform.

The robotic exploration allows national space agencies to engage the public at effective cost by showing results and discoveries from frequent missions, by linking to fundamental questions, by showing the positive role of science, technology and space exploration for society.  Also robotic missions allow a continuous programme for continuous build up of workforce, with acceptable development time scales providing challenges, education opportunities, ownership and fostering experience for exploration and innovation that are needed for the sustainable development of our knowledge-based society.

# CHAPTER FIVE: THE CASE FOR INTERNATIONAL COOPERATION IN ROBOTIC AND HUMAN EXPLORATION OF SPACE BEYOND LOW EARTH ORBIT

*The case for international cooperation in robotic and human exploration of space beyond low earth orbit, and summary of some key areas where there are opportunities for interested countries to participate at a level consistent with their country's desires and abilities*

As has been elucidated in the previous chapters, international cooperation in robotic and human exploration of space beyond low Earth orbit is now ingrained in the thinking and actions of most if not all of the space agencies of the world that are capable of contributing to such an adventure. This is a very important shift since, until 1992, when the Presidents of the USA and Russia agreed to cooperate in space exploration, exploration of space both robotically and especially with humans was considered a strategic asset that defined the technical and scientific achievements of a country as part of a larger goal to win the hearts and minds of non-aligned nations. The period from 1957 to 1992 was one of great discoveries and adventures covering all five classes outlined in chapter one – inner planets, Mars, giant planets, satellites of the giant planets and primitive bodies. The Soviet exploration of Venus, the many successes and failures relating to Mars including the two successful US Viking probes to Mars, the Voyager missions to the outer planets and moons, and, the incredible Apollo missions are some of the highlights of this period.

Although the 1992 agreement was a watershed that led to the 1993 accord to construct an international space station, a very important precursor to this event was the success of the international collaborative program between the space agencies of the Soviet Union, the United States of America, Europe and Japan that was created to coordinate various national (or, in the case of Europe, multi-national) scientific missions to comet Halley in 1985. The success of this cooperation, formalised through an Inter-Agency Consultative Group (IACG) created in 1981, especially the sharing of information to maximise the data gathering from all partner missions, provided the confidence that larger cooperative space exploration programs could be considered.

A more recent success of an international mission to the outer planets and their moons is the NASA – ESA – Italian Space Agency (ASI) joint mission to Saturn and its moon, Titan, named Cassini-Huygens. This is an excellent example of both the challenges of international partnerships and the importance of them in ensuring success. Cassini-Huygens was conceived in 1982, launched in 1997 and entered orbit around Saturn in 2004. It had to undergo a number of near-termination measures and political turmoil but, ultimately succeeded because it was an international collaboration. This model has been successfully adopted in current scenarios relating to the future exploration of Mars and, potentially, another joint mission to the outer planets, as described in more detail below.

Recently, a number of countries have developed and flown indigenous missions to the moon. This includes the USA (NASA), Europe (ESA), Japan (JAXA), China (CNSA) and India (ISRO). While all have been successful, have established independent capabilities in exploration technologies and science, and have included, at least in part, some international collaboration through the sharing of instruments, they have, overall, been notable by and large by the lack of collaboration at the planning and mission level that has meant that the scientific return has perhaps been less than might have been achieved had a closer relationship been established between the agencies as was experienced during the comet Halley and Cassini-Huygens programs noted above.

Throughout the last decade, a number of informal international space exploration working groups have been established open to all parties interested in exploration of both specific bodies (e.g., International Mars Exploration Working Group (IMEWG), International Lunar Exploration Working Group (ILEWG), and Mars Exploration Program Analysis Group (MEPAG) (NASA)), and with wider purviews (e.g., Planetary Exploration Committee (PEX) (COSPAR), Human Exploration Study Group (IAA), and Space Exploration Committee (IAF)). An important development in 2006 that arose out of the excellent work from the above mentioned informal groups saw 14 space agencies come together to more formally discuss global interests in space exploration. This culminated in the elaboration of a vision for peaceful robotic and human space exploration focussing on destinations within the solar system where humans may one day live and work. These common exploration themes were articulated in a document entitled *The Global Exploration Strategy: The Framework for Coordination* [http://esamultimedia.esa.int/docs/GES_Framework_final.pdf] that was released in May 2007. A key finding of the Framework Document is the need to establish a voluntary, non-binding, international coordination mechanism through which individual agencies may exchange information regarding interests, objectives and plans in space exploration with the goal of strengthening both individual exploration programs as well as the collective effort. The coordination mechanism is now called the International Space Exploration Coordination Group (ISECG) [http://www.globalspaceexploration.org/]. ISECG produces annual reports that describe key coordination activities between the partners as well as highlights of Space Agency Exploration Activities.

## *POTENTIAL AREAS FOR INTERNATIONAL COLLABORATION*

As noted, most nations now consider space exploration as an international, collaborative endeavour. This is as much guided by fiscal realities as by altruistic considerations. Sending sophisticated probes to solar system bodies and, especially, contemplating sending humans beyond low-Earth orbit is mostly beyond the means of any one nation, although exceptions still apply to robotic missions to near-Earth objects. The impetus for international collaboration has recently been boosted by statements made by the leaders of the United States space program who have publically embraced the policy of exploring space through international partnerships, especially in relation to human exploration. The experience with the International Space Station (ISS) has provided significant knowledge and confidence in working on a multilateral level on such complex and challenging programs. While the ISS model has some limitations, it has proven to be a success in terms of achieving its goals, albeit over a much longer timeframe and with a much larger budget than was originally predicted – lessons that will no doubt be applied to future similar enterprises.

In returning to the list of classes of bodies outlined in chapter one, the following is a synopsis of current and future international collaborative opportunities realising that each nation will make its own assessment of possibilities based on interests and capabilities.

### Inner Planets:

Recent probes to Mercury, Venus and especially the Earth's Moon have revealed many insights into the history and composition of these bodies. However, fascinating questions still remain. In most instances, these bodies are still amenable to robotic missions developed by single nations, although multi-national programs where spacecraft of different nations combine to create a complementary study, e.g. the joint ESA-JAXA BepiColombo mission to Mercury, can provide significant advantages. Of particular interest is the future of lunar exploration, especially given the recent armada of international spacecraft that have recently probed this body (see above). Most if not all of the nations who have flown recent missions to the Moon are planning future robotic investigations, many centred on the volatiles trapped in the Moon's polar regions. An international coordination of these missions currently in the planning stage would have many advantages, although, so far, this remains elusive.

With respect to human exploration of the inner planets, until recently, the Moon has been the centre of attention. With the change of direction by the United States, however, other scenarios are being considered, at least by the USA and its partners. China has publically expressed interest in developing a program to land a Chinese taikonaut on the Moon within the next 15 years and a recent meeting between the Presidents of China and the USA called for "a dialogue on human space flight and space exploration, based on the principles of transparency, reciprocity and mutual benefit."

## Mars:

The exploration of this fascinating planet continues to be one of the most important goals for most space-faring nations. Recent probes have uncovered a wealth of information on the origin, composition and volatility of this body but many fundamental questions still remain unanswered, especially with respect to extinct or extant life. The major thrust with respect to robotic exploration is concentrated on a future international sample return mission or missions in order to bring back pristine samples to sophisticated laboratories on Earth for detailed and exhaustive analysis. While many individual nations are developing plans to send probes to the Mars system in the next decade, including the Russia probe Phobos-Grunt currently planned to be launched in 2011/12, recently, the United States and Europe have made a landmark pronouncement by agreeing to collaborate on their Mars exploration programs focussing on the 2016 and 2018 launch opportunities as precursors to a proposed sample return mission in the early to mid 2020s. The projected cost of a Mars sample return mission leads to the expectation that an international approach will be developed to achieve this goal, possibly through a continuation of the NASA-ESA accord, the ISECG or an offshoot of this approach.

Human missions to Mars are still too far away to seriously contemplate formal agreements between partners, however, informal discussions relating to the development of enabling technologies for a future international human mission to the red planet is a potential area ripe for consideration.

## Giant planets and their satellites:

The success of the Cassini-Huygens mission, noted above, has led to discussions between NASA and ESA to consider a follow-on flagship mission to either Jupiter, Europa and Ganymede, or to return to Saturn and Titan. As noted in chapter one, other planets and moons in the Jupiter-Saturn-Uranus-Neptune region remain largely unexplored although fascinating in their own right, however, given the attention to other exploration targets as noted in this section, it is considered unlikely that a concerted international effort beyond the NASA-ESA potential collaboration noted above will be supported in the near future.

## Primitive bodies:

Missions to comets and asteroids are of great interest to planetary scientists given the interest in understanding the origin of our solar system. Several missions have already been launched including the comet Halley probes mentioned above, Galileo, Near Earth Asteroid Rendezvous (NEAR), Deep Space 1, Stardust, Deep Impact, Hayabusa, Rosetta and Dawn. One of these missions had successfully returned material from the coma of comet Temple-2, and other mission is attempting to bring back pristine samples from asteroid Itokawa for analysis on the Earth. However, the technical challenges are, so far, proving taxing. These missions remain, for the most part, amenable to the resources of single space agencies (principally NASA, ESA, and JAXA), however, a coordinated approach could provide significant benefits in terms of contingencies and duplication.

Of recent interest are the considerations by the US in relation to asteroids as a possible primary destination for future human missions. If this results in a firm decision it would be expected that a number of robotic missions to characterise in detail potential targets would be developed by the partners involved in this next stage of human exploration.

## *CONCLUSION*

Exploration of the Solar System will continue to be a primary thrust of the major space-faring nations for the foreseeable future. Although missions over the past fifty years have given us a new vision of the Solar System, there is much more to learn. Missions to all areas of the Solar System except those beyond Neptune (with the exception of the New Horizons mission to Pluto and the Kuiper Belt) are either in progress or being planned, and most are open to potential international collaboration. Recent changes to the program of the United States have lessened the focus on the Moon as a destination for future human missions and opened up new possibilities. Such an adventure will certainly be developed with international partnerships. Details as to how such partnerships will be formalised still remain to be defined. However, the recent formation of the International Space Exploration Coordination Group that includes all space-faring nations with strong capabilities in space exploration provides a possible framework for such collaboration.

**International Academy of Astronautics**

**Future Planetary Robotic Exploration:**
**The Need for International Cooperation**

## Appendix 1

## Contributors

Chairs:
- Gregg Vane, USA
- J.N. Goswami, India
- Lev Zelenyi, Russia

Rapporteur(s):
- Bernard Foing, France

Members:
- Patricia Beauchamp, USA
- Anil Bhardwaj, India
- Andrea Boese, Germany
- Catherine A. Conley, USA
- Brian Duffy, USA
- James Green, USA
- Giancarlo Genta, Italy
- Scott Hovarter, USA
- Junichiro Kawaguchi, Japan
- David J. W. Kendall, Canada
- Vitaly Lopota, Russia
- Francis Rocard, France
- Rafael Rodrigo, Spain
- Ji Wu, China

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# Appendix 2

## Heads of Space Agencies Summit

**Heads of Space Agencies Summit**

**November 17, 2010, Washington DC, USA.**

This year the International Academy of Astronautics (IAA) marks its 50th Anniversary since its founding in Stockholm. In the past five decades, the Academy has brought together the world's leading experts in disciplines of astronautics on a regular basis to recognize the accomplishments of their peers, to explore and debate cutting-edge issues in space research and technology, and to provide direction and guidance in the non-military uses of space and the ongoing exploration of the solar system.

The 50th Anniversary of the IAA has been recognized and celebrated throughout the second half of the year with a series of symposia around the globe, and culminating with a Heads of Space Agencies Summit on November 17, 2010 at the Ronald Reagan Building and International Trade Center in Washington DC.

After 50 years of existence the International Academy of Astronautics is recognized by space agencies as a unique elite body that can help advancing international cooperation. It has been observed that much current cooperation programs are aging such as the International Space Station (ISS) initiated with just a few countries.

The world is flattening as many newcomers are joining the club of emerging space countries. In the meantime the major space countries face budgetary challenges and politicians as well as decision-makers face competing priorities. In addition, the USA and Russia can no longer exclusively taxi the growing international space community to low Earth orbit. The result is a need to enlarge significantly the circle of the current partners for international space cooperation.

A consensus widely recognized is that future global challenges can only be solved by international cooperation with all countries committed to work together. However space agencies have to balance new aspirations with constraints of existing programs/budgets and national interests/needs. The large number of new players brings the question: how to efficiently cooperate while the number of partners significantly increases? Confidence, trust, transparency, best practice sharing will have to be the key points for reducing impediments while promoting a safe and responsible use of space. It is anticipated that the ISS experience will be used to leverage new cooperation.

To serve as the foundation for discussion among the Summiteers, four IAA study groups composed of renowned international experts in climate change/green systems; disaster management/natural hazards; human spaceflight and planetary robotic exploration have been assembled and have published these studies and recommendations for deliberation by agencies. This is a historic and unique event as not only 24 Heads of Space Agencies have confirmed their participation in the Summit as of October 1$^{st}$, 2010, but also the IAA has thorough studies that support their discussions and provide background expert documentation.

**International Academy of Astronautics**

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# Appendix 3

# IAA in Brief

**International Academy of Astronautics**

**A Brief Description**

**Founded:** 16 August 1960, Stockholm, Sweden by Theodore Von Karman. The IAA became an independent organization in 1983 and a nongovernmental organization recognized by the United Nations in 1996. President: Dr. Madhavan Nair, India, Past President: Prof. Edward C. Stone, USA, Vice-Presidents: Mr. Yannick d'Escatha, France, Prof. Hiroki Matsuo, Japan, Dr. Stanislav Konyukhov, Ukraine, Prof. Liu Jiyuan, China, Secretary General: Dr. Jean-Michel Contant, France.

**Aims:** Foster the development of astronautics for peaceful purposes; recognize individuals who have distinguished themselves in a related branch of science or technology; provide a program through which members may contribute to international endeavours; cooperation in the advancement of aerospace science.

**Structure**: Regular Meeting, Board of Trustees, four Sections: Basic Sciences, Engineering Sciences, Life Sciences and Social Sciences.

**Activitie**s: Encourage international scientific cooperation through scientific symposia and meetings and the work of specialized Study Groups and Program Committees coordinated by six Commissions: on Space Physical Sciences, D. Baker (USA), on Space Life Sciences, P. Graef (Germany), on Space Technology and System Development, J. Mankins (USA), on Space Systems, Operations and Utilization, A. Ginati (Germany), on Space Policies, Law and Economics, S. Camacho (Mexico) and on Space and Society, Culture and Education, P. Swan (USA). A major initiative of the Academy is the development of a series of "Cosmic Studies" and Position Papers dealing with the many aspects of international cooperation (see http://iaaweb.org/content/view/229/356/).

**Events**: Establishment of cooperation with national academies in UK (2008), Sweden (1985), Austria (1986, 1993), France (1988, 2001), Finland (1988), India (1990, 2007), Spain (1989), Germany (1990), Netherlands (1990, 1999), Canada (1991), U.SA (1992, 2002), the U.S. National Academy of Engineering (1992, 2002), Israel (1994), Norway (1995), China (1996), Italy (1997), Australia (1998), Brazil (2000), the U.S. National Institute of Medicine (2002), Czech Republic (2010).

**Publications**: Acta Astronautica (monthly) published in English; IAA e-Newsletter; Proceedings of Symposia, Yearbook, Dictionaries and CD-ROM in 24 languages.

**Members**: 1243 Members and Corresponding Members in four Trustee Sections and Honorary Members in 89 countries.

**Mailing Address**: IAA, PO Box 1268-16, F-75766 Paris Cedex 16, France
Secretariat: 6 rue Galilée, 75116 Paris, France,
IAA Study Center in Beijing, China; IAA Secretariat Branch in Bangalore, India,
35 Regional Secretaries in all continents (see http://iaaweb.org/content/view/139/238/)

**Web Site**: http://www.iaaweb.org
Phone: 33 1 47 23 82 15, Fax: 33 1 47 23 82 16, email: sgeneral@iaamail.org