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Review

Toward a global space exploration program: A stepping stone approach

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Abstract

In response to the growing importance of space exploration in future planning, the Committee on Space Research (COSPAR) Panel on Exploration (PEX) was chartered to provide independent scientific advice to support the development of exploration programs and to safeguard the potential scientific assets of solar system objects. In this report, PEX elaborates a stepwise approach to achieve a new level of space cooperation that can help develop world-wide capabilities in space science and exploration and support a transition that will lead to a global space exploration program. The proposed stepping stones are intended to transcend cross-cultural barriers, leading to the development of technical interfaces and shared legal frameworks and fostering coordination and cooperation on a broad front. Input for this report was drawn from expertise provided by COSPAR Associates within the international community and via the contacts they maintain in various scientific entities. The report provides a summary and synthesis of science roadmaps and recommendations for planetary exploration produced by many national and international working groups, aiming to encourage and exploit synergies among similar programs. While science and technology represent the core and, often, the drivers for space exploration, several other disciplines and their stakeholders (Earth science, space law, and others) should be more robustly interlinked and involved than they have been to date. The report argues that a shared vision is crucial to this linkage, and to providing a direction that enables new countries and stakeholders to join and engage in the overall space exploration effort. Building a basic space technology capacity within a wider range of countries, ensuring new actors in space act responsibly, and increasing public awareness and engagement are concrete steps that can provide a broader interest in space exploration, worldwide, and build a solid basis for program sustainability. By engaging developing countries and emerging space nations in an international space exploration program, it will be possible to create *a critical bottom-up support structure* to support program continuity in the development and execution of future global space exploration frameworks. With a focus on stepping stones, COSPAR can support a global space exploration program that stimulates scientists in current and emerging space-faring nations, and that will invite those in developing countries to participate—pursuing research aimed at answering outstanding questions about the origins and evolution of our solar system and life on Earth (and possibly elsewhere). COSPAR, in cooperation with

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national and international science foundations and space-related organizations, will advocate this stepping stone approach to enhance future cooperative space exploration efforts.

Keywords: Space exploration; Planetary protection; International cooperation

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Contents

1. Executive summary

Space exploration is a multifaceted endeavor and a “grand challenge” of the 21st century. The political agendas of a growing number of nations highlight space exploration as a goal and frame it as an international cooperative adventure. In response to the growing importance of space exploration, the objectives of the COSPAR Panel on Exploration (PEX) are to provide high quality, independent science input to support the development of a global space exploration program while working to safeguard the scientific assets of solar system bodies.

Science roadmaps and recommendations for planetary exploration have been produced by an acronym-rich array of national and international working groups. These include IAA Cosmic Studies and reports by the US NRC, IAA, IAF, ILEWG, ESSC, LEAG, and MEPAG. Such studies highlight the most compelling aspects of fundamental and applied scientific imperatives related to the exploration of the Moon, Mars, and small bodies of the solar system, and together they comprise a touchstone for space exploration that can enable architectural studies for robotic and human exploration.

Several nations are currently engaging in, or planning for, space exploration programs that target the Moon, Mars and near-Earth asteroids, and propose voyages of exploration for robots and humans alike. These journeys can provide answers to some of the most fundamental scientific and philosophical questions – “How did our solar system and home planet form?” “Does life exist beyond the Earth?” and “What are the potential opportunities for humanity in our local space environment?” A shared scientific vision, grounded in these fundamental questions and focused on the theme of “Origins and evolution of our solar system and life,” has the power to unite space exploration stakeholders, challenge scientists, and capture the public imagination. With such a vision in hand, the science community can guide and accelerate the progress of robotic and human space exploration and share the benefits that these activities confer to society.

Building a new space infrastructure, transport systems, and space probes and creating a sustainable long-term space exploration program will require international cooperation. Accordingly, it will be essential to address the question “How can the established space community cooperate on a truly international level while engaging newly emerging spacefaring nations in meaningful ways?” The COSPAR Panel on Exploration proposes a stepwise approach to creating effective and efficient partnerships for future space exploration.

The following elements provide stepping stones along a pathway to help make a shared vision for space exploration a reality:

- Extreme environments on Earth can pose conditions analogous to those at potential landing/operation sites on the Moon and Mars. Expertise obtained from Earth-based field research campaigns, worldwide, should be exploited to generate a coordinated international exploration testbed. Such expeditions will allow different stakeholders (space and Earth scientists, engineers, entrepreneurs, journalists, etc.) from various cultures to advance related space exploration science and technology by working together to further mutual goals.
- The ISS is the best example of international cooperation in space exploration to date and represents a major milestone that will shape future international space partnerships, for exploration in particular. This achievement should be capitalized upon by ensuring the science exploitation of the ISS enabling exploration, during its extended lifetime. This activity would use recently integrated facilities and enhanced crew capabilities to advance our knowledge of living and working at LEO and beyond.
- As a means of effecting worldwide collaboration on small missions, an international CubeSat program in support of exploration can act as a model that could enable a new generation of light-weight, low-cost nanosatellites, suitable for “piggyback rides” to Moon and Mars. An international CubeSat program would be particularly interesting for less-advantaged partners, such as small space agencies and developing countries.

- In preparation for larger endeavors, a system-of-systems approach with small exploration missions, e.g., small orbiters and landers, as described in the Global Robotic Village concept of ILEWG, can initiate and enhance additional international collaborations, as well as science, commercial and public engagement opportunities.
- Robotic sample return missions from the Moon, near-Earth asteroids, and Mars have the highest priority for the science community. Such complex space missions will be much more affordable when conducted cooperatively, allowing worldwide expertise to be applied. Multi-element sample return mission scenarios, implemented by the major space powers, provide opportunities for emerging countries to contribute either payloads or manpower for a joint mission. Dedicated curation facilities, constructed and maintained within an international framework, can also foster extensive science and engineering collaborations.
- A multinational consortium based on the Antarctic model could be formed as an organizational approach to coordinating the development and operation of national and international space outposts, whether on the Moon, on Mars, or elsewhere in the solar system.

These stepping stones can transcend cross-cultural barriers, leading to the development of technical interfaces and shared legal frameworks and fostering coordination and cooperation on a broad front. Such advances can address scientific and technical prerequisites and provide a foundation for the creation of a successful global space exploration program. The long-term sustainability of a global space exploration program will benefit from the participation and support of a broader community outside of the current space industry, including their financial and logistical support, and the inclusion of the public through a variety of measures targeted at a non-specialist audience.

In cooperation with national and international science foundations and space-related organizations, COSPAR should adopt and advocate this stepping stone approach to prepare for future cooperative space exploration efforts. The involvement of existing, emerging, and developing space nations in such endeavors will both strengthen existing partnerships and foster new ones and bolster capacity building. COSPAR should promote the development of synergistic science programs with open data access, ensure retention of its leadership role in providing requirements for responsible space exploration, and support efforts to exploit synergies between Earth science and space exploration.

While science and technology are the heart, and often the drivers for space exploration activities, other stakeholder communities should be more robustly integrated and involved than they have been to date. Long-term planning and development of major space architectures for exploration can only succeed when all stakeholders: governments, space agencies, the commercial space sector, space entrepreneurs, and the public can work toward common, or at least compatible, goals at national and international levels.

A shared vision of how to proceed and progress on these stepping stones can be the basis for a successful global space exploration program. Science has the power to act as a bridge between spacefaring nations and other stakeholders and the ability to engage society and promote participation while delivering direct benefits to the public. An interchange of scientific insights can lead to the development of new, common exploration policies and the training of a new space generation that can sustain space exploration over decades.

PEX, working with COSPAR Scientific Commissions and Panels, and with the international science foundations, the IAA, IAF, UN, and the IISL, will support science-driven national and international space exploration working groups as well as space agency groups such as ISECG that assist in the analysis and implementation of possible architectures in the new era of planetary exploration. COSPAR's input, as gathered by PEX, will be intended to express the consensus view of the international scientific community and should ultimately provide a series of guidelines to support future space exploration activities and cooperative efforts, leading to outstanding scientific discoveries, opportunities for innovation, strategic partnerships, technology progress, and inspiration for people of all ages and cultures worldwide.

> "***All truths are easy to understand once they are discovered; the point is to discover them.*" *Galileo Galilei (1564–1642)***

2. Vision for the robotic and human scientific exploration of the Earth–Moon–Mars space

In this section we compile highlights from the science roadmaps and recommendations for planetary exploration from International Academy of Astronautics (IAA) reports, National Research Council (NRC) reports, the International Lunar Exploration Working Group (ILEWG), the Lunar Exploration Analysis Group (LEAG) and the Mars Exploration Program Analysis Group (MEPAG) to create and exploit synergies between similar programs of national and international science working groups. The excellent science documents/roadmaps prepared by the afore-mentioned science and analysis working groups allow us to summarize compelling scientific imperatives that can be used to provide vision for space exploration and context for architectural studies for robotic and human exploration of the Earth–Moon–Mars space (see also Appendix B).

The content of several roadmaps, discussed below, includes elements of both applied and fundamental science. While science and technology represent the core and, often, the drivers for space exploration activities, several other disciplines (such as Earth science, the legal sector, humanities, etc.) and their stakeholders should be more robustly interlinked and involved (Ehrenfreund and Peter, 2009). A shared vision is thus crucial to provide direction that enables new countries and stakeholders to join and engage in an overall effort supported by the public.

In 2007 the "*Global Exploration Strategy* (*GES*)*: The Framework for Cooperation*" was released as the first product of an international coordination process among fourteen space agencies (GES, 2007). The International Space Exploration Coordination Group (ISECG) has been created to implement and coordinate the GES. ISECG supports the analysis and implementation of possible space exploration architectures in the new era of planetary exploration. In theme 1: "*New Knowledge in Science and Technology*" the GES acknowledges that systematic, science-driven space exploration reveals fundamental truths about the history of the solar system and the origin and nature of life and that both robotic and human exploration are necessary to answer the key questions.

The European Space Sciences Committee (ESSC) released in 2009 the "*Science-Driven Scenario for Space Exploration*" which defined overarching scientific goals for Europe's exploration program, dubbed "*Emergence and co-evolution of life with its planetary environments*", focusing on those targets that can ultimately be reached by humans, *i.e.,* Mars, the Moon, and Near-Earth Objects (NEOs).

A NEO technological demonstration mission was recommended as well as the active participation in a lunar robotic exploration program. Mars was recognized as the main exploration target and a Mars Sample Return (MSR) mission as the primary goal. The report also addressed human exploration and stressed that "manned missions to Mars are expected to increase public awareness of science and expand funding and activities in many related scientific and technological field. This will lead to an increase in scientific knowledge and an expansion in the economy at a global level". Furthermore the report clearly states that Europe should position itself as a major actor in defining and leading a Mars Sample Return mission (ESSC 2009). In the following the consensus view of the international scientific community as summarized by IAA and US NRC reports, ILEWG, LEAG and MEPAG is presented:

2.1. IAA Cosmic Study 2004 "Next Steps in Exploring Deep Space"

In 2004 the Cosmic Study undertaken by the IAA summarized a new vision for the "*Next Steps in Exploring Deep Space*" (Huntress et al., 2004). The study defined four key destinations as the most important targets: the Moon, Libration Points (gravitationally balanced locations that are ideal for maintaining spacecraft, telescopes, etc.) such as the one located away from the Sun and behind the Earth that is called "SEL2", Near-Earth Objects (NEOs) and the planet Mars. The following overarching science questions were defined as:

- Where did we come from?
- What will happen to us in the future?
- Are we alone in the Universe?

Investigations of the terrestrial planet environment allow us to gain knowledge on the formation and early history of our solar system. Investigating the Earth–Moon–Mars space, including NEOs, may answer long-standing questions about the origin and future destiny of the human race. In order to understand the origin of the Earth–Moon system and the processes on the young Earth that led to the origin of life, the Moon is a priceless target to be investigated with robots and humans.

The Moon and Lagrange points provide a unique platform to study the origins of our Universe and the formation of planetary systems. Investigating the physical properties and chemical processes on small bodies provides us with a glimpse into the earliest periods of our solar system. Mars, which has been extensively investigated for water and its mineralogy in the past, is the prime target in our solar system for discovering evidence of extinct life and possibly extant biosignatures. Any science breakthroughs on the search for life on Mars will have a strong impact on all future exploration missions.

Current missions that are planned to explore the Earth–Moon–Mars space in the next decade include lunar orbiters and landers, sample return missions to the Moon, Phobos, NEOs and Mars, as well as orbiters, landers and rovers to explore the martian atmosphere, surface and subsurface, (see national roadmaps of the main spacefaring nations listed in Appendix A).

For its 50th anniversary the International Academy of Astronautics (IAA) prepared positions papers for the "Space Agency Summit" in November 2010 including reports on robotic exploration (IAA, 2010a) and on Human Spaceflight (IAA, 2010b). These papers sought to reach a broad consensus on international cooperation in order to consider new concrete initiatives.

2.2. US NRC Planetary Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013–2022"

The US NRC Planetary Decadal Survey is asked once each decade to prioritize NASA planetary science goals. The Committee on the Planetary Science Decadal Survey that was established to write the most recent report "*Vision and Voyages for Planetary Science in the Decade 2013–2022*" determined the current state of knowledge and identified the most important scientific questions for the coming decade. The report released in March 2011 presented a decadal program of science and exploration with the potential to yield revolutionary new discoveries (NRC, 2011a). The basic motivations for planetary science were summarized into three broad, crosscutting themes:

- Building new worlds—understanding solar system beginnings.
- Planetary habitats—searching for the requirements for life.
- Workings of solar systems—revealing planetary processes through time.

In order to help develop recommendations, the committee commissioned technical studies of many candidate missions. These candidate missions were selected for study largely on the basis of white papers submitted by the scientific community.

The committee devoted considerable attention to the relative priorities of the various large-class mission candidates. The Mars community, in their inputs to the Decadal Survey, was emphatic in their view that a sample return mission is the logical next step in Mars exploration. Therefore the highest priority Flagship mission recommended for the decade 2013–2022 is a mission to cache samples that will begin the NASA–ESA Mars Sample Return campaign. As second highest priority Flagship mission a first in-depth exploration of Jupiter's icy moon Europa has been identified. The Uranus Orbiter and Probe mission was selected as third highest priority Flagship mission as an important next step in the exploration of the giant planets. The NRC committee recommended that NASA's suite of planetary missions for the decade 2013–2022 should consist of a balanced mix of Discovery, New Frontiers, and Flagship missions, enabling both a steady stream of new discoveries and the capability to address larger challenges like sample return missions and outer planet exploration.

3. Destination: Moon

The Moon is a valuable and crucial target for planetary science: it represents a window through which to explore the origin of our solar system and the Earth–Moon system. Created by a destructive impact to Earth in the early history of our solar system, the Moon provides a unique platform to search for clues about the conditions of the primitive solar nebula and the formation of terrestrial planets.

In the early history of solar system formation, some 3.9 billion years ago, the destabilized solar nebula disk caused a massive delivery of planetesimals to the inner solar system. This so-called Late Heavy Bombardment (LHB) phase was likely triggered by rapid migration of giant planets. As a consequence numerous small bodies including comets and asteroids and their fragments (meteorites and Interplanetary Dust Particles) impacted on young planets (Gomes et al., 2005). The bombardment record is uniquely revealed by the Moon (see Fig. 1), as the early record has been erased on Earth by plate tectonics and erosion. Evidence for water on the Moon was recently provided by four different spacecraft (Lunar Prospector, Chandrayaan-1, Lunar CRater Observation and Sensing Satellite LCROSS, and the Lunar Reconnaissance Orbiter LRO). Investigating the distribution of water on the Moon and searching for embedded molecules in polar ice deposits are exciting yet challenging avenues to pursue. Understanding the formation of the Moon, its internal structure and environment, and the impact history of the inner solar system are of particular importance in reconstructing the details of processes that occurred in the early solar system, and to shed light on the origin of life on Earth.

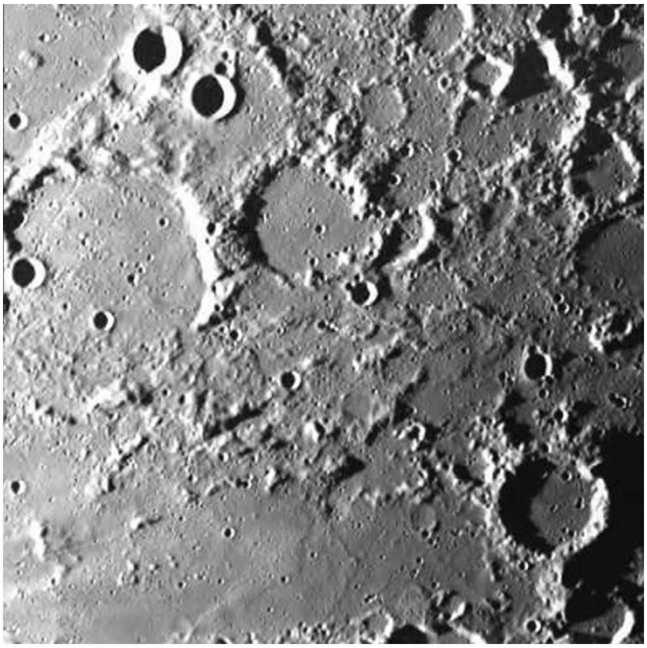

Fig. 1. One of the first images taken by the AMIE instrument (clear filter) onboard SMART-1 in December 2004 shows an area of the Moon featuring the Mouchez crater near to lunar zero longitude. Illumination variations were monitored over polar regions during the mission. *Image Credit: ESA/SMART-1/Space-X, Space Exploration Institute.*

3.1. Results from recent Moon missions

Since the US Apollo and Soviet Union Luna missions, spacecraft from various countries were sent to the Moon (see Neal, 2009, for more details). However, after the last Soviet lunar lander in 1976 (Luna 24 – a robotic sample return mission from Mare Crisium), no new science missions were sent to the Moon until the US Clementine (launched 25 January 1994; Nozette et al., 1994) and Lunar Prospector (launched 7 January 1998; Binder, 1998) orbital missions. These missions produced the most comprehensive lunar data sets to date, highlights of which include:

- Tantalizing data that supported the presence of H or H_2O deposits at the lunar poles (Nozette et al., 1996; Feldman et al., 1998).
- Refinement of the pre-existing gravity model of Bills and Ferrari (1977) from Lunar Orbiter and Apollo 15 and 16 subsatellites on the basis of Clementine data (Zuber et al., 1994; Lemoine et al., 1997).

- Evidence for three new large "mascons" (mass concentrations – Muller and Sjogren, 1968; Melosh, 1978) on the nearside of the Moon as well as partially resolving four mascons on the farside (Konopliv et al., 1998, 2001).
- The most comprehensive lunar surface compositional maps to date (e.g., Lucey et al., 1995, 1998, 2000; Elphic et al., 1998, 2002; Lawrence et al., 1998; Gillis et al., 2003, 2004; Feldman et al., 2004a; Prettyman et al., 2006).
- The first lunar topographic map (e.g., Spudis et al., 1994).
- Compositional data on the central peaks of impact craters and possible exposed upper mantle at South Pole-Aitken basin (e.g., Pieters et al., 1997; Pieters and Tompkins, 1999; Tompkins and Pieters, 1999).
- Identification of a thorium-rich "hotspot" on the lunar nearside centered on Mare Imbrium (Lawrence et al., 1998, 2003, 2004, 2005; Haskin, 1998; Haskin et al., 2000), which was hinted at by the Apollo gamma-ray spectrometer data (e.g., Metzger et al., 1977; Haines et al., 1978; Hawke and Bell, 1981).
- Evidence for induced crustal magnetism at the antipodes of major impact basins (Lin et al., 1998; Halekas et al., 2003) as well as compositional evidence for antipodal ejecta deposits (e.g., Haskin et al., 2000).
- Evidence for the presence of a small iron-rich core with a radius of ~340 km (Hood et al., 1999).
- Definition of different terranes on the lunar surface by Jolliff et al. (2000) based on the data from the Clementine and Lunar Prospector missions, which included the Procellarum-KREEP Terrane, the Feldspathic Highlands Terrane, and the South Pole-Aitken Terrane.

The next mission to the Moon was SMART-1 launched by the European Space Agency (ESA) on 27 September 2003, arriving at the Moon during March 2005 (see Foing et al., 2006).

SMART-1 was launched as a solar ion propulsion drive technology demonstration, rather than a full science mission. SMART-1 carried seven instruments onboard performing various science and technology investigations. Among them were three remote sensing instruments: an X-ray spectrometer (D-CIXS), a lunar infrared spectrometer (SIR) and the smallest visual digital camera (AMIE Advanced Moon Imaging Experiment). SMART-1 provided advances in our understanding of the origin and evolution of the Moon by studying surface composition, bombardment history (see Fig. 1), volcanism and the morphology of large basins (Foing et al., 2008). SMART-1 reported major element data of the lunar surface from the D-CIXS instrument (e.g., Grande et al., 2007; Swinyard et al., 2009), and multi-angular imagery of selected targets (e.g., Kaydash et al., 2009). A coordinated campaign permitted observations of the flash and debris from the SMART-1 controlled grazing impact in 2006 (Burchell et al., 2010). SMART-1 also studied the seasonal variations of illumination of polar areas, and pointed to potential sites of quasi-eternal light, that could be relevant for future robotic outposts and human bases (Foing et al., 2006, 2008).

Between 2007 and 2009, four more orbital missions were launched to the Moon: Selene/Kaguya launched by Japan (JAXA) on 14 September 2007; Chang'E-1 launched by China (CNSA) on 24 October 2007 (Sun et al., 2005; Huixian et al., 2005); Chandrayaan-1 launched by India (ISRO) on 24 October 2008 (Bhandari, 2005; Goswami, 2010). The dual launch of the Lunar Reconnaissance Orbiter (LRO: Chin et al., 2007; Vondrak et al., 2010) and the Lunar Crater Observation and Sensing Satellite (LCROSS: Colaprete et al., 2010a) was achieved by the United States (NASA) on 18 June 2009. Data for these recent missions are still being collected, refined and interpreted. A number of exciting new results have been published:

- All missions (except LCROSS) carried laser altimeters. These data increased the fidelity of the topography map produced using Clementine data and extended it to cover the entire Moon (e.g., Araki et al., 2009; Ping et al., 2009; Huang et al., 2010; Smith et al., 2010).
- The Selene/Kaguya mission carried subsatellites that were used to define the gravity field of the lunar farside (Namiki et al., 2009).
- Global temperature variation maps have been produced from the LRO instrument suite (e.g., Gladstone et al., 2010a; Paige et al., 2010).
- The lunar radiation environment is being quantified by the LRO mission (e.g., Spence et al., 2010).
- The presence of H_2O and hydroxyl species on the lunar surface well away from the permanently shadowed regions (PSRs) has been documented by the Chandrayaan-1 mission (e.g., Pieters et al., 2009, see Fig. 2), and the Cassini mission (Clark, 2009).
- Data also show the presence of volatile species in and around the polar PSRs (Mitrofanov et al., 2010a; Bussey et al., 2010a; Heldmann et al., 2010; Hong et al., 2010; Spudis et al., 2010).
- Polar illumination has been tracked using Kaguya data (Bussey et al., 2010b).
- The first microwave emission map was produced from Chang'E-1 data (Jiang et al., 2010).
- New lunar lithologies, not represented in the sample return collection, have been discovered using orbital data (Ohtake et al., 2009; Sunshine et al., 2010; Pieters et al., 2011).
- Detailed images of the lunar surface have been collected that allow surface processes and potential hazards to be studied (e.g., Robinson et al., 2010).

The concentration of water ice in the regolith at the LCROSS impact site was estimated to be 6 ± 3% by mass. Other volatile compounds were reported, including light hydrocarbons, sulfur-bearing species, and carbon dioxide (Colaprete et al., 2010b). LRO observed the plume generated

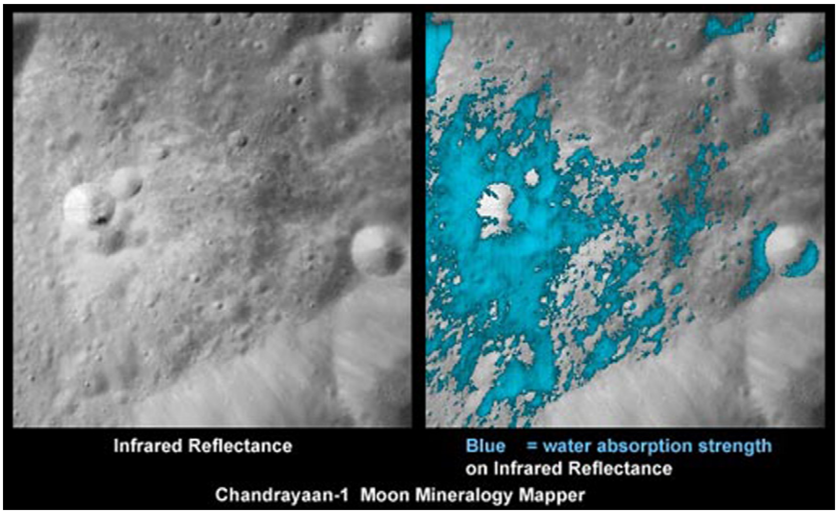

Fig. 2. NASA's Moon Mineralogy Mapper on the Indian Space Research Organization's (ISRO) Chandrayaan-1 spacecraft shows a very young lunar crater on the side of the Moon that faces away from Earth. *Left:* image showing brightness at shorter infrared wavelengths. *Right:* the distribution of water-rich minerals (light blue) is shown around a small crater. Both water- and hydroxyl-rich materials were found to be associated with material ejected from the crater. *Image Credit: ISRO/NASA/JPL-Caltech/USGS/Brown University*.

by the LCROSS impact with the Lyman-alpha Mapping Project (LAMP) as far-ultraviolet emissions from the fluorescence of sunlight by molecular hydrogen and carbon monoxide, plus resonantly scattered sunlight from atomic mercury, with contributions from calcium and magnesium (Gladstone et al., 2010b). The Diviner instrument detected a thermal emission signature (Hayne et al., 2010). LRO Lunar Exploration Neutron Detector (LEND) data show several regions where the epithermal neutron flux from the surface is suppressed, which is indicative of enhanced hydrogen content. These regions are not spatially coincident with permanently shadowed regions of the Moon (Mitrofanov et al., 2010b). Recent *in situ* measurements of water in lunar melt inclusions reported 615–1410 ppm of water (as well as amounts of fluorine, sulphur and chlorine), very similar to primitive terrestrial mid-ocean ridge basalts data (Hauri et al., 2011).

The data sets already acquired and those currently being collected will be used to advance lunar science and exploration, including location and study of potential hazards and resources, as well as characterization of the cratering process, polar volatiles, volcanism and space weathering, among others. NASA mission that are currently on route or scheduled to visit the Moon include GRAIL and LADEE.

- The Gravity Recovery And Interior Laboratory (GRAIL, launched September 2011): a mission to refine the total lunar gravity field that will, in essence, peer deep inside the Moon to reveal its internal structure and thermal history (Zuber et al., 2008, 2011).
- The Lunar Atmosphere and Dust Environment Explorer (LADEE); the mission is intended to explore the tenuous lunar exospheric species and dust above the Moon's surface (Delory et al., 2010).

China's Chang'E-2 Moon orbiter has been launched on 1 October 2010 and Chang'E-3 Moon lander and rover are to be launched later in the decade. Japan plans to send two Moon orbiters Selene 2 and 3 during this decade. The Russian Luna-Glob mission (anticipated launch date in 2013/2014) consists of an orbiter and landing probe. Contact *in situ* investigations in the lunar near-pole area are envisaged with the Luna Resource/1 mission composed of a Russian lunar lander and an Indian orbiter and mini-rover. A lunar multi-element mission (lander, rover, re-transmitting satellite), Luna Resource/2, is planned for later in the decade.

The interest of several nations to undertake lunar missions will continue to place the Moon at the forefront of science and exploration for the foreseeable future. In particular, there is substantial international interest in the development of an International Lunar Network (ILN), a lunar geophysical network whereby various nations contribute stations/nodes and/or instruments to explore the deep lunar interior to unlock the secrets of early planetary evolution (ILN, 2008). Building on ILN, this strong focus on the Moon provides a unique opportunity for increased international collaboration in science, instruments, missions and exploration of the solar system (see Appendices A and B). The NRC Planetary Decadal Survey 2013–2022 has identified a Lunar Geophysical Network mission, based in part on the ILN concept, as a possible NASA New Frontiers class mission for the second half of that decade (NRC 2011a).

Many COSPAR Moon volumes (ASR, 1994, 1996, 1999, 2002, 2006) and 11 ILEWG Conference Volumes and Declarations (ICEUM1–11) have compiled information in the last two decades on what science can be done: *of, on and from the Moon*.[1] Among the more recent

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[1] http://www.sci.esa.int/ilewg.

ambitions is to use the Moon for Earth sciences and to study fundamental solar system processes. NRC, LEAG and ILEWG have roadmaps on-line that outline fundamental and applied science concepts for Moon missions. The lunar farside, shielded from terrestrial radio emission, allows exploration of the cosmos from the Moon.

3.2. NRC report 2007 "*Scientific Context for the Exploration of the Moon*"

This NRC report outlines what exciting research can be performed to decipher many important questions of rocky worlds (NRC, 2007).

The overarching themes are the investigation of:

- The early Earth–Moon System.
- Terrestrial planet differentiation and evolution.
- Solar system impact record.
- The lunar environment.

Eight science concepts and goals were defined that include:

- Investigation of the bombardment record of the Moon.
- Moon interior structure.
- Lunar crustal rocks.
- Lunar poles.
- Lunar volcanism.
- Impact processes.
- Lunar regolith.
- Lunar dust and atmosphere environment.

3.3. International Lunar Exploration Working Group (ILEWG)

Relevant science recommendations from ILEWG Conferences on Exploration and Utilisation of the Moon (ICEUM) include:

Exploration4science:

- What does the Moon tell us on processes that are shaping Earth-like planets (tectonics, volcanism, impact craters, erosion, space weathering, volatiles)?
- What is the present structure, composition and past evolution of the lunar interior?
- Did the Moon form from a giant impact and how? How was the Earth evolution and habitability affected by this violent event, and by lunar tidal forcing?
- How can we return samples from large impact basins as windows to the lunar interior, and as records of the early and Late Heavy Bombardment?
- What can we learn on the delivery of water and organics by comets and asteroids from sampling cores of the lunar polar ice deposits? Are there prebiotic ingredients in lunar soil or ice?
- How to find and return samples ejected from the early Earth (and possibly the oldest fossils) now buried within the few meters of lunar regolith?
- How to use most effectively the Moon as a platform for astrophysics, cosmology and fundamental physics, compared to Earth or space-based laboratories?
- How to use a "Global Robotic Village" (as recommended by ILEWG) to provide the measurements to fulfill these scientific objectives?

Among the recent ILEWG recommendations are:

"Recognizing the importance of the geophysical studies of the interior of the Moon for understanding its formation and evolution, the necessity for a better monitoring of all natural hazards (radiation, meteorite impacts and shallow moonquakes) on the surface, and the series of landers planned by agencies in the period 2010–2015 as a unique opportunity for setting up a geophysical network on the Moon, we recommend the creation of an international scientific working group for definition of a common standard for future Moon network instruments, in a way comparable to Earth seismology and magnetism networks. We encourage interested agencies and research organizations to study inclusion of network instruments in the Moon lander payload and also piggyback deployment of a Moon Geophysical and Environmental Suitcase (ICEUM8, Beijing, 2006)."

"To address outstanding lunar science questions remaining to be resolved (relating to mineralogy, geochemistry, interior structure, gravity, topography, polar regions, volatiles, environment protection) as well as the scientific investigations that can be performed from the Moon as a platform (astrophysics, solar physics, Earth observations, life science) (ICEUM9, Sorrento, 2007)."

"We, the participants in the ILEWG/LEAG/SRR 2008 conference, reaffirm our commitment to international lunar exploration, from the analysis and integration of current lunar orbiter data, to the development of lunar landers and rovers, the build up of a "Global Robotic Village", and the preparation for human settlements and International Lunar Bases (ICEUM10, Cape Canaveral, 2008)."

467 International Lunar Explorers, delegates from 26 countries, assembled at the Global Lunar Conference GLUC including the 11th ILEWG Conference on Exploration and Utilisation of the Moon (ICEUM11) from 31 May to 3 June 2010, in Beijing. GLUC-ICEUM11 was a truly historical meeting that demonstrated the worldwide interest in lunar exploration, discovery, and science. The community feels strongly that joining the forces of spacefaring nations to explore the Moon should be seriously implemented, with the views of expanding a "Global Robotic Village" and building in the long run a Manned International Lunar Base. "We, the delegates of the GLUC-ICEUM11 conference, commit to an enhanced global cooperation toward international lunar exploration for the benefit of humankind (GLUC-ICEUM11, Beijing, 2010)."

3.4. The Lunar Exploration Analysis Group (LEAG)

The Lunar Exploration Analysis Group (LEAG) has constructed a Lunar Exploration Roadmap (LER), which is a hierarchical document that is comprised of three themes with subsequent goals, objectives, and investigations or initiatives.[2] The objectives and investigations/initiatives have been time phased using Early Stage, Middle Stage, and Late Stage.

Definitions of these terms are:

- **Early**: Robotic precursors and up to the second human landing ($\leqslant$1 lunar day).
- **Middle**: Initial outpost build-up to including stays of 1 lunar day and including part of the lunar night, as well as robotic missions.
- **Late**: Outpost established, stays of >30 days, including robotic missions.

For road-mapping efforts, the Early Stage has been subdivided into pre-Early (Robotic Precursor Missions) and Early (Robotic & Short Human Sortie $\leqslant$1 Lunar Day). Low, medium, and high prioritizations have been assigned by the LEAG road-mapping team to the objectives and investigations in terms of what is interpreted, through contact with leaders in the community, as general thinking of how particular science communities (i.e., Earth observing, heliophysics, and astrophysics) could best use the Moon.

For lunar science, LER defers to the NRC (2007) "*Scientific Context for the Exploration of the Moon*" report for prioritization of science concepts and goals, which specifically studied the issue of prioritization. The priorities are intended to help gauge, within the range of uses of the Moon that have been proposed over the years within these communities, which concepts appear to offer the most promise.

Low Priority:
Would be good to do, but is not essential for habitat/exploration development; would only give an incremental advance to our scientific knowledge; and/or could be conducted more efficiently elsewhere.
Medium Priority:
Falls in between Low and High Priority; could be enabled with sufficient infrastructure investment.
High Priority:
Is essential to do in order to make progress in habitat/exploration development; would facilitate a fundamental advance in our scientific knowledge; is facilitated by or should be facilitated by the Lunar Architecture; and/or is best done on the lunar surface.

The Moon has been and will continue to be the scientific foundation for our knowledge of the early evolution and impact history of the terrestrial planets. Remotely sensed, geophysical, and sample data allow us to define investigations that test and refine models established for lunar origin and evolution. For example, documenting the diversity of crustal rock types and the composition of the shallow and deep lunar mantle will allow refinement of the lunar magma ocean hypothesis. Dating the formation of large impact basins will relate directly to the crustal evolution of all the terrestrial planets and, possibly, to the bombardment history of the outer solar system. Establishing a global lunar geophysical network will allow, for the first time, the deep lunar interior to be studied in detail. This is critical for understanding the early evolution of the terrestrial planets. The main themes within the LER are summarized below.

Science Theme: Pursue scientific activities to address fundamental questions about the solar system, the Universe, and our place in them.

This theme addresses four main goals along with objectives:

- Understand the formation, evolution and current state of the Moon (9 objectives, 36 investigations).
- Use the Moon as a "witness plate" for solar system evolution (2 objectives, 9 investigations).
- Use the Moon as a platform for astrophysics, heliophysics, and Earth-observation studies (3 objectives, 28 investigations).
- Use the unique lunar environment as a research tool [this goal is subdivided into combustion research (4 objectives, 11 investigations), fluid physics and heat transfer research (4 objectives, 11 investigations), materials processing research (3 objectives, 5 investigations), and life sciences research (11 objectives, 29 investigations)].

The LEAG roadmap describes how the Moon is a unique platform for fundamental astrophysical measurements of gravitation, the Sun, and the Universe. A number of high priority heliophysics investigations are defined in the LER. Long-term observations of the whole Earth disk from the Moon provide a broad picture of annual fluctuations in atmospheric composition and, over several years, can map trends in these fluctuations. The high priority Earth-observing investigations include: Monitor the variability of Earth's atmosphere; detect and examine infrared emission of the Earth; develop radar interferometry of Earth from the Moon.

Feed Forward Theme: Use the Moon to prepare for future missions to Mars and other destinations.

This theme will establish mission risk reduction technologies, systems and operational techniques that could be developed through a lunar exploration program to explore other airless bodies and Mars. The following evaluation criteria will be used to evaluate candidate ideas:

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[2] http://www.lpi.usra.edu/leag/.

- Mars Risk Reduction Value: How well do the candidates address the key risk reduction areas identified through NASA's Airless Body and Mars robotic and human mission planning studies.
- Lunar Platform Value: Do candidates leverage the unique attributes of a lunar program to achieve success – or – would other platforms be more effective from a technical/cost perspective.

There are three goals under this theme. Two are Mars specific (FF-A and FF-B) and one is specific to Airless Bodies (FF-C):

- Identify and test technologies on the Moon to enable robotic and human solar system science and exploration (9 objectives and 38 investigations).
- Use the Moon as a testbed for mission operations and exploration techniques to reduce the risks and increase the productivity of future missions to Mars and beyond (3 objectives and 13 investigations).
- Preparing for future missions to other airless bodies (11 objectives and 44 investigations).

Timing for individual investigations is driven by when the capability would be required for lunar applications since these technologies would be supporting lunar activities not done specifically as Mars technology demonstrations.

Sustainability Theme: Extend sustained human presence to the Moon to enable eventual settlement.

The fundamental purpose of activity involving the Moon is to enable humanity to do there permanently what we already value doing on Earth: science, to pursue new knowledge; exploration, to discover and reach new territories; commerce, to create wealth that satisfies human needs; settlement, to enable people to live out their lives there; and security, to guarantee peace and safety, both for settlers and for the home planet. Achieving permanent human presence depends on ensuring that profitable, economically self-sustaining commercial endeavors will develop wherever possible and ethically appropriate. Activities not within the commercial domain must define and produce value sufficient to justify continuing government and non-profit funding.

Initial human and robotic presence must lay a solid foundation in science and technology demonstrations, showing the value of extended and expanded presence, so that our opportunity to live and work on the Moon can be sustained. The "Sustainability Theme" within the Lunar Exploration Roadmap has many dimensions that share the unifying notion that *sustained* lunar activities are only possible when they are *sustainable* through ongoing return of value, realized and anticipated, from those activities. The long-term objective of permanent human presence in the form of a self-sustained settlement is the titular purpose of the elements described in this theme, but such an objective is most readily defensible when strongly linked to the sister themes of "Science" and "Feed Forward" of the lunar experience to the human exploration of other destinations in the solar system. Therefore, the direct mingling of science and exploration goals and objectives is explicitly made in this theme of the roadmap.

The role of commercial activity as an indispensible aspect of sustainability is self-evident in times when the limits of governmental support are so apparent, but the effective integrated phasing of initiatives across all the themes, goals and objectives is at the core of establishing a sustainable expansion of human presence away from Earth. The "Sustainability Theme" is comprised of several goals:

- Maximize commercial activity (5 objectives, 19 initiatives).
- Enable and support the collaborative expansion of science and exploration (12 objectives, 77 initiatives).
- Enhance security, peace and safety on Earth (5 objectives, 9 initiatives).

The Lunar Exploration Roadmap is a *living document* that is updated annually to include new data and changing national and international political situations. For example, the 2011 review will include a review of the "Science Theme" in light of the 2011 release of the NRC Planetary Decadal Survey. In addition, this review will develop mission concepts to implement the early stages of lunar exploration as defined by the roadmap.

4. Destination: Near-Earth Asteroids

The remaining planetesimals of the solar system formation process - those that were not integrated into planets – exist today as small bodies such as asteroids and comets. Most of the asteroids and comets are confined to stable orbits (such as the asteroid belt between Mars and Jupiter) or reservoirs in the outer solar system (such as the Kuiper Belt) or beyond our solar system (such as the Oort cloud). Icy planetesimals in the outer solar system occur as comets, Centaurs, and Kuiper-Belt objects. The investigation of comets and asteroids provides us with important insights into the original composition of the solar nebula from which the planets formed. Comets and asteroids and their fragments (meteorites and Interplanetary Dust Particles IDPs) frequently impacted the young planets in the early history of the solar system (Gomes et al., 2005). The large quantities of extraterrestrial material delivered to young terrestrial planetary surfaces during this period may have provided the material necessary for the emergence of life (Chyba and Sagan, 1992; Ehrenfreund et al., 2002).

4.1. NRC report 1998 "Exploration of Near-Earth Objects"

Near-Earth Objects (NEOs) orbit in close proximity (<1.3 AU[3]) of the Earth and may pose a hazard to life on

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[3] 1 AU = astronomical unit = 149.60×10^6 km.

Earth. The NRC report "*Exploration of Near-Earth Objects*" discusses that "approximately 5% of NEOs are the most readily accessible extraterrestrial bodies for exploration by spacecraft" (NRC, 1998). The energy requirements to rendezvous with and land on these bodies are less than those to land on the surface of the Moon. The combination of the diversity and accessibility of these bodies presents new opportunities and challenges for space exploration and indicates a need for sufficient ground-based observations of NEOs to identify targets of highest scientific interest. Fundamental science questions to address are:

- How many objects are there?
- What are their size distribution and composition?
- How often do they strike Earth?

4.2. NEO sample return

The Japanese Hayabusa mission explored the asteroid Itokawa (Yano et al., 2006; Michikami et al., 2010, see Fig. 3). Hayabusa is the first asteroid sample return mission to sample pristine early solar system material from a NEO. The sample return capsule was retrieved in Australia on 13 June 2010. The sample content is being investigated in Earth laboratories and first results have been presented at recent conferences (Tsuchiyama et al., 2011).

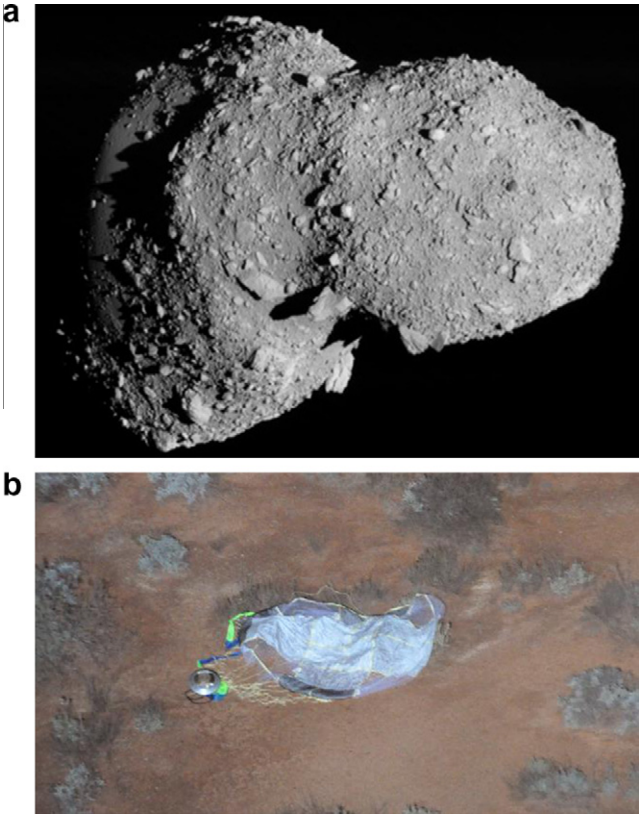

Fig. 3. *Top:* The near-Earth asteroid Itokawa has been observed by the Hayabusa mission that confirmed an S-type composition. The image shows a surprising lack of impact craters but a very rough surface. *Bottom:* The sample return capsule was retrieved on 13 June 2010 in Australia. *Image Credit: JAXA.*

Mission concepts for NEO sample return missions have been extensively studied by independent experienced teams in the US, Europe, and Japan. NASA's New Frontier program has selected in June 2011 the Origins Spectral Interpretation Resource Identification Security Regolith Explorer spacecraft, called OSIRIS REx (for launch in 2016), planned to rendezvous and orbit a primitive asteroid. MarcoPolo-R, a mission whose primary objective is a sample return from a primitive NEO, has been selected for the assessment study phase of ESA M3 missions. Hayabusa-2 is JAXA's follow on mission to the Hayabusa mission that targets asteroid 1999 JU3 with a proposed launch date in 2014. An important goal for NEO sample return missions is the acquisition of samples together with known geologic context. Finally, thorough contamination control is essential to achieve the objective of returning a pristine sample. It is crucial to return an uncontaminated sample to Earth in an amount sufficient for molecular, organic, isotopic, and mineralogical analyses.

4.3. NEO science through robotic and human exploration

Many asteroids are primitive, having escaped high-temperature melting and differentiation. The chemical and physical nature, distribution, formation, and evolution of primitive asteroids are fundamental to understanding solar system evolution and planet formation.

The analysis of carbon compounds in fragments of asteroid 2008 TC_3 revealed recently interesting insights into asteroid chemistry (Jenniskens et al., 2009; Glavin et al., 2010, see also Fig. 4). Given our current technology and launch limitations, sample return from a carbonaceous NEO has been suggested to provide the highest science return with the lowest implementation risk (Lauretta et al., 2009).

A number of broad science themes can be identified for NEO science (NRC, 1998):

- Measuring the physical characteristics of NEOs.
- Understanding the mineralogical and chemical compositions of asteroids.
- Deciphering the relationships among asteroids, comets, and meteorites.
- Understanding the formation and geologic histories of NEOs.

These science themes are usually associated with ground-based and robotic exploration but would be augmented by human exploration missions. In addition to addressing fundamental science questions, knowledge acquired during a human NEO mission would facilitate development of methods to mitigate their potential hazard. Near-Earth asteroids can closely approach the Earth and therefore present a threat to humans and life on Earth. However, these objects are mineral-rich and their close proximity make them

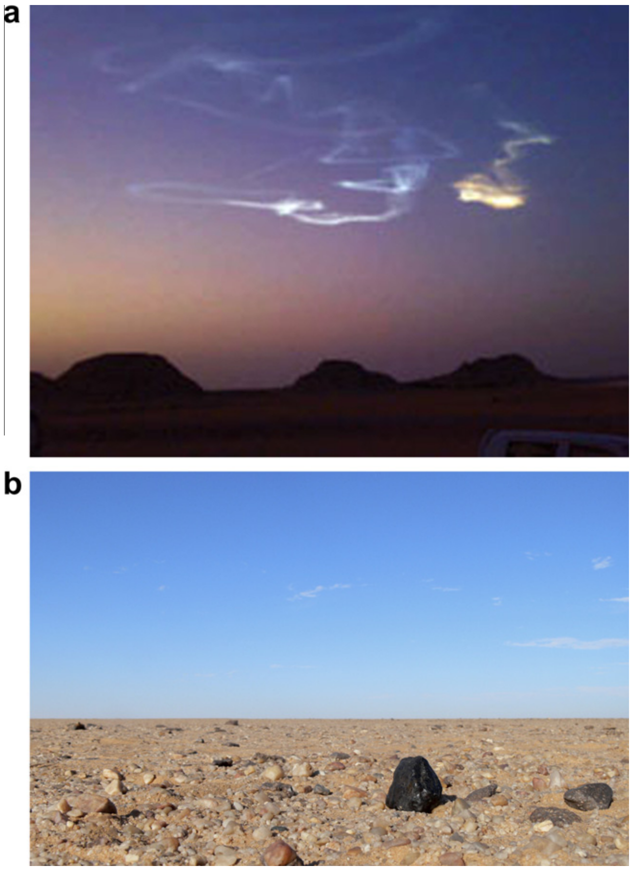

Fig. 4. *Top:* A small near-Earth asteroid entered Earth's atmosphere on 7 October 2008 and exploded over the Nubian Desert of northern Sudan. Scientists expected that the asteroid 2008 TC_3 disintegrated into dust in the resulting high-altitude fireball. Image taken by cell phone of the contrail left by 2008 TC_3 during its decent. *Image Credit: Shaddad Bottom:* Almahata Sitta meteorite number 15 (a remnant of asteroid 2008 TC_3) *in situ* on the desert floor during its find on 8 December 2008. *Image Credit: P. Jenniskens, SETI Institute.*

interesting targets for the exploitation of raw materials and supporting interplanetary journeys.

Applied science goals include:

- Understanding the NEO surface physical properties so as to allow the design of systems that impact, or attach to these surfaces.
- Understanding bulk properties of NEOs so as to allow modeling of their response to impacts, detonations or external forces.
- Determining the diversity of objects within the NEO population with respect to mechanical and bulk properties.
- Calibrating the ability of Earth-observations to remotely determine the essential physical properties of NEOs.

The NASA space exploration roadmap envisages a visit by humans to an asteroid after 2025. For both, applied and fundamental science, a human NEO mission would produce a wealth of data, at the same time expanding our human spaceflight experience base beyond low-Earth orbit and the Earth–Moon system, proving space-qualified hardware directly applicable to lunar and Mars exploration, and providing a valuable and visible "milestone" akin to the impact of Apollo 8. An astronaut Extra Vehicular Activity (EVA) to the surface of a near-Earth asteroid would be of value to both the applied and fundamental science goals listed above as well as providing an important public outreach and demonstration relevant to hazard mitigation.

The statistical distribution of NEO orbits has been investigated by Chesley and Spahr (2004). In the most recent NRC report (2010) on "*Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*" a peer-reviewed, targeted research program in the area of impact hazard and mitigation of NEOs is recommended that should encompass surveys, characterization and mitigation. The scope of the research program should include analysis, simulation as well as laboratory experiments. The role of ground- and space-based facilities in addressing NEO survey goals was investigated in detail. It was recommended that the US takes the lead in organizing and empowering a suitable international entity to participate in developing a detailed plan for dealing with the NEO hazard. Rendezvous spacecraft missions can help in the detailed characterization of NEOs and thus provide valuable information for the design and development of hazard mitigation. Finally it was recommended that any human mission to NEOs should maximize data obtained for NEO characterization (NRC, 2010).

NASA's Human Exploration Framework Team (HEFT) has been recruited to analyze exploration and technology concepts and to compile inputs on the key components of a safe, sustainable, affordable and credible future human space exploration endeavor for the nation.[4] Their recent report envisages a capability-driven approach where evolving capabilities would enable increasingly complex human exploration missions over time.

The Open Global Community NEO Workshop[5] (February 2011) has provided a substantial technical review and conclusive peer support for NEO precursors, emphasizing that a NEO survey mission is necessary to realize a future human exploration mission in the 2025–2035 timeframe.

5. Destination: Mars

Mars continues to be an object of keen interest in the context of planetary evolution and extraterrestrial life. Its climate has changed profoundly over time and the planet's surface still retains physical and chemical evidence of early planetary and geologically more recent processes. A primary objective of future international planetary exploration programs is to implement a long-term plan

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[4] http://www.nasa.gov/pdf/525162main_HEFT_Final_Brief_508_20110309.pdf.

[5] http://www.targetneo.org/pdfs/TargetNEOWorkshopReport.pdf.

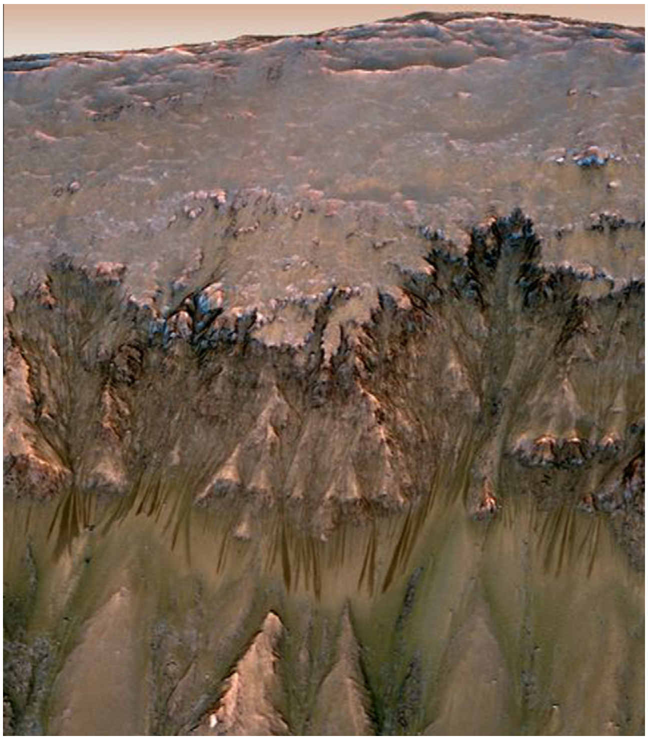

Fig. 5. Oblique view of warm season flows in the Newton Crater. An image combining orbital imagery with 3-D modeling shows flows that appear in spring and summer on a slope inside Mars' Newton crater. *Image Credit: NASA/JPL-Caltech/Univ. of Arizona.*

for robotic and human exploration of Mars, and as part of these programs, to search for extinct or extant life on Mars. Although currently the surface of Mars may be uninhabitable by indigenous life, regions in the subsurface may still harbour life or remnants of past life. Recent missions, such as Mars Global Surveyor (MGS), Mars Odyssey, the Mars Exploration Rovers (MER), Mars Express (MEx), Mars Reconnaissance Orbiter (MRO), and Phoenix, have added significantly to our knowledge of the history of water at the martian surface and the evolving role it has played in interacting with the crust. The geological record indicates a diversity of water-modified environments, including promising ancient habitable environments. Observations from NASA's Mars Reconnaissance Orbiter have revealed possible flowing water on the surface during the warmest months on Mars (McEwen et al., 2011) (see Fig. 5).

The presence of methane gas suggests a dynamic system on Mars that couples its interior and atmosphere, even as its reported variability challenges our present understanding of atmospheric chemistry. In the coming decade, Mars is the only target addressing the search for life that, realistically, can be visited frequently by robotic spacecraft, paving the way for returned samples and human exploration. Finally, the consensus of the Mars science community is that the greatest progress in determining biological potential of Mars is through returning samples from the Mars surface to be analyzed in Earth laboratories (NRC Mars, 2007).

5.1. Results from recent Mars missions

5.1.1. General

- Mars has benefited over the last decades from a fleet of orbital and landed spacecraft. Orbital remote sensing has revealed a complex geologic record that appears to span most of the history of the planet, and that formed in response to processes that include volcanism/plutonism, weathering/erosion, sedimentation, glaciation, polar ice cap processes, fluid/rock interactions, tectonism, and others. Example references include Christensen et al. (2003), Neukum et al. (2004), Hahn et al. (2007), Tanaka et al. (2005), Heldmann et al. (2007) and Frey (2008), and many of the references listed below.

5.1.2. Ancient Mars

On ancient Mars, water was persistent in shallow surface bodies, lakes, connected networks, and as groundwater near the surface, and Mars therefore likely had a very different climate than it does today (Malin and Edgett, 2003; Hynek and Phillips, 2003; Howard et al., 2005; Irwin et al., 2005; Squyres and Knoll, 2005; Baker, 2006; Jolliff et al., 2006; Knoll and Grotzinger, 2006; Irwin et al., 2008; Squyres et al., 2009; Murchie et al., 2009; Fairén, 2010).

- A diverse suite of minerals, including hydrated sulfates, phyllosilicates, and silica, produced by the action of water on martian crustal rocks has been identified both from orbit and from the martian surface (Poulet et al., 2005, 2009; Chevrier and Mathé, 2007; Squyres et al., 2006a; Arvidson et al., 2008; Morris et al., 2008; Mustard et al., 2008; Squyres et al., 2008; Ehlmann et al., 2008; Hecht et al., 2009). The character and concentration of at least some of these minerals systematically change on a global scale over geologic time (Bibring et al., 2006), generally indicating more alteration by liquid water early in Mars history. Recent observations identified more than 990 hydrated mineral exposures on Mars (Carter et al., 2011). At the Mawrth Vallis region phyllosilicate units are observed that resemble terrestrial sedimentary deposits (Bishop et al., 2011).
- The detailed processes of rock formation and weathering, and the influence of these two processes on mineralogy and morphology/texture has been established at two martian sites of very different geological character (e.g., Grotzinger, 2005; McLennan et al., 2005; Squyres and Knoll, 2005; Squyres et al., 2006b; Squyres et al., 2007).
- Remnant magnetism in the ancient crust shows that there was a powerful global magnetic field that shut down early in Mars history, exposing the atmosphere to increased erosion by the solar wind (Connerney et al., 2001; Lillis et al., 2008) and perhaps triggering a profound change in climate and surface-atmosphere interaction (Bibring et al., 2006).

- Determination of the planetary figure and gravity fields (Neumann et al., 2004) provide key information on the distribution of mass and the degree of isostatic equilibrium.

5.1.3. Geologically Young Mars

- Layering in the polar caps and in sedimentary rock in many places, often with remarkably repetitive sequences of layer thicknesses, indicate cyclical processes (e.g., Laskar et al., 2002; Milkovich and Head, 2005; Lewis et al., 2008).
- The north and south polar caps are different in many ways: the north appears younger and has no remnant summertime layer of CO_2. Layer thicknesses for the north have typical variations consistent with computed changes in the planet's obliquity and orbital eccentricity on time scales of several hundred thousand to a few million years (e.g., Phillips et al., 2008).
- An array of glacial and periglacial landforms, including debris covered shallow ice-deposits in mid-latitudes, points to massive transport of volatiles, especially water, from the polar reservoirs to lower latitudes, presumably in response to the cyclical changes of polar insolation (Head et al., 2003, 2005; Holt et al., 2008; Plaut et al., 2009).

5.1.4. Modern Mars

- Ground ice extends over most of the high latitudes in the top meter of surface material. Its depth (therefore volume) is not known, but a subsurface cryosphere may today hold a significant fraction of ancient liquid water (Boynton et al., 2002; Feldman et al., 2004b; Smith et al., 2009).
- Suface change: Impact craters continue to be identified, helping to calibrate the crater-dating algorithms and providing insight into the material beneath the dust-covered surface. New gullies have been observed; whether dry avalanches or water-aided movement, they indicate a landscape that continues to change even today (Malin and Edgett, 2000; Malin et al., 2006; McEwen et al., 2007).
- A multi-year record of the seasonal cycles of water, CO_2 and dust, including spectacular, episodic hemispheric and global dust events, has revealed processes which operate over much longer time scales (Smith, 2004, 2008). Actively precipitating water ice clouds have now been observed (Whiteway et al., 2009).
- Earth-based observations, building on orbital indications, have detected methane in the atmosphere of Mars (e.g., Mumma et al., 2009). Its very presence suggests an active subsurface source. Reported variations in space and time, still controversial, are inconsistent with our present understanding of processes affecting the martian atmosphere (Zahnle et al., 2011). The all-important provenance of the methane, whether geochemical or biochemical, remains to be determined.

Future missions to Mars include the NASA's Mars Science Laboratory (MSL) that will be launched in November 2011 and explore the martian surface with a rover carrying sophisticated instrumentation. The overall scientific goal of the mission is to explore and quantitatively assess a local region on Mars' surface as a potential habitat for life, past or present. The Gale crater that holds a mountain has recently been selected as landing site for the MSL rover Curiosity. At the base of the mountain clays and sulfates have been identified, both known to form in water. Scientists are hoping to find organic molecules in this environment.

NASA's Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft is scheduled for launch in late 2013. A long-term ESA-NASA cooperation on the exploration of Mars has been developed with the ExoMars mission that is planned to be conducted in 2016 and 2018, respectively. For the 2016 mission ESA intends to provide a Mars Orbiter and an Entry, Descent and Landing Demonstrator Module (EDM). The Trace Gas Orbiter (TGO) will accommodate scientific instruments for the detection of atmospheric trace gases.

The current scenario is to send a joint rover to the Martian surface to search for biosignatures and cache samples for a future Mars Sample Return mission. Current landing site strategies for future Mars missions and in particular scenarios for Mars Sample Return MSR landing sites argue for high diversity of samples for *in situ* analysis and sample return as summarized in the recommendations of the recent workshop on landing site strategies for exploration missions (Zegers, 2011). The Russian Phobos-Grunt mission to the martian moon Phobos was launched in November 2011 together with the Chinese Yinghuo-1 (YH-1) orbiter. However, due to an engine failure the probe did not leave low Earth orbit.

5.2. The Mars Exploration Program Analysis Group (MEPAG) Roadmap

The MEPAG Goals document summarizes a consensus-based list of broad scientific objectives organized into a four-tiered hierarchy: goals, objectives, investigations, and measurements. The goals have a very long-range character and are organized around major areas of scientific knowledge and highlight the overarching objectives of the Mars Exploration Program (Arvidson et al., 2006). MEPAG documents are regularly updated and available to the public, on-line at http://mepag.jpl.nasa.gov/. The most recent roadmap summarizing the Mars science Goals and Objectives, Investigations and Priorities has been compiled in 2010.[6]

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[6] http://mepag.jpl.nasa.gov/reports/MEPAG_Goals_Document_2010_v17.pdf.

The goals of the MEPAG roadmap version (MEPAG 2009, 2010) are listed below:

- Goal 1: Determine if life ever arose on Mars.
- Goal 2: Understanding the processes and history of climate on Mars.
- Goal 3: Determine the evolution of the surface and interior of Mars.
- Goal 4: Prepare for human exploration.

MEPAG has identified cross-cutting strategies that could be used to guide the present and future exploration of Mars:

- Follow the water.
- Understand Mars as a system.
- Seek habitable environments.
- Seek signs of life.

Most recently, MEPAG has considered the following science objectives for the next decade (Mustard, 2009):

- How does the planet interact with the space environment, and how has that affected its evolution?
- What is the diversity of aqueous geologic environments?
- Are reduced carbon compounds preserved and what geologic environments have these compounds?
- What is the complement of trace gases in the atmosphere and what are the processes that govern their origin, evolution, and fate?
- What is the detailed mineralogy of the diverse suite of geological units and what are their absolute ages?
- What is the record of climate change over the past 10, 100, and 1000 million years?
- What is the internal structure and activity?

5.3. Mars Sample Return

The return of martian samples to Earth has long been recognized to be an essential component of a cycle of exploration that begins with orbital reconnaissance and *in situ* martian surface investigations. However, spacecraft instrumentation cannot perform critical measurements such as precise radiometric age dating, sophisticated stable isotopic analyses and definitive life-detection assays, and therefore the major questions about life, climate and geology require answers from state-of-the-art laboratories on Earth. Returned sample studies could respond radically to unexpected findings, and returned materials could be archived for study by future investigators with even more capable laboratories. Unlike martian meteorites, returned samples could be acquired with known context from selected sites on Mars according to the prioritized exploration goals and objectives (MEPAG ND-SAG, 2008).[7]

The return of carefully selected samples even from a single well-chosen site would be the means to make the greatest progress at this point in planetary exploration. The recognized challenges of definitively detecting biosignatures, especially when attempted *in situ*, has raised the priority of sample return for astrobiological studies (NRC Mars, 2007) to the same high level given sample return for geochemistry, including geochronology. For both science areas, the return of samples would provide the opportunity for repeated experimentation with the latest analytic tools, including the all-important ability to follow-up on preliminary discoveries with new or revised analytic approaches. Knowledge of the samples' context on Mars, including detailed knowledge of the environment from which they were selected, would also be crucial for defining the laboratory analyses and interpreting their results (Mustard, 2009). In contrast to Earth, Mars still retains rocks from its very early history that provide clues to its ancient conditions and possible habitable environments. Several recent documents describe in detail sample return goals and scenarios (e.g., iMars, 2008; MEPAG ND-SAG, 2008).

The Mars community consensus holds that the search for life, geochemical studies and age dating, as well as climate and coupled atmosphere–surface–interior processes can be best studied with samples returned to Earth and analyzed in state-of-the-art laboratories. The field of life in extreme environments has strongly progressed in the last decade and some living species on Earth have been shown to survive under conditions of extreme radiation, subfreezing temperatures, high salinity, extremely high and low pH, and cycles of hydration to dehydration as present on Mars today. Advances in the knowledge of environmental conditions on Mars today and in the past, combined with advances in understanding of the environmental limits of life, reinforce the possibility that living entities could be present in samples returned from Mars. The Next Decade Mars Sample Return Science Analysis Group (ND-MSR-SAG) formulated the 11 high-level scientific objectives that should allow for a balanced program to return samples from Mars (MEPAG ND-SAG, 2008). A crucial element is to gather samples with a variety of geologic histories such as sedimentary material, hydrothermally altered rocks, low temperature altered rocks, igneous rocks, regolith samples, polar ice (if possible) as well as atmospheric gas.

The following factors that would affect our ability to achieve MSR's scientific objectives have been identified:

- Sample size.
- Number of samples.
- Sample encapsulation.
- Diversity of the returned collection.
- *In situ* measurements for sample selection and documentation of field context.
- Surface operations.
- Sample acquisition system.
- Sample temperature.
- Planning considerations involving the rover caches.
- Planetary protection.
- Contamination control.

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[7] http://mepag.jpl.nasa.gov/reports/ndsag.html.

The NRC Planetary Decadal Survey identified MSR as the Next Step (NRC, 2011a). Experience based on previous studies (e.g., of meteorites, the Moon, cometary dust, and the solar wind) strongly supports the importance of sample analysis. "The analysis of carefully selected and well documented samples from a well characterized site will provide the highest scientific return on investment for understanding Mars in the context of solar system evolution and addressing the question of whether Mars has ever been an abode of life".

Driven by the emergence of a diverse landscape, both morphologically and compositionally, the scenario now under consideration for Mars Sample Return (MSR) involves a sequence of mission elements referred to as the MSR campaign spanning multiple launch opportunities. An initial mission element in the multi-mission scenario would be NASA-ESA 2018 Mars mission currently under development with the capability to cache samples. Subsequently, a potential future MSR rover element utilizes a flexible rover to recover the cached samples, which would be launched from Mars with a Mars Ascent Vehicle (MAV) into orbit. A Mars Sample Return Orbiter (Sample capture and Earth Entry Vehicle) would rendezvous with the orbiting sample container and return the samples to Earth. The returned samples would be handled in a Sample Receiving Facility (SRF) and sample curation facility, the two ground segments of MSR.

The SRF is particularly important, because it must assess biohazards while at the same time avoiding damaging contamination of the samples. This multi-element MSR concept readily accommodates international cooperation (see Fig. 6). A major challenge is to select a site where significantly diverse regions can be sampled during one mission. Another challenge is to preserve sample integrity upon re-entry and transfer to a SRF (Pratt et al., 2009). The pursuit of the proposed sample return campaign in a step-by-step approach now appears to be within the international community's grasp, both scientifically and technically. Orbital reconnaissance, experience with surface operations and the development of the MSL Entry/Descent/Landing system have reduced both the scientific and technical risks of sample return, in accordance with the NRC recommendations (NRC, 2003; NRC Mars, 2007) so that NASA and other space agencies can take steps to implement a sample return mission as soon as possible.

The next mission steps in the proposed sample return campaign would be:

- Collection of appropriate samples and caching them at an appropriate site.
- Acquisition of the cache and launch of it into Mars orbit.
- Rendezvous with the cache in Mars orbit and return to Earth.

The activities for the next decade with regard to the proposed sample return are:

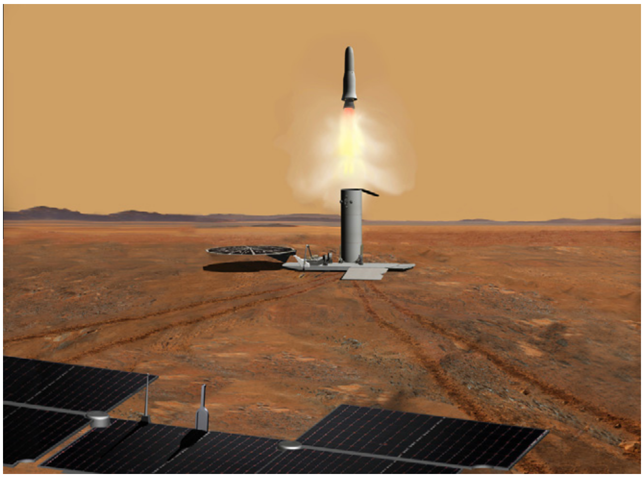

Fig. 6. Artist's concept of the Mars Sample Return mission showing the ascent phase from the martian surface. Once the sample container reaches Mars orbit it will rendezvous with a Mars Sample Return Orbiter that returns the collected samples to Earth. *Image Credit: Jet Propulsion Laboratory*.

- Identification of the sample return site.
- Deployment of a caching rover, preferably launched in the 2018 opportunity.
- Initiation of a technology development program for the proposed sample return cacher, Mars ascent vehicle, and Earth-return orbiter.
- Planning for sample handling and analysis facilities for returned samples.

MSR development would likely advance readiness and reduce risks for future human missions through knowledge gained about hazards and resources and by demonstrating scaled versions of key technologies such as *In Situ* Resource Utilization (ISRU) (Stetson et al., 2009).

The following goals for the period 2016–2025 related to preparing for human exploration are listed in the NASA Roadmap 2005.[8] Many of these are still active, others have shifted as priorities and budgets have evolved:

- Laboratory study of Mars samples.
- Intensive search for life.
- Subsurface exploration.
- Understand potential Mars hazards – toxicity, biohazards.
- Scalable demos of key capabilities (ISRU, EDL) and dress rehearsal.
- Expand Mars telecom infrastructure.
- Human habitation and operation validation on the Moon.
- Select and validate human Mars architecture.
- Select site for robotic outpost.
- Commit to timetable for human Mars exploration.

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[8] http://images.spaceref.com/news/2005/srm2_mars_rdmp_final.pdf.

Table 1
Potential near-term international initiatives in space exploration (adapted from Ehrenfreund and Peter (2009)).

Initiatives	Potential specific missions	Participants
Preparation for future robotic and human planetary exploration missions	International Earth-based field research program	Current and emerging spacefaring nations, developing countries, private sector
Joint program for international research activities	Science exploitation of the ISS enabling exploration	ISS partners and potential new space partners
Cooperation on low-cost missions accessible to emerging spacefaring nations	International CubeSat program in support of space exploration	Current and emerging spacefaring nations, developing countries, private sector
System-of-systems approach: small orbiters and landers	Global Robotic Village	Current and emerging spacefaring nations, developing countries, private sector
Joint exploration missions	Moon, NEO, Mars sample return mission	Current and emerging spacefaring nations, developing countries, private sector
Concept studies for an international space infrastructure	International lunar base or post-ISS infrastructure	Current and emerging spacefaring nations, developing countries, private sector

The NRC Planetary Decadal Survey identified the Mars Astrobiology Explorer-Cacher (MAX-C) as the highest priority large mission for the decade 2013–2022. Recent political developments indicate that a joint US-European rover will reach the surface in 2018 and initiate the multi-decadal Mars Sample Return mission.

MEPAG has recently compiled ten investigations necessary to prepare for Human Exploration of Mars (Goal IV – Prepare for Human Exploration)[9]:

1. Atmospheric measurements.
2. Biohazard and back planetary protection.
3. *In Situ* resource utilization (ISRU).
4. Radiation.
5. Toxic effects of martian dust on humans.
6. Atmospheric electricity.
7. Forward planetary protection.
8. Effect of dust on surface systems.
9. Trafficability.
10. Properties of dust storms affecting extra-vehicular activity.

Human exploration of Mars is likely several decades away but *in situ* exploration by humans could lead to a deeper understanding of the evolution of the solar system and the origin and evolution of life.

6. Stepping stones toward a global space exploration program

As outlined in the previous chapter the major spacefaring nations have developed plans for ambitious space exploration programs to explore the Earth–Moon–Mars space in the new millennium. Appendix A lists space exploration capabilities and planned exploration missions for this decade. National exploration programs are developed under different political realities and follow different interests, but are also subject to different authority and influences from the various space exploration stakeholders. Therefore it will require many steps to reach a united space exploration governance structure. In the transition period toward a truly global endeavor robust stepping stones in preparation of global space exploration can unite key stakeholders already in an early phase (Ehrenfreund and Peter, 2009; Ansdell et al., 2011). Stepping stones can improve and ease technology transfer rights or other regulations as well as the development of interfaces which are all major prerequisites and building-blocks for a future global space exploration program. Different initiatives providing clear milestones, as illustrated in Table 1, could be used as intermediary steps to support joint research, foster transnational alliances, and educate and inspire a new generation of researchers.

6.1. International Earth-based field research program

Extreme environments on Earth can pose conditions analogous to those at potential landing/operation sites on the Moon and Mars. By increasing our knowledge of the geology and biology of terrestrial analogues, our understanding of other planetary bodies and the limits/adaptability of life can be ultimately enhanced (Foing et al., 2011). Moreover, the technologies required for scientific investigations in extreme environments on Earth are similar to those needed for operations in space (Chung et al., 2010; Osinski et al., 2010). Thus, analogue studies in extreme environments also provide a unique opportunity to foster collaboration between the Earth science and space exploration communities. Testing related technologies and protocols and training science and operations teams in extreme environments will be beneficial for interpreting and validating information from orbiter and rover missions on extraterrestrial bodies (Léveillé, 2009).

International cooperation on terrestrial analogue activities is a logical first step to implementing international Moon-Mars missions. This is an ideal time for such partnerships as many countries are embarking on ambitious space exploration activities beyond their budgetary means. It provides a unique opportunity to establish international cooperation at an early stage that will evolve into a truly

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[9] http://mepag.jpl.nasa.gov/Goal4/index.html.

integrated space exploration program designed to share costs and reduce risks.

Field research in support of planetary exploration include in general: the investigation of geological and geochemical context; drilling of cores and sampling; remote controlled field rovers; cameras; instruments; evaluation of crew operations; simulations and Extra Vehicular Activities (EVAs) and many other aspects. Numerous programs are currently undertaken worldwide that include various stakeholders (Ansdell et al., 2011). Among the most international oriented programs in alphabetical order are:

6.1.1. Concordia

Concordia Station is a permanently inhabited research facility in Antarctica for conducting scientific research in the fields of glaciology, atmospheric sciences, astronomy and astrophysics, Earth sciences, and human biology and medicine. Currently there are 13 people living in the station. The station is impossible to leave and reach during the winter months. The European Space Agency (ESA) cooperates on aspects of human exploration and sends regularly crew members to the station.

6.1.2. CAREX

The European Commission has initiated within its "7th Framework" a program called CAREX (Coordination Action for Research Activities on life in Extreme Environments), that coordinates and sets scientific priorities for research of life in extreme environment. CAREX endorses cross-sector interests in microbes, plants, and animals evolving in diverse marine, polar, and terrestrial extreme environment as well as outer space (CAREX, 2010). The recently released CAREX roadmap presents a solid scientific consensus from a community of European and international experts studying life in every type of extreme environment. It prioritizes four high-level research themes, recommending them as the basis for a future international collaborative initiative.[10]

6.1.3. MDRS/F-MARS

The Mars Society operates two simulated Mars habitats, the Flashline Mars Arctic Research Station (F-MARS) on Devon Island and the Mars Desert Research Station (MDRS) in Utah, USA. MDRS is a societal endeavor that engages public applicants.

6.1.4. ILEWG field tests

ILEWG has developed with task groups on "Technology" and "Lunar Base", technical pilot projects that organized and coordinated field campaigns at MDRS in Utah (see Fig. 7), at Eifel volcanic park (Germany), Rio Tinto (Spain), and other sites, in collaboration with ESA, NASA and academic/industrial partners. The goals of ILEWG field campaigns include: (1) testing instruments, rovers, landers, EVA technologies, habitat and field laboratory; (2) performing Moon-Mars analogue field research in geology, sample analysis, exobiology; (3) studying human factors and crew aspects; (4) outreach and student training.

Fig. 7. ILEWG-ESA-NASA Mars Desert Research Station MDRS Crew #77 (GeoMoonMars campaign), testing sampling procedures, instrumentation, *in situ* analysis and human exploration aspects in Utah, February 2009. *Image Credit: ILEWG/MDRS.*

6.1.5. PISCES

The Pacific International Space Center for Exploration Systems (PISCES) is located in Hawaii in Hilo (UH-Hilo) and dedicated to the development of new technologies needed to sustain life on the Moon and beyond. PISCES was conceived by the Japan-US Science, Technology and Space Application Program (JUSTSAP) and established as an official center at Hilo in 2007 (PISCES, 2007). The concept for the International Lunar Research Park (ILRP) begins with a terrestrial prototype at PISCES and would be migrated to the Moon robotically via planned and future international missions, including private launches by the Google Lunar X-Prize contestants and others.

6.1.6. Mars500

On 3rd June 2010, a crew of six men (from Russia, Europe and China) started a simulated mission to Mars. The simulation lasted 520 days (250-day trip to Mars, 30-day stay on the surface, and 240-day return journey). The crew lived and worked in a sealed facility in Moscow to investigate the psychological and medical aspects of long-duration space missions. Efforts to reproduce a real trip to Mars included limiting supplies and imposing an artificial 20-min delay in communications each way. The isolation study is conducted under the auspices of ESA and the Russian Institute for Biomedical Problems (IBMP) and receives strong media attention. The Mars 500 simulation ended in November 2011.

The large number of existing and planned terrestrial analogue programs shows the importance of these activities

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[10] http://www.carex-eu.org/.

and provides foundations upon which cross-disciplinary expeditions can be initiated under the auspices of both developed and emerging space nations (Ansdell et al., 2011). Although there are many terrestrial analogue field sites currently in operation around the world, no integrated program exists to date to bring together these common efforts. Consequently there is no common focus, database, nor roadmap.

CAREX has been active for two years in delineating a multidisciplinary scientific community and has established a comprehensive roadmap for research on life in extreme environments through working meetings and field trips. The approach proposed as one of this roadmap's core themes: "*Life and Habitability*" could serve as a model for an international research program that prepares for future robotic and human exploration of the Earth–Moon–Mars space and that combines efforts to exploit synergies between Earth science and space exploration. Understanding and protecting life on Earth requires similar concepts that are needed for the exploration of environments and possible life beyond Earth (Chung et al., 2010).

Successful transnational cooperation in this research area will stimulate sharing expertise and resources and will encourage the establishment of common standards, methodologies and frameworks. An "*International Earth-based field research program*" as a stepping stone for global space exploration, supported by national science foundations and executing a roadmap that has been established in consensus with many international partners, will provide sustainability and a stimulus for emerging countries to join such an international effort (Ansdell et al., 2011; Nordheim et al., 2010). A comprehensive study and literature survey on analog missions targeting human exploration on Mars has been undertaken by the International Space University (ISU, 2010). The Master project 2010 was devoted to elaborate a Human Analog Roadmap, namely Project Mars Analog Path "MAP". Nine analog studies were carried out under this framework that targeted a 30-year timescale. The proposed analog studies covered four main categories by location: Earth-based, in Low Earth Orbit (LEO), on the surface of the Moon, and between Earth and Mars as well as topics such as bed rest studies, an integrated transit simulation, an interior habitat design study, testing life support systems and research in Antarctica. Some programs have strong synergies with experiments and science investigations conducted on the ISS that investigate, for example, human physiology in microgravity.

Improved coordination of terrestrial analog research (including isolation studies), ISS-based research as well as experiments from supporting parabolic flights can provide an important base of knowledge for long-duration missions. A database of the various aspects of robotic and human exploration simulations will be crucial to perform more complex integrated studies that prepare for challenging human exploration missions visiting the Moon, Mars and NEOs. A recent COSPAR report on this topic has been released in August 2011 (PEX, 2011).

6.2. Science exploitation of the ISS enabling exploration

Research on the International Space Station (ISS) delivers increasing science return. Over 400 experiments have been performed in the last 10 years on topics including human life science, biological science, human physiology, physical science, material science, Earth science and space science that are summarized in the publication: "*International Space Station Science Research Accomplishments During the Assembly Years: An Analysis of Results from 2000–2008*" (Evans et al., 2008).

The European Programme for Life and Physical Science in Space (ELIPS) makes Europe the largest scientific user of the ISS. Among the future ESA research objectives on the ISS is the "Preparation of Human Exploration of Space".

ELIPS 3 conducts studies on:

- Radiation biology and physiology.
- Health care and human performance under extreme conditions.
- Life-support and thermal control systems.
- Food production in space.
- Fluid handling and processing in space.
- Material exposure and advanced materials.
- Contamination and planetary protection studies.

A Decadal Survey conducted by the US National Research Council (NRC) on "*Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era*" has been completed (NRC, 2011b) that investigated objectives for life and physical sciences research to meet the needs of exploration missions. An integrated microgravity research portfolio was recommended. "Some of the key issues to be addressed in the integrated research portfolio are the effects of the space environment on life support components, the management of the risk of infections to humans, behavior having an impact on individual and group functioning, risks and effects of space missions on human physiological systems, fundamental physical challenges, applied fluid physics and fire safety, and finally, translational challenges arising at the interface bridging basic and applied research in both life and physical sciences".

Space radiation is a major barrier to human exploration of the solar system. It is therefore crucial that precursor missions carry instrumentation to make environmental measurements. The materials of future spacecraft and habitats have to be optimized for their shielding efficiency against space radiation. Predictions of the nature and magnitude of the radiation risks of space radiation are subject to large uncertainties due to limited and inconclusive sets of observations. Large ground-based radiobiology research experimental programs are currently ongoing to reduce these uncertainties with regard to such biological effects as carcinogenesis, central nervous system damage, immunological effects, and cataract development caused by

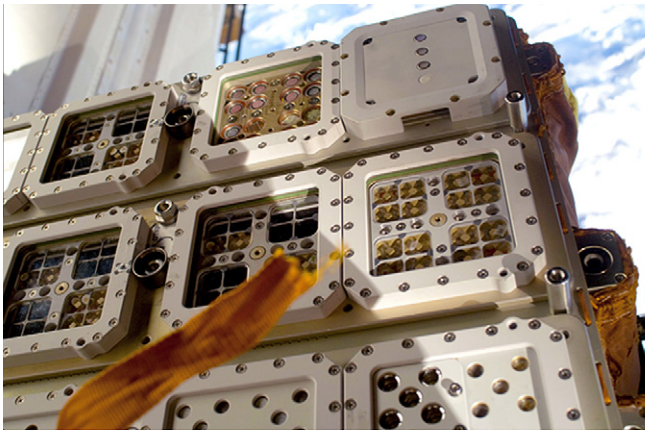

Fig. 8. The external exposure facility EXPOSE-R was operational on the ISS between March 2010–January 2011 and will be relaunched in 2012. EXPOSE-R is a multi-user facility that accommodates biological and biochemical experiments. It is attached to an external platform URM-D on the Russian segment and investigates the effects of space radiation on biological material. The research conducted on this facility provides a model for successful European-US-Russian collaboration. *Image Credit: ESA*.

heavy ions. These studies are conducted in the USA (at the NASA Space Radiation Laboratory at Brookhaven National Laboratory, New York), Europe (at GSI in Darmstadt, Germany), and Japan (at HIMAC in Chiba) using facilities that need to be maintained or even strengthened.

More facilities, a larger crew, better equipped laboratories that are used in international cooperation offer an environment that can be used to prepare for robotic and human exploration. Below we describe in more detail a few of the national ISS facilities that are particularly suited for exploration science (see also Fig. 8).

Laboratories like MISSE (Materials International Space Station Experiment) test spacecraft materials in the environment of atomic oxygen, vacuum, solar radiation, charged particle radiation, micrometeorites, thermal cycling, etc. Testing of new materials is necessary to determine the durability of materials in space and improve the design of stronger, more durable spacecraft components.

The Japanese Experiment Module KIBO provides a laboratory that enables experiments for space medicine, biology, Earth observations, material production, biotechnology and communications research. The Remote Manipulator System (RMS) connects the pressurized laboratory to the Exposed Facility, a platform that can hold up to 10 experiment payloads.

The Russian greenhouse LADA from Roskosmos studies fundamental plant biology and in particular the growth of sweet peas, wheat, tomatoes, and lettuce in microgravity, and provides an important contribution to research related to food safety issues.

The Canadian OSTEO (Osteoporosis Experiments in Orbit) Bone Culture System enables the growth of bone cells in microgravity. OSTEO has been used successfully on US Space Shuttle and Russian Foton recoverable orbital flights and is also available for use on the ISS.

The ESA-Facility MATROSHKA uses a human phantom equipped with radiation measurement devices providing depth dose distributions which will be used for a better correlation between skin and organ dose for astronauts in order to improve radiation risk assessments. This research is critical for our understanding how to protect crew members from radiation as they spend long durations in space on board the International Space Station (ISS), or on a possible journey to the Moon and Mars.

The European Laboratory Columbus harbors several facilities that provide a testbed for exploration: the Biolab for experiments on micro-organisms, cells and tissue cultures, and plants in microgravity; the European Physiology Modules Facility (EPM) that tests effects of long-duration spaceflight on the human body; the Fluid Science Laboratory (FSL) that investigates the weightless liquids; the European Drawer Rack (EDR); the European Transport Carrier (ETC) and the Microgravity Glove Box (MGB) as support for experiment activities in Columbus; and its external facilities EuTEF and SOLAR.

EXPOSE as part of EuTEF tested the effect of solar radiation and space vacuum on biological and organic material and SOLAR provides measurements of the solar spectral irradiance throughout virtually the whole electromagnetic spectrum. Additional ISS research capabilities are outlined in the recent booklet "*Research in Space*".[11]

Supporting non-ISS projects that involve bed rest and isolation campaigns, parabolic flights and drop tower campaigns as well as sounding rocket experiments are important as they represent crucial elements in the preparation phase for space exploration. A recent study by the International Space University (ISU) investigated in detail analog studies for the preparation of human missions to Moon and Mars that proposed to establish a metric to enhance cooperation, ease standardization and to exploit sufficiently datasets of analog studies worldwide (Nordheim et al., 2010) (see also Section 6.1).

The objective of the European Community funded program THESEUS is to develop an integrated life sciences research roadmap enabling European human space exploration in synergy with ESA strategy. THESEUS will focus on pending technological, medical and psychological issues for future human space flight such as protection against ionizing radiation, psychological issues, behaviour and performances, prevention of bone loss, and others.[12]

All current roadmaps of national and international space exploration working groups (as well as ISS partners) recognize the importance of the "*Science exploitation of the ISS enabling exploration*". Expanding international cooperation to non-ISS partners (such as China and India) is essential for future global space exploration. A long-term

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[11] http://www1.nasa.gov/pdf/393789main_iss_utilization_brochure.pdf.

[12] http://www.theseus-eu.org/.

science program utilizing modular payload racks may be suited to involve developing countries supported by United Nations (UN) bodies (Ansdell et al., 2011).

6.3. International CubeSat program in support of exploration

Development of the smallest of the small satellites, the “nano” and “pico” categories in which so-called CubeSats belong, was pioneered by universities, where they were recognized some twenty years ago for their potential as highly effective educational vehicles. Conventional satellite development for the most part is a capital- and expertise-intensive endeavor requiring multi-year development and large professional teams, severely limiting opportunities for science and engineering students to participate. Recognizing the need for student access to aerospace development programs, Jordi Puig-Suari of California Polytechnic Institute (CalPoly) and Robert Twiggs of Stanford University co-developed the CubeSat specification.

Though pioneered in universities, the potential impact of small satellite technology was not lost on governmental space and research agencies, e.g., NASA, NSF and ESA. NASA’s O/OREOS CubeSat launched in November 2010 is depicted in Fig. 9.

In addition to governmental programs, CubeSats have spawned significant commercial activity, including numerous commercial entities spun off from academic institutions. The United Nations (UN) have formally recognized the benefits small satellites provide to developing and emerging nations. The utility CubeSats for science and technology as research platforms is now recognized (Woellert et al., 2010) and providers are responding by offering affordable instrumentation normally seen only for larger satellites. CubeSats are able to capitalize on the latest technology to fly instruments that truly are “state of the art” and can address the latest high priority issues. A new initiative within the framework of the UN, the UN Basic Space Technology Initiative (UNBSTI), plans to act as an information broker and interface between stakeholders (Balogh and Haubold, 2009; Balogh et al., 2010).

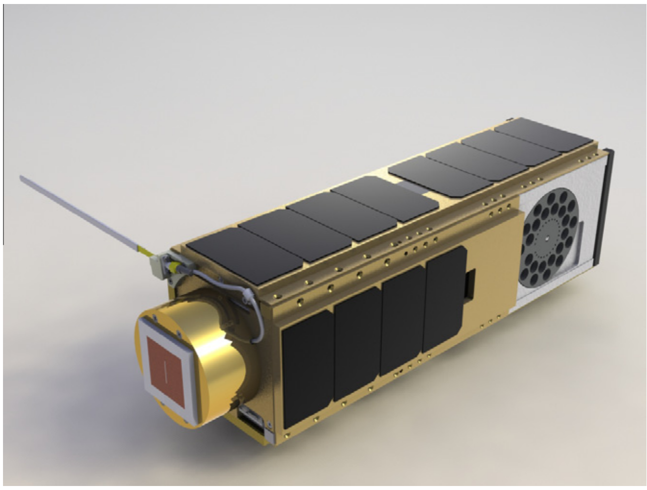

Fig. 9. NASA’s Organism/Organic Exposure to Orbital Stresses, or O/OREOS nanosatellite, is a triple CubeSat that weighs approximately 5 kg and includes two separate science payload instruments testing the stability of organic material and micro-organisms in Low Earth Orbit (LEO), respectively. It was launched in November 2010 and fulfilled all success criteria in May 2011 in 650 km orbit. *Image Credit: NASA Ames Small Spacecraft Office.*

As small-satellite technologies begin to facilitate bona fide science experiments, their comparatively low cost and the ubiquitous opportunities to deliver them to space will make it possible to replicate experiments across multiple space flights. The rapid evolution of capable instruments for CubeSats promotes them as possible hitchhikers on Moon and Mars orbiters.

An “*International CubeSat program in support of exploration*” could perform exciting research in biology, atmospheric science, space weather, material processing and other areas that are relevant for space exploration (Ansdell et al., 2011). For emerging countries that are not able to contribute to rovers and orbiters such a program would allow them to participate and form and educate a space generation (Woellert et al., 2010).

6.3.1. CubeBots as low-cost robotic surface component

Extending the concept of traditional CubeSats in orbit, exceptionally small, CubeSat-class mobile surface systems may also provide affordable, high-value opportunities for broad-based participation and scientific discovery in future exploration missions. During the past decade, exceptionally small robotic systems have become practical. Fig. 10 provides an illustration of one such concept, a small surface robot in the 5-kg class.

These systems, which could range from 1 to 100 kg, can leverage advances in computing and electronics, imaging, actuators, etc. and enable very low-cost candidate payloads

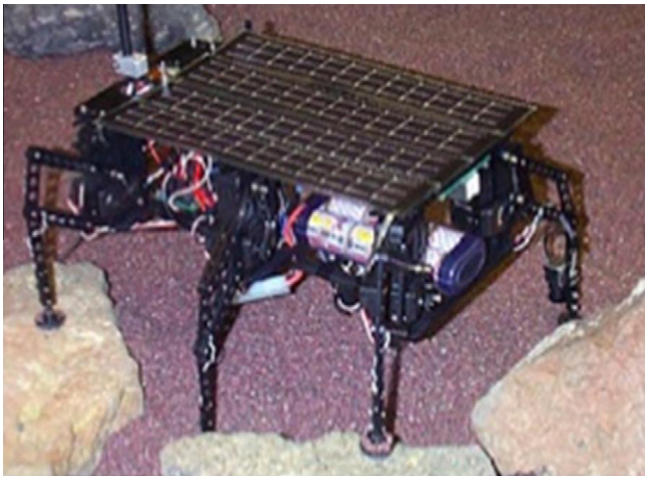

Fig. 10. A small surface robot in the 5-kg class. *Image Credit: Jet Propulsion Laboratory.*

for future surface missions. It is evident that these systems have several critical limitations, primarily in the functional areas of (1) safe and precise transportation to lunar or planetary surfaces, (2) communication, and (3) power and (especially) thermal management. However, each of these challenges could be dealt with through collaboration with more traditional space programs and missions or employing distributed and networked operation paradigms. For example, multiple "CubeBots" from various sources might readily be deployed as a single payload with much larger landers – scattering autonomously at a surface site to collect useful data from highly hazardous but scientifically interesting sites.

In addition, the challenge of delivering data from such robots could readily be accomplished in several ways. For example, a number of such "CubeBots" could be ganged together in a wireless network to transfer data via successive line-of-site links from a remote location back on the lander from which they were deployed.

Alternatively, multiple "CubeBots" might be merged into a single synthetic aperture using a simple retro-directive phased array technique to provide data to an orbiter directly. Also, the challenge of thermal management – particularly providing heat during extreme environmental conditions – could be provided by a "nesting" approach.

For example, after two weeks of exploration on the Moon, any surviving "CubeBots" could attempt to return to the system that deployed them (i.e., a lander). This system would then provide the needed heating to enable the smaller "Bots" to survive the extended lunar night and resume exploration the next day. Overall, the integration of multiple small CubeSat-class robots with large surface systems could dramatically extend the potential for participation in surface exploration activities, as well as the reach of more traditional systems into scientifically promising, but potentially risky environments. Combining multiple such "CubeBots" together and linking them to larger systems on the surface or in orbit could readily expand the data returned from these novel, low-cost exploration systems and involve a large community of scientists worldwide.

6.4. Global Robotic Village (model ILEWG)

The ILEWG community recommended a sequence of technology, exploration and commercial missions on the road to human Moon presence (see Fig. 11). ILEWG supports the cooperation of a series of missions including polar orbiters and landers and network missions. Robotic engineering precursors for *in situ* resource utilization and deployment of infrastructures preparing for human-tended operations are recommended (ICEUM5, Hawaii, 2003).

"The community recognized that the lunar exploration program must later include advanced orbital instruments as well as *in situ* analyses from several surface stations and targeted sample return, and urged broad and open discussion and coordination for selections of landing sites to

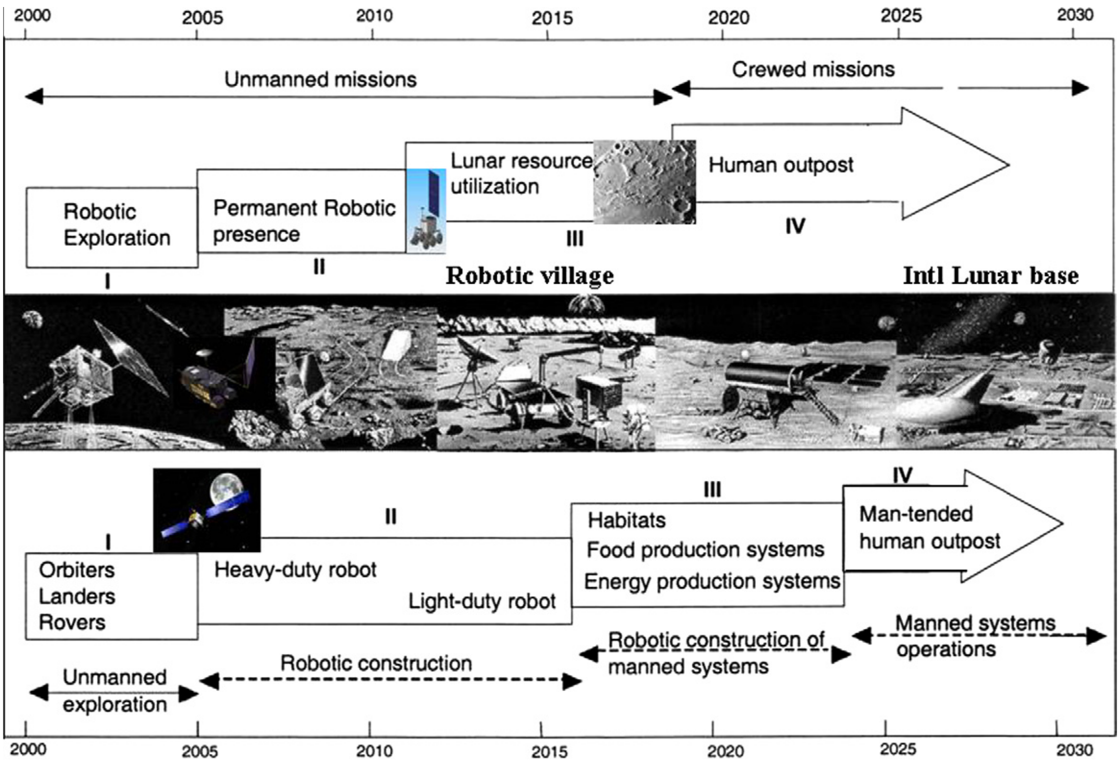

Fig. 11. The ILEWG roadmap: from precursor missions via a Global Robotic Village to Human Outposts and an International Lunar Base. *Credit: ILEWG.*

optimize the science return and benefit for exploration (ICEUM6, Udaipur, 2004)".

ILEWG supports the goals of a comprehensive series of surface elements including landers and rovers at the poles and other key sites. The model envisages the deployment of landers from different countries that are developed and operated in coordination. The rovers should perform complementary cooperative robotics and exploration tasks, and demonstrate enabling technologies. Such a program will initiate and enhance international collaboration, as well as science, commercial and public engagement opportunities. Various infrastructure assets such as telecom, power generation, can be shared by the international partners. "The planning and development of a Global Lunar Robotic Village will encourage and stimulate the peaceful and progressive development to investigate the Moon, and foster international cooperation between nations, space agencies and private companies (ICEUM7, Toronto, 2005)."

The rationale for and possible implementation of a lunar Global Robotic Village have been discussed by the ILEWG community, with a phased approach with orbital reconnaissance, small landers, a network of landers for science (of, on and from the Moon) and exploration. Then advanced robotic precursors to human missions with deployment of large infrastructures, including resource utilization, would conduct operations imminent to human arrival, during and between human early missions (see Fig. 11). Possible elements of the Global Robotic Village are discussed in ILEWG volumes (ICEUM4, 2000, pp. 219–263, pp. 385–391; ICEUM9, 2007, pp. 82–190).

ILEWG developed a research pilot project called "ExoGeoLab" supported by ESA, NASA and partners to test a lander, with rovers and instruments, and cooperative Robotic Village operations (see Section 6.1).

6.4.1. Google Lunar X Prize and other entrepreneurial efforts

Exciting precursors to a Global Robotic Village will be emplaced before 2015 benefiting from the Google Lunar X Prize competition. In the domain of robotic exploration the X PRIZE Foundation and Google announced in 2007 a new cash prize competition, the Google Lunar X PRIZE with 30 million US dollars in incentives. The goal of the new prize is to land a privately funded robotic rover on the Moon that is capable of completing several mission objectives.[13] The International Lunar Research Park initiative studies an approach by establishing a terrestrial prototype with PISCES (see Section 6.1), followed by a tele-operated robotic village on the Moon, culminating in a human settlement, all developed by the governments of many nations and private entities.[14]

The new era of space exploration provides ample opportunities for the commercial sector (Ehrenfreund and Peter, 2009). The commercial space sector and space entrepreneurs will support operations and infrastructures to enable the government sector to engage in exploration activities, but will also take independently the lead in certain exploration endeavors. The recent successful launch of the Falcon 9 rocket (Space X) was a first step toward the goal of using private contractors to deliver people and cargo to the International Space Station. The free-flying, reusable spacecraft Dragon, being developed by Space X under NASA's Commercial Orbital Transportation Services (COTS) program, will resupply the ISS in the near future.

6.5. International Sample Return missions from Moon, NEOs and Mars

The analytical precision and accuracy obtainable in modern Earth-based laboratories exceeds that of any *in situ* instrument onboard spacecraft, due to limited resources of power and sample preparation. As discussed before sample return missions to Moon, NEOs, Phobos and Mars have highest priority for the science community.

The Russian planetary exploration mission Phobos-Grunt was launched to the martian moon Phobos in November 2011 to return samples from Phobos to Earth for scientific research and study the Mars environment concerning atmosphere, dust storms, plasma and radiation. China's Yinghuo-1 orbiter hitchhiked on the Russian Phobos-Grunt mission to conduct space-environment, atmospheric, gravity, and surface-imaging studies of Mars (see Fig. 12). After an engine failure both probes remained in low Earth orbit.

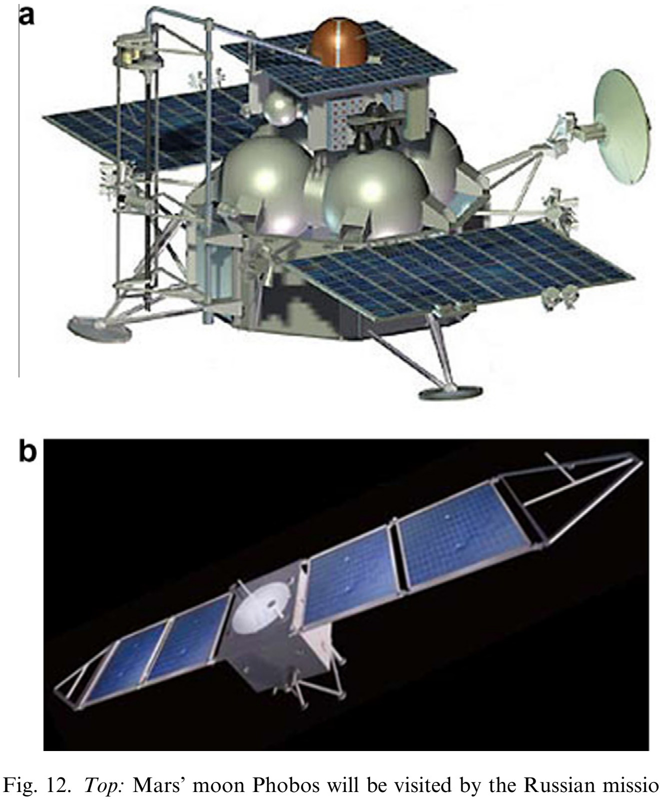

Fig. 12. *Top:* Mars' moon Phobos will be visited by the Russian mission Phobos-Grunt that will return samples to Earth for scientific research. *Bottom:* China will send the Yinghuo-1 (YH-1) orbiter piggyback on the Russian mission. *Image Credit: Roskosmos, CNSA.*

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[13] http://www.googlelunarxprize.org/.

[14] https://sites.google.com/site/internationallunarresearchpark/.

NASA's New Frontiers program has selected in June 2011 the Origins Spectral Interpretation Resource Identification Security Regolith Explorer spacecraft, called OSIRIS REx (to be launched in 2016), that will rendezvous and orbit a primitive asteroid. After characterizing the target, instruments will collect material from the asteroid surface for return in 2023 to Earth.

The Chinese Chang'E program foresees a lunar sample return mission by 2017. A second Japanese NEO sample return mission Hayabusa-2 is planned for launch in 2014. A general concept for a Mars Sample Return mission is discussed in detail in Section 5.3.

The Moon's proximity to Earth allows lunar sample return to act as a testbed for robotic technologies enabling sample return from more distant planetary bodies. Between 1969 and 1972 the six Apollo missions that landed astronauts on the Moon returned a collection of over 2000 soil samples (in total, 382 kg). However, Apollo samples were collected from a relatively small, equatorial area of the Moon that consists of conditions that are atypical for the Moon as a whole. Therefore many follow-on lunar sample return options have been evaluated in the last decade to bring back samples from other locations on the Moon, 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 via *in situ* exploration.

The rationale for lunar sample return is described in the LEAG roadmap and ILEWG documents (ICEUM1, 1994, pp. 51–63, ICEUM9, 2007, pp. 59–60). Priority areas include the South Pole Aitken Basin impact melts (as a probe of lower crust and upper mantle material, and a constraint on the chronology of early bombardment), samples of polar volatiles, and from the youngest lunar volcanic units in Procellarum. Lunar samples can be returned with automatic missions such as MoonRise (proposed to NASA's New Frontiers program) and Chang'E-3 or from future human missions to the surface.

Touch and go and surface-collection missions to the Moon have been investigated by the Curation and Analysis Planning Team for Extraterrestrial Material (CAPTEM). Current mass estimates for a sample collection lander for the Moon (or Mars) are in the range of 1000–1500 kg, and sample-return operations are complex. Indeed, sample return technology is highlighted as the closest simulation for human exploration missions. Enabling technologies have been defined that can be used for many sample acquisition types and sample return mission scenarios, and include: sample acquisition methods; sample transfer mechanisms; sample container technology; low mass lander/ascent vehicle infrastructure; development of cold/cryogenic curation and storage protocols; development of non-silicate aerogel for dust sampling and environmental monitoring (CAPTEM, 2007).

Sample return missions from asteroids are technically simpler as they require docking, rather than descent and ascent vehicles. Those automated sample returns will make use of curatorial and sample distribution facilities and methodologies developed for lunar samples, with potential added complexity imposed by planetary protection and contamination requirements.

Sample return missions will be much more affordable when conducted in cooperation and when worldwide expertise can be exploited. As seen for the Mars Sample Return mission, a multi-element mission scenario (discussed in detail in Section 4.3) is currently anticipated that would provide opportunity for other nations to join and develop one of the elements. Cooperation with space powers that build major hardware (space probes, descent modules, ascent modules, etc.) and provide launchers can be augmented by other current and emerging spacefaring nations that provide either payload or manpower for joint missions. An Earth-based challenge is the curation of returned samples.

Dedicated curation laboratories will need to be designed and constructed, and there may be specialized requirements for long-term preservation of ice samples and other volatiles, which would require storage and manipulation of such samples at sub-freezing temperatures. Building such a facility in international cooperation could foster extensive science and engineering collaboration in support of future international sample return missions.

6.6. International Lunar Base

Planetary science stands to be a major beneficiary of human space exploration. Human exploration of the Moon facilitates landing, operating and maintaining massive and complex scientific equipment as well as large-scale exploratory activities such as drilling. Human exploration can enable the intelligent and efficient collection of samples in large quantities, covering different locations and wider geographical areas (Cockell 2004; Crawford et al., 2009). Human exploration of the Moon allows for increased opportunities for serendipitous discoveries. Furthermore, it takes advantage of the fact that human beings can work intelligently and quickly, make sense of complexity and are able to troubleshoot unforeseen problems with inherent flexibility. Whereas robots are expendable, environmentally robust, continuously present, and characterized by physical durability, they suffer from limited intellectual capability, a slow data rate and power constraints. Overall, however, robotic exploration is comparatively cheap – both in terms of cost and risk. Humans, in turn, are mechanically flexible, able to communicate and can handle difficult terrain.

Humans can easily adapt to different situations, are intellectually flexible, but they require life support, and need to sleep and eat. Overall, human exploration is expensive. In order to make the best use of each system's advantages, a sensible long-term exploration roadmap should envision that robots and humans explore in synergistic partnership (Huntress et al., 2004; Cockell, 2004; Hubbard, 2005; ESSC, 2009; Stetson et al., 2009; LEAG and ILEWG roadmaps, IAA, 2010a,b).

Different enabling technologies that are needed to prepare for human exploration:

- Soft and precision landing.
- Ascent and return capability.
- Surface mobility.
- Samples collection and *in situ* analysis.
- Advanced life support systems.
- Radiation protection.
- *In situ* resource utilization (ISRU).
- Habitats as living and working area.
- Energy production and storage.
- Advanced robotic tools.
- Astronaut assisted drilling.
- Laboratory facilities.

An International Lunar Base design requires the knowledge of many different disciplines, e.g., scientists, engineers, architects, industrial designers and medical personnel (see Fig. 13). The vision for space exploration introduced by US President G. Bush envisaged the return of humans to the Moon by 2020.[15] ILEWG and LEAG have worked for more than a decade on concepts for a lunar base as an important milestone in their roadmap. The International Astronautical Federation (IAF)/International Academy of Astronautics (IAA) Lunar Development Forum acts as an informal group of world citizens in the development of space travel. They observe and participate in public discussions of current and future activities to the Moon and beyond, and have been publishing a newsletter "Lunar Base Quarterly" since 1990. In 2003 ESA's Human Spaceflight Vision Group has identified a Moon Base programme as a "societal project" and "an ideal stepping stone to another world that will open the door to future exploration of the solar system".[16] From a political point of view, the development of a lunar base as an example for international cooperation has been identified by the Beijing Declaration 2008.[17] A recent ESA-NASA architecture study ("The NASA-ESA Comparative Architecture Assessment")[18] offered a unique possibility to discuss the requirements and implementation aspects of human lunar exploration missions by sharing capabilities. A "*Reference Architecture for Human Lunar Exploration*" has been completed by the International Space Exploration Coordination Group (ISECG), that includes 3 scenarios: Polar Lunar Outpost Scenario; Lunar Sortie Mission Scenario; and an Extended-Stay Mission Scenario (see also Appendix B).

Considerations about the preparation for a human lunar base are described in ILEWG volumes (ICEUM4, 2000, pp. 265–329, ICEUM9, 2007, pp. 192–223, ICEUM10, 2008) including transportation, architecture, power, life support systems, support technologies and robotics, operations, research and crew aspects.

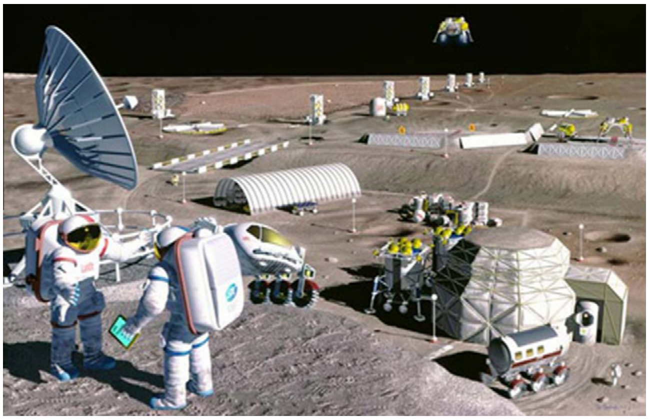

Fig. 13. An artist's concept of a lunar outpost. *Image Credit: NASA GRC.*

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):

- What technologies need to be developed now for human return to the Moon?
- 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 lunar 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 drilling challenges on planetary surfaces and how can they be addressed?
- How can future lunar surface activities be optimized?
- What precursor lunar surface experiments are of highest priority for space settlement/commercial development?

An important element for lunar outpost architecture is the habitation module. Its configuration is an important element of the outpost architecture definition, and it is a function of the environmental requirements, of the radiation shielding approach, of the transportation/operation constraints and of the distribution of functions between habitat elements (separated or integrated in the habitation core). Looking at the different solutions analyzed in the past and at the several trade-offs performed on the radiation protection options, the cylindrical module option provides advantages. Additional deployable volumes will

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[15] http://www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf.

[16] http://esamultimedia.esa.int/docs/exploration/StakeholderConsultations/Moon_The_8th_Continent.pdf.

[17] http://iaaweb.org/iaa/Scientific%20Activity/declaration.pdf.

[18] http://www.nasa.gov/pdf/259237main_NASA_ESA_CAA-Report.pdf.

allow extending the internal volumes with limited impacts in mass and in transportation volumes. Radiation protection can be provided by bags filled with regolith.

The Center for Strategic and International Studies (CSIS) has made a cost estimate for a lunar base based on available concepts and publications. Costs for such an endeavour would be about $ 35 billion for a 4 person crew, with additional operating costs of about $ 7.35 billion assuming no ISRU (all material supplied from Earth; CSIS, 2009).

Comprehensive studies and multidisciplinary analyses are needed to optimize the design of the human lunar outpost, the delivery of cargo logistics, and to develop evolutionary concepts for making use of local resources to enable sustainable human presence and fruitful operations on the surface of Moon and Mars. Concerning our understanding of the adaptation of the human body and its functions to the conditions of spaceflight, above all weightlessness, Europe has a leading role (e.g., ESSC, 2009, HUMEX study[19]). Someday, larger lunar outposts may serve as a backup for civilization in case of a global catastrophe, like an asteroid impact or a pandemic. Requirements and implementation of human missions and space habitats throughout the solar system including an economic analysis have been recently compiled and analyzed (McNutt et al., 2010).

6.7. Antarctic bases as analogues for Moon and Mars

The US South Pole station is the model for a research base on the Moon or Mars. Antarctica, like the Moon or Mars is of scientific interest and is also an international arena where nations compete and cooperate with each other. The US constructed the base at South Pole over 50 years ago and continues to operate it. The US Antarctic Program has the biggest bases on that continent and does the most scientific exploration of any nation. Also like the Moon and Mars, Antarctica is a place where humans cannot live without technology providing life support. Antarctica is the only continent that did not have native people. The first base was emplaced by Argentina in 1904. The Scientific Committee on Antarctic Research (SCAR) is charged with the coordination of scientific research in Antarctica.[20]*** SCAR also provides international, independent scientific advice to the Antarctic Treaty system and other bodies. Thirty-one countries pursue active scientific research programs in Antarctica and joined SCAR as full members.

Looking at why and how the US South Pole station is operated is a way to see why and how humans will operate a base on the Moon. The why traces back to competition and cooperation between nations. No nation may have any interest in “owning the Moon” but major space nations and emerging space actors will certainly want to have a major say in any treaties or agreements that involve the Moon, for both scientific and commercial purposes. In the Antarctic, only nations that have active bases have a say in the treaties and agreements. While geopolitics may be what ultimately motivates the US program in Antarctica, the activities conducted at the South Pole station are all related to scientific exploration (see Fig. 14). Commercial activities such as tourism are not supported by the US-operated infrastructure.

On the Moon as well, science will be what the astronauts do, although (due to the potential for commercial synergies) commercial activity may be conducted nearby, as well as in support of scientific research. Although the South Pole station has been in continuous operation since 1956 it is not a “settlement” or a “colony”. Scientists and support staff go to the station for a definite work period usually less than 1 year at a time. The crews change in and out so there is always someone at the station.

This may also be how a Moon base is operated: crews coming in, going out. Like Antarctica, initial efforts will yield research bases, and not colonies or settlements – at least not right away.

Another way that Antarctica is a model for the Moon is time. The South Pole station and the other US bases in Antarctica are over 50 years old and going strong. New discoveries are being made and students continue to flock to Antarctica to do their research. The US just opened a

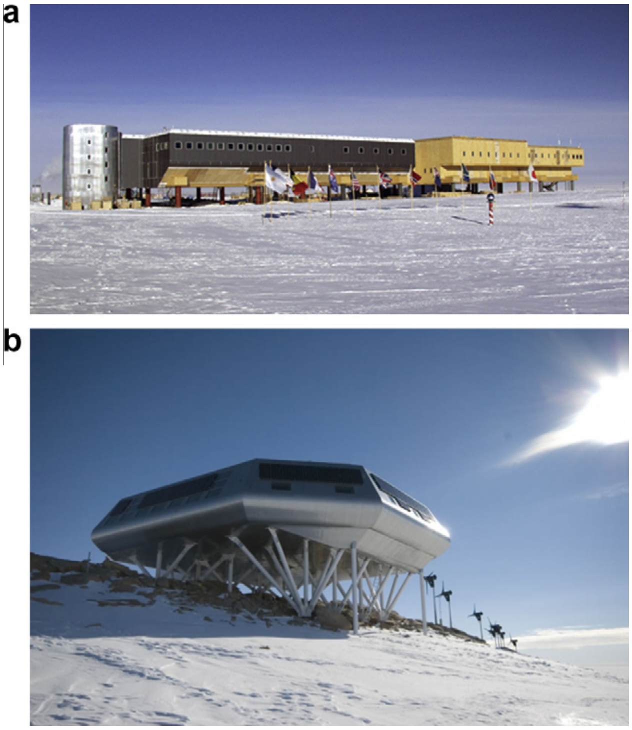

Fig. 14. *Top:* The Amundsen-Scott South Pole Station (US Antarctic Program) constructed in 1956 is continually inhabited by rotating crews. *Bottom:* The Belgium Princess Elisabeth Antarctica station is in use since 2009 and was constructed with eco-friendly construction materials. *Image Credit: NSF/USAP photo,* International Polar Foundation/René Robert.

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[19] http://www.esamultimedia.esa.int/docs/gsp/completed/comp_sc_00_S55.pdf.

[20] http://www.scar.org/about/.

new base at the South Pole with a design lifetime of more than 30 years. Plans for a Moon base should also be built with this sort of long-term stay in mind. Like Antarctica, the more we study the Moon the more new questions will arise. We can only guess at what we might learn. All of this also applies to Mars. Long term research bases with rotating crews doing scientific exploration can be planned for >100 years.

In Antarctica we have made long-term scientific exploration a reality. The US Antarctic Program has maintained a continuous research program in Antarctica for over 50 years. Scientists and other federal agencies propose research programs to the Office of Polar Programs OPP (NSF) ranging from astronomy to zoology. There are special programs for teachers, writers and artists, and news reporters. All aspects of the Antarctic Program, both logistics and science, are managed from the same office at NSF, which maintains a liaison and cooperative activities with the Antarctic programs of other nations working under the Antarctic Treaty System. On the national level, or if a multinational consortium were formed, this organizational approach could be used for a Moon/Mars base program.

7. Protecting the lunar and martian environments for scientific research

It has been long recognized that the environments of the bodies most likely to be the targets of intense robotic and human exploration in the coming decades, namely the Moon and Mars, possess a degree of fragility and can easily be degraded if appropriate actions are not taken by the spacefaring nations.

As an example, the total mass of the lunar atmosphere is ~100 tons, 90% of the molecular composition of which is still unidentified. The risks are various. According to the "Science Goal 8" of the NRC report on the scientific exploration of the Moon (NRC 2007): "Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state", human lunar exploration that encompasses landings, lift-offs, and EVA's will inject tons of non-native gas into the atmosphere and transform the pristine environment. On the purely scientific level, we risk losing the ability to measure and understand the subtle pristine conditions of these bodies before they are irrevocably altered by human-induced activity. At the other end of the spectrum, we risk undertaking activities which may compromise non-scientific activities through environmental disturbance and modification.

Amongst the environmental factors that are relevant here are issues such as dust raising, seismic disturbance, biological contamination, site destruction, electromagnetic interference, solar wind and radioactive contamination. The importance of these issues varies depending on the target body (Moon, Mars, asteroid, etc.), the disturbing activity (e.g., construction, *in situ* resource exploitation, large scale human activities, power generation, communications infrastructure, etc.) and the potential activity which may be compromised (i.e., scientific, exploration, operations, etc.). Each of the disturbing activities is likely to be of some significance on all target bodies, but their effects differ greatly in scale depending on the specific circumstances.

Accordingly, it is instructive to mention some specific examples. The lunar farside has long been recognized as a scientifically valuable resource. It can provide a site for the location of low frequency radio telescopes for the exploitation of one of the few parts of the electromagnetic spectrum so far not accessed. This may provide insights into the cosmologically significant "epoch of re-ionization". The lunar farside provides shielding from terrestrial man-made and natural radio interference, and partial shielding from strong solar radio emission. However, this unique location would clearly be compromised by inappropriate emplacement of lunar navigation and communication infrastructures. The IAA Cosmic Study on "*the Protected Antipode Circle PAC*" discusses that the farside of the Moon should be kept free from man-made Radio Frequency Interference (RFI) (Maccone, 2008).

Some of the planetary protection issues are already quite well-covered by other bodies. In this category is the topic of biological and organic-chemical contamination which has been extensively considered by the COSPAR Panel on Planetary Protection (PPP) and has resulted in the internationally recognized regulations to which most of the spacefaring nations adhere and which have been in place for 40 years. Other bodies which have an interest in these issues include the United Nations Committee on the Peaceful Uses of Outer Space (UN-COPUOS), the International Astronautical Federation (IAF), the International Academy of Astronautics (IAA) and the International Astronomical Union (IAU), as well as individual space agencies.

However, it seems that it would be of significant value to provide a focus in one place for all of these activities and in particular to give consideration to the impact on scientific research of these potentially deleterious activities. This may be particularly important at the present time when decisions taken in the US, still the largest individual nation in terms of space activities, mean that a great emphasis will be placed on the provision of space services by non-governmental, commercial interests. This may well mean that there is an even greater need than previously for highlighting the need for environmental protection in space as commercial pressures might relegate such considerations to a lower priority than previously, when space activities were the remit of only non-commercial interests (Masson-Zwaan, 2008).

The IAA Cosmic Study on "*Protecting the Environment of Celestial Bodies*" (PECB) examines current planetary protection controls for avoiding biological contamination and considers whether and how protection might extend to geophysical, industrial and cultural realms. In this context the establishment of planetary parks has been proposed by Cockell and Horneck (2006). The PECB Study report identified a variety of problems related to environmental protection, including the lack of suitable detection methodologies and an insufficient legal framework, a paucity of economic analytical tools, and a shortage of the political will to address the issues ahead (PECB, 2011; Race, 2011).

The activities of COSPAR's PEX include the identification of the environmental contamination issues and where possible the quantification of their effects on science (and other) activities, legal aspects, and the identification of entities (both within and outside COSPAR) which have an interest and work already undertaken. It may well be that some irreversible degradation of these delicate environments is unavoidable. In this case, one of the duties of PEX will be to identify these and provide the impetus for the relevant scientific measurements to be made while they still can be done. PEX also helps to identify principles regarding the imposition of different levels of protection on various target bodies or specific locations on those target bodies. Such principles should identify both the environments that are specifically sensitive and needing protection, as well as those that can be developed for non-science uses. A June 2010 Workshop on "*Ethical considerations for planetary protection in space exploration*" organized by COSPAR's Panel on Planetary Protection (PPP) advocated that COSPAR (PPP and PEX) and other bodies consider positive steps toward environmental stewardship for solar system bodies in addition to currently accepted regulations on planetary contamination.

8. Legal aspects of planetary exploration

The current legal regime governing Moon exploration is laid down in the UN Space treaties, specifically the 1967 Outer Space Treaty and the 1979 Moon Agreement.[21,22] The former has been ratified by 100 States and parts of it could be said to apply even to non-parties on the basis of having become customary international law.

The latter only has 13 States Parties, none of which are major space powers (Australia, Austria, Belgium, Chile, Kazakhstan, Lebanon, Mexico, Morocco, the Netherlands, Pakistan, Peru, the Philippines, Uruguay). The Outer Space Treaty applies to outer space, including the Moon and other celestial bodies. The Moon Agreement applies to the Moon and other celestial bodies in the solar system other than the Earth, and reference to the Moon includes orbits around, or other trajectories to or around it. It does not apply to extraterrestrial materials that reach the surface of the Earth by natural means.

General (Outer Space Treaty) principles governing Moon exploration include:

- Freedom of scientific investigation.
- Province of all mankind.
- Non-appropriation.
- Compliance with international law including the UN Charter.
- Prohibition of nuclear weapons and weapons of mass destruction (not defined).
- International cooperation and mutual assistance.
- Non-interference with activities of other states.
- International (state) responsibility and liability, also for activities carried out by private entities (which require "authorization and continuing supervision").

The Moon Agreement, main provisions include:

- Use for exclusively peaceful purposes.
- Prohibition of threats and hostile acts.
- Prohibition of military and weapons-related activities.
- Sharing of information on mission and its results.
- Report to UN if discovery of organic life or phenomena endangering human life/health.
- Notification of placement or use of radio-active materials on celestial bodies.
- Any person on the Moon is considered an astronaut; refuge to be offered in case of distress.
- Non-interference and consultations for surface and underground activities/settlements.
- (Parts of) the surface or subsurface of the Moon, or natural resources "in place" may not become property of a state, Inter-Governmental Organization (IGO), Non-Governmental Organization (NGO), national organization, or natural person.
- Samples may be collected and removed for scientific purposes, appropriate quantities may be used to support missions.
- Moon and its resources are the "*Common Heritage of Mankind*" and an international regime is to be established when exploitation of resources is about to become feasible.

During the past four decades, neither the Outer Space Treaty nor any of the subsequent treaties have established specific rules for activities related to the commercialization, exploitation, or use of natural resources of the Moon or other celestial bodies by either public or private entities. It should be noted that exploitation of lunar resources is a different topic, the "next step", and mainly the reason why the Moon Agreement has remained of limited influence. The Moon Agreement is the only of the five UN space treaties that explicitly addresses exploitation, and discussions about the meaning of Art. 11, declaring the Moon and its natural resources the "*Common Heritage of Mankind*", have sparked heated debate.

The Moon Agreement prescribes that an international regime be set up to govern exploitation, "as such exploitation is about to become feasible", and in relation herewith the question of the review of the Moon Agreement is foreseen

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[21] http://www.unoosa.org/oosa/en/SpaceLaw/gares/html/gares_21_2222.html.

[22] http://www.unoosa.org/oosa/en/SpaceLaw/gares/html/gares_34_0068.html.

ten years after its entry into force. The Moon Agreement entered into force in 1984, but no decision about review was taken since – perhaps because exploitation is still not "about to become feasible", but more likely because it did not provide for stable and predictable regulations on commercial, economic activity by either private interests or States Parties. Lunar exploration will benefit when new regulations encompass and balance a diverse set of stakeholder interests such as the protection of sensitive scientific areas on the Moon and commercial exploitation.

With regard to the important topic of the protection of the environment of celestial bodies Art. IX of the Outer Space Treaty provides a general obligation to protect the celestial bodies, including the Earth, from harmful contamination, which is not defined further. Art. IX stipulates avoidance of harmful contamination, protection of exploration, and prevention of "adverse" changes on Earth from the return of extraterrestrial materials. The implementation of Art. IX has resulted in a long and successful history of planetary protection (from living or organic contamination) of celestial bodies during space exploration. For recent discussions about Art. IX of the Outer Space Treaty, reference is made to the 5th Eilene M. Galloway Symposium on "Critical Issues in Space Law", held in December 2010, which addressed the topic "Art. IX of the Outer Space Treaty and Peaceful Purposes: Issues and Implementation".[23]

A similar provision is contained in Art. 7 of the Moon Agreement, but it qualifies such contamination as taking place "through the introduction of extra-environmental matter or otherwise". There is no prohibition of abandoning space objects on, or under, the surface of the Moon or on its trajectories. The IAA Cosmic Study on this subject developed new proposals, such as a differentiation of space activities and areas of the Moon, a new interpretation of the term "due diligence", the creation of "planetary parks" and a model for licensing procedures (PECB, 2011).

Art. 7 also states the possibility of creating international scientific preserves for areas of the Moon having special scientific interests, thus providing a means for protecting parts of the lunar environment for scientific research. Noteworthy is the 2008 "*Joint Statement*" in the UN-COPUOS Legal Subcommittee by the States Parties, attempting to convince other States to ratify the Moon Agreement by highlighting its advantages, pointing out that in conjunction with the Outer Space Treaty, the Moon Agreement is helpful for rejecting "idle claims to property rights" that have surfaced in recent years. Also, the International Institute of Space Law (IISL) has issued two statements, in 2004 and 2009, about claims to private property rights in space.[24,25] The 2009 statement says: "International Law establishes a number of unambiguous principles, according to which the exploration and use of outer space, including the Moon and other celestial bodies, is permitted for the benefit of mankind, but any purported attempt to claim ownership of any part of outer space, including the Moon and other celestial bodies, or authorization of such claims by national legislation, is forbidden as following from the explicit prohibition of appropriation, and consequently is prohibited and unlawful".

Parallels for the regime governing the exploration and exploitation of the Moon can be found in the Law of the Sea regime[26] and in the Antarctica regime.[27] The Law of the Sea regime also contains the term "*Common Heritage of Mankind*" with regard to resources of the deep seabed. Subsequent amendments have attempted to bring the system more in line with political and economic realities, and thus more readily acceptable by all States.

Antarctica and outer space have a lot in common. Both are hostile environments for humans, both are viewed with the potential for extensive and valuable resources of different types, and both are of intense interest for scientific research and exploration. As far as the Antarctic regime is concerned, the situation is somewhat different as several States have claimed sovereign rights over the area, which have subsequently been "frozen" but which are still "around" (this is not the case for the celestial bodies or parts thereof). In 1991 the "Consultative Parties" (i.e., the most interested parties with regard to these claims) decided to refrain from mining Antarctica and to "commit themselves to the comprehensive protection of the Antarctic environment and dependent and associated ecosystems and hereby designate Antarctica as a natural reserve, devoted to peace and science".[28] The mineral resources of Antarctica have not been declared the "*Common Heritage of Mankind*".

The Antarctic Treaty system is different from the legal regulation of outer space. The initial 1959 Antarctic Treaty (not a United Nations Treaty) has been supplemented by some 200 agreements and measures that have been developed and ratified via the ATCM process (Antarctic Treaty Consultative Meetings). This provides for a flexible, incremental system that can be supplemented with additional measures that become binding upon the parties after their acceptance, without the need to amend the Treaty itself. In contrast to the Antarctic Treaty System, the Outer Space Treaty has not developed a comprehensive framework of mandated environmental protections similar to that afforded by the Antarctic Treaty System. Part of the difference is based on the lack of scientific information available about Earth versus outer space. Therefore the implementation of the Outer Space Treaty's "*no harmful contamina-*

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[23] See for a report: http://www.iislweb.org/docs/2010_Galloway_report.pdf and for the presentations: http://www.spacelaw.olemiss.edu/event_Galloway2010.html. The papers are published in the 2011 IISL Proceedings.

[24] http://www.iislweb.org/docs/IISL_Outer_Space_Treaty_Statement.pdf.

[25] http://www.iislweb.org/docs/Statement%20BoD.pdf.

[26] http://www.un.org/Depts/los/index.htm.

[27] http://www.ats.aq/documents/ats/treaty_original.pdf.

[28] 1991 Protocol on Environmental Protection to the Antarctic Treaty, Article 2, see http://www.ats.aq/documents/recatt/Att006_e.pdf.

tion" article has focused on biological contamination avoidance, rather than on environmental protection, per se.

Although an understanding of Antarctic microbes and ecosystems has only recently developed, our understanding about flora, fauna, and environments on Earth is extensive, and can be applied to Antarctica for developing environmental and resource protections. Our limited knowledge about planetary environments, possible associated biota and dependent ecosystems in outer space makes it more difficult to establish appropriate levels of protection drawn directly from scientific analogies or legal precedents on Earth. It thus seems that the Antarctic Treaty framework is currently better prepared to tackle future challenges such as the growing interest in bioprospecting, increasing demand for tourism, and continued interest in mineral exploitation, oil and gas extraction, and expansion of economic activities (Race, 2011).

However, given the wide variety of different environments found in outer space, notions like environmental stewardship, sustainability, preservation, resource use, exploitation, or adverse impacts on, under or above celestial bodies have yet to be defined and discussed in detail, because in many cases hostile space environments are incapable of sustaining life. Accordingly, there are no general guidelines for how to address the protection of lifeless environments in the solar system (Race, 2011).

Many of the ideas identified as ways to move forward in outer space bear striking similarities to elements of the Antarctic Treaty's framework for environmental management, such as the designation of special management areas or protected zones, the development of a comprehensive environmental protection protocol, or the establishment of code(s) of conduct appropriate for different types of celestial bodies and environments and an elaboration of how these may apply to various categories of activities and different sectors (Race, 2011).

It is necessary to clarify and complement the legal regime currently regulating the exploration of the Moon and other celestial bodies. The broad principles that were adopted in the 60s and 70s remain valuable today and the delicate balance reached at that time should be maintained. However, additional regulation to implement the treaties is necessary to ensure valuable, safe, economic, and broadly-based space exploration, development and use that will benefit both current and future generations. The possibility provided by Art. 7 of the Moon Agreement to create international scientific preserves may be an interesting option to reach a similar situation as the one that was agreed for Antarctica, which has an initial focus on science, but still allows for commercial activity (e.g., tourism, support and supply operations) while controlling irreversible contamination of sensitive environments.

9. Synergies and recommendations

Solar system exploration in robotic/human synergy will spur scientific discoveries, strategic partnerships, technology progress, and public inspiration. Broad engagement of all stakeholders (governments, space agencies, the commercial space sector, space entrepreneurs, and public constituencies) will be required to create a sustainable global space exploration platform (Ehrenfreund and Peter, 2009). A global space exploration program will aid in the development of sufficient capability to implement an innovative long-term roadmap that will allow new countries to join and become engaged in an overall effort that can unite all stakeholders (see Fig. 15).

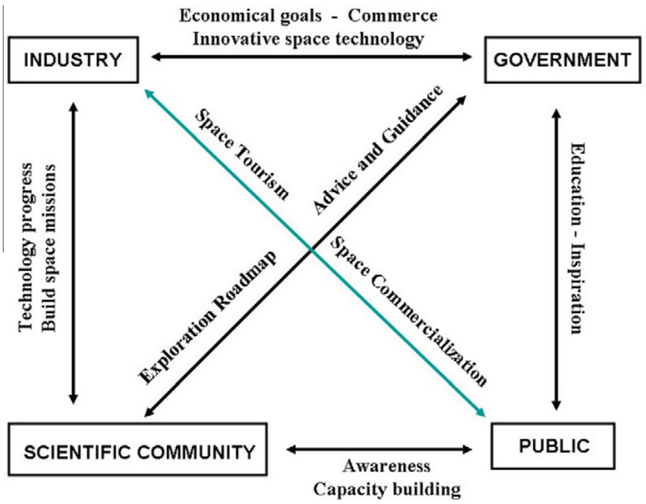

Fig. 15. Relationships of the main stakeholders in global space exploration (Ehrenfreund and Peter, 2009).

It is important to note that national and international science and analysis working groups have already invested considerable effort in developing science roadmaps, mission planning and mission scenarios (see Sections 1 and 2, Appendices). Future planning of space exploration should build on this substantial body of work, taking into account the latest scientific discoveries, technological development and the geopolitical context. For each exploration mission a minimum science payload should be considered.

9.1. Vision

Efforts have to be made to reiterate and reinforce the role of the scientific community in defining and fulfilling robotic and human space exploration goals: exploring the Moon, Mars and near-Earth asteroids. Exploration of the Earth–Moon–Mars space can provide answers to key questions of our existence: how our solar system formed, whether life exists beyond Earth, and what our future prospects may be.

The roadmaps of the national and international working groups discussed in Section 2.5 show a reoccurring theme, namely to explore the

"*Origins and evolution of our solar system and life*"

The study of this theme encompasses the integrated investigation of:

- The Earth–Moon system.
- The bombardment record on the Moon.
- Primitive asteroid material in the solar system.
- Possible life on Mars (past or present).
- Human endeavors to visit the Earth–Moon–Mars space.

Focusing on this theme can provide a clear and credible vision for a global planetary exploration science roadmap. A shared vision is crucial to give overall direction, and to unite stakeholders in sustaining a global space exploration program. The focus should be complementary to existing programs of robotic exploration of the solar system.

9.2. Synergies of robotic/human exploration

Planetary exploration calls for the development of an integrated human/robotic science strategy. Robotic precursor missions in support of human exploration are proposed by several exploration stakeholders and spacefaring nations. Such missions can test engineering capabilities, identify hazards, probe resource utilization and scout future destinations. Robotic precursor missions are also needed to perform technology and flight system demonstrations, and to deploy infrastructure to support future human exploration activities. Human–robotic partnerships will increase productivity, reduce costs and mitigate risks. For example the Moon is an excellent place to develop capabilities for minimally-contaminating equipment, facilities, and human support, as well as a location to build and test capabilities that will be required for future exploration. NEOs represent both a rich future resource for space exploration and a threat to humankind. These objects are pathfinders for missions to bodies with higher gravity. Mars has been the subject of intense fascination to the public and is accessible to spacecraft launched from Earth every 26 months. Forging a partnership between robotic science and human exploration can help provide a unified long-range vision for planetary exploration (e.g., Huntress et al., 2004; Stetson et al., 2009). Clearly there is no conceptual separation between human and robotic exploration; rather the distinction is a result of bureaucratic structures within the national space agencies. Improved organizational development within space agencies should ensure ways to better work around this divide in order to realize a more effective, synergistic and sustainable space exploration program.

9.3. Synergies of Earth science and space exploration

Oceans represent the largest ecosystem on Earth, but less than 5% of the water column and less than 2% of the ocean floor are currently explored. Twelve humans have walked on the Moon, but only two scientists have visited the deep part of the ocean. Efforts should continue in order to exploit synergies of Earth science and space exploration. Analogue research in preparation of space exploration includes the simultaneous investigation of Earth's ecosystems, through field research and supporting satellite observation as well as studies to understand habitability in extreme environments. Protecting life on Earth requires similar concepts and information as investigations of life beyond Earth. Instrumentation and data handling, and the technology to probe the surface and subsurface likewise require similar methods. Recently, a network has been proposed to enable interchange of scientific insights involving both the Earth science and space exploration communities, leading to the development of new common policies (Chung et al., 2010 and references therein). Others have argued for recognition of the potential of Mars exploration to contribute to the understanding of global climate change on Earth by investigating synergies of martian climate history and the emergence (or lack) of life on Mars (Stetson et al., 2009). Furthermore, Earth observation programs from the ISS or from the lunar surface are on the agenda of space agencies and science working groups.

9.4. Planetary protection of planetary scientific assets and related legal frameworks

There is currently a need to consider environmental protection in space as commercial plans introduce new pressures beyond those experienced with past activities by exclusively non-commercial interests. As space activities diversify, it is necessary to clarify and complement the legal regime currently regulating the exploration of the Moon and other celestial bodies. The interest of society, and even future commercial activities, must be balanced against the temptation to proceed without restraints for the purposes of immediate gain, only to find that great knowledge and great value have been displaced by unrestrained contamination or uncontrolled alteration of valuable solar system environments. Existing regulations need to be expanded to ensure valuable, safe, economic, and broadly-based exploration that encompass and balance a diverse set of stakeholder interests and will benefit both current and future generations. The creation of international scientific preserves similar to the ones agreed for Antarctica may be one facet of such regulations. Recently, a COSPAR international workshop on planetary protection undertook the first organized discussion on the diverse environmental management, legal, and ethical considerations that are involved.[29] It was concluded that COSPAR and other bodies should consider environmental stewardship for solar system bodies in addition to existing regulations for planetary contamination.

9.5. Participatory exploration

In order to achieve highly ambitious space exploration goals for exploring the inner solar system both robotically

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[29] Workshop on Ethical Considerations for Planetary Protection in Space Exploration, 8 - 10 June 2010, Princeton, NJ, USA.

and with humans, space agencies must improve and expand their efforts to inform the public about what they are doing, and why. Various public surveys suggest that the part of society that supports the space program and believes that space exploration is a noble endeavor does not necessarily agree that governments should allocate substantial financial resources to achieve those exciting space missions. To attain long-term support for a sustainable space exploration program, it is advisable to adopt new participatory communication techniques aimed at informing and engaging the public, as well as reaching the younger generation in particular (Ehrenfreund et al., 2010b). The International Space University (ISU), for example is active in raising cultural awareness in the space domain, representing an environment of intercultural spirit through its "3I" approach (International, Interdisciplinary, Intercultural dimensions).

The ESSC report "*Humans in Outer Space*" discussed recently how space activities worldwide are now entering an era where the contribution of the humanities is crucial besides political, industrial and scientific considerations to nurture public constituencies for long-term space exploration (ESSC, 2008). It is necessary to engage public stakeholders in the planning and the process of space exploration. Consultation, collaboration and consensus building with public stakeholders will help to ensure sustainability of a long-term space exploration program and foster aspirations for exploring the unknown.

9.6. Stepping stones toward a global space exploration program

How can the space exploration community learn to cooperate on a truly international level while engaging newly emerging spacefaring nations in a meaningful way? Small steps to perform preparatory research for exploration as described in Section 6 can improve and ease technology transfer and cultural competition issues while ensuring the development of effective interfaces that must form the major prerequisites and building-blocks for a future global space exploration program. For example, COSPAR can take a leadership role in supporting a stepwise approach to this new era of cooperation in space exploration and help create effective and efficient partnerships for the future.

Expertise obtained from an Earth-based field research program could serve as a foundation to create a truly terrestrial international exploration testbed – where established and emerging space actors (scientists, engineers, space entrepreneurs, etc.) from many different cultures and nations can learn to work together. In cooperation with ESF, NSF, and science foundations of other spacefaring nations, an "*International Earth-based field research program*" is an ideal stepping stone toward global space exploration when built on the execution of a consensus roadmap established by many international partners (PEX, 2011).

Similarly, COSPAR should support the "*Science exploitation of the International Space Station enabling exploration*" which should be accomplished during its prolonged lifetime (beyond 2020). Scientific contributions to the ISS from China and India are being discussed, and could strengthen existing partnerships while fostering new ones. The science participation of developing countries in ISS research is supported by UN bodies.

Collaborating on small missions, such as an "*International CubeSat program in support of exploration*", can enable a new generation of low-cost payload opportunities for "piggyback rides" to Moon and Mars. CubeBots can serve as low-cost complementary surface components on planetary surfaces. Both, CubeSats and CubeBots can address preparatory research supporting exploration missions (e.g., concerning human exploration risks, planetary protection, etc.). These new payloads can provide ample opportunities for developing countries that are financially limited in their participation to a global space exploration program while enabling mature space actors to tap into a global robotics talent pool.

In preparation for larger endeavors, a system-of-systems approach with small exploration missions (e.g., small orbiters and landers as described in the "*Robotic Village concept of ILEWG and ILRP*") will initiate and enhance international collaboration, as well as science, commercial and public engagement opportunities.

"*Sample return missions to the Moon, near-Earth asteroids and Mars*" will be much more affordable when conducted in international cooperation. Multi-element mission scenarios provide opportunities for several spacefaring nations to join and develop one of the elements. International sample curation facilities will foster extensive science and engineering collaboration and exploit worldwide expertise. The Antarctic Program, which involves both logistics and science, is managed by the effective liaison and cooperation between Antarctic programs of a number of nations working under the Antarctic Treaty System. An organizational approach based on the Antarctic Program could be used as a model for international Moon and Mars bases.

In the preparation phase toward a global space exploration program, COSPAR should promote the development of synergistic science programs with open and full access to each other's data. Several active systems are already available: NASA's Planetary Data System (PDS) archives,[30] the Analyst's Notebook (a tool for accessing a number of PDS-compliant archives that demonstrates the value of creating standards-compliant archives with adequate data documentation and meta-data to support cross-instrument and cross-mission data searches), and ESA's Planetary Science Archive (PSA)[31] (compatible with PDS). The International Planetary Data Alliance (IPDA)[32]

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[30] http://pds.nasa.gov/.

[31] http://www.rssd.esa.int/index.php?project=PSA.

[32] http://planetarydata.org/.

is recognized by COSPAR as the official body for definition of planetary science archive standards. All those efforts could play an important role in standardization and construction of interoperable systems for a future global space exploration program.

10. Conclusion

The year 2010 led to important decisions for a future global space exploration program. The US NRC Decadal Surveys on "*Planetary Science*" and "*Biological and Physical Sciences in Space*" were released and provide science directions for space exploration in the next decade (NRC, 2011a,b). In November 2011 the EU-ESA consultation process on space exploration will discuss future scenarios during a high-level conference in Brussels. Japan's space policy and JAXA's exploration roadmap are currently under review. The Canadian Space Agency CSA is implementing its new space plan to participate in human and scientific exploration of the Moon, Mars and asteroids. All space partners involved in the International Space Station are engaging in new programs that prepare for ISS research during its prolonged lifetime.

Finally, the International Academy of Astronautics IAA, celebrated its 50th anniversary with a "Space Agency Summit" in November 2010 that addressed four key areas; among them are "Planetary Robotic Exploration" and "Human Space Flight" (IAA, 2010a,b). The attempt is to reach broad consensus on international cooperation in order to consider new concrete initiatives in the future.

The objective of the COSPAR Panel on Exploration (PEX) is to provide the best, independent science input to support the development of a global space exploration program and to safeguard the scientific assets of solar system objects. PEX will engage with COSPAR Commissions and Panels, ESF, NSF, and other science foundations, IAA, IAF, UN bodies, and IISL to support in particular national and international space exploration working groups and the new era of planetary exploration.

PEX will take specific actions to:

- Support an "International Earth-based field research program".
- Support the "Science exploitation of the ISS enabling exploration".
- Support an "International CubeSat program in support of exploration" for developed and developing countries.
- Support the "Global Robotic Village".
- Support studies and precursor activities toward "International human bases" (Moon, Mars) using research activities in Antarctica as a model.
- Support "Synergies between space exploration and Earth science".
- Support the COSPAR Panel on Planetary Protection in "Protecting the lunar and martian environments for scientific research".
- Support "Environmental stewardship" to protect the Earth–Moon–Mars space.
- Support "Activities in capacity building" for space exploration.
- Involve and "Engage the public stakeholder" and youth in participatory ways.

These PEX activities will contribute to fostering a global space exploration program that stimulates scientists in current and emerging spacefaring nations as well as developing countries to participate in research aimed at answering outstanding questions about the origins and evolution of our solar system and life on Earth and possibly elsewhere.

"***The only thing that will redeem mankind is cooperation.***"
Bertrand Russell (1872–1970)

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Acronyms and abbreviations

AMIE	Advanced Moon Imaging Experiment
ASI	Italian Space Agency
ASTEP	NASA Astrobiology Research Program and Investigations at Analogue Sites
ASTID	Astrobiology Science, Technology and Instrument Development
ATS	Antarctic Treaty System
AU	Astronomical Unit (the mean Earth–Sun distance)
BSTI	UN Basic Space Technology Initiative
CAPTEM	Curation and Analysis Planning Team for Extraterrestrial Material
CAREX	Coordination Action for Research Activities on life in Extreme Environments
CARN	Canadian Analogue Research Network
Centaurs	Minor planets that behave with characteristics of both asteroids and comets
Chang'E	Space mission in the framework of the Chinese Lunar Exploration Program (CLEP)
CNES	French Space Agency
CNSA	Chinese Space Agency
COSPAR	Committee on Space Research
CSA	Canadian Space Agency

CSIS	Center for Strategic and International Studies
Desert RATS	Desert Research and Technology Study
DOMMEX	Drilling on the Moon and Mars in Human Exploration
EANA	European Astrobiology Network Association
EC	European Commission
EDL	Entry, Descent and Landing
EDR	European Drawer Rack
EDM	Descent and Landing Demonstrator Module
ELIPS	European Programme for Life and Physical Sciences
EPM	European Physiology Modules Facility
EPO	Education and Public Outreach
ESA	European Space Agency
ESF	European Science Foundation
ESSC	European Space Science Committee
ESTEC	European Space Research and Technology Centre
ETC	European Transport Carrier
EVA	Extra Vehicular Activity
ExoMars	US/European 2016/2018 Mars Mission
FSL	Fluid Science Laboratory
GER	Global Exploration Roadmap
GES	Global Exploration Strategy
GLUC	Global Lunar Conference
GRAIL	Gravity Recovery and Interior Laboratory
GSI	Gesellschaft für Schwerionenforschung
HIMAC	Heavy Ion Medical Accelerator in Chiba, Japan
IAA	International Academy of Astronautics
IAF	International Astronautical Federation
IAU	International Astronomical Union
IBMP	Institute for Biomedical Problems
ICEUM	Conference on Exploration and Utilisation of the Moon
ICSU	International Council for Science
IDP	Interplanetary Dust Particle
IISL	International Institute of Space Law
ILEWG	International Lunar Exploration Working Group
IMEWG	International Mars Exploration Working Group
ILRP	International Lunar Research Park
IPDA	International Planetary Data Alliance
ISECG	International Space Exploration Coordination Group
ISRO	Indian Space Research Organization
ISRU	*In Situ* Resource Utilization
ISS	International Space Station
ISU	International Space University
JAXA	Japanese Aerospace Exploration Agency
KARI	Korea Aerospace Research Institute
KIBO	Japanese Experiment Module on the International Space Station
Kuiper Belt	Region of the Solar System beyond the planets extending from the orbit of Neptune to approximately 55 AU from the Sun
LADA	Greenhouse facility on the International Space Station
LADEE	Lunar Atmosphere and Dust Environment Explorer
LAMP	Lyman-alpha Mapping Project
LCROSS	Lunar CRater Observation and Sensing Satellite
LEAG	The Lunar Exploration Analysis Group
LEND	Lunar Exploration Neutron Detector
LEO	Low Earth Orbit
LER	Lunar Exploration Roadmap
LHB	Late Heavy Bombardment
LRO	Lunar Reconnaissance Orbiter
MA	Moon Agreement
MAP	Project Mars Analog Path (ISU)
MAV	Mars Ascent Vehicle
MAVEN	Mars Atmosphere and Volatile EvolutioN
Marco-Polo-R	European near Earth Asteroid Sample Return Mission (in study phase)
MDRS	Mars Desert Research Station
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover
MEx	Mars Express Orbiter
MGB	Microgravity Glove Box
MISSE	Materials International Space Station Experiment
MPLM	Multi-Purpose Logistics Module
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NAC	NASA Advisory Council
NAI	NASA Astrobiology Institute
NAR	NASA Astrobiology Roadmap
NASA	National Aeronautics and Space Administration
NEA	Near Earth Asteroid
NEEMO	NASA Extreme Environment Mission Operations
NEO	Near Earth Object
NLSI	The NASA Lunar Science Institute
NOAA	National Oceanic and Atmospheric Administration
NRC	US National Research Council
NSF	US National Science Foundation
OSTEO	Osteoporosis Experiments in Orbit
O/OREOS	Organism/Organic Exposure to Orbital Stresses (nanosatellite)
OPP	Office of Polar Programs

OSIRIS-REx	Origins Spectral Interpretation Resource Identification Security Regolith Explorer spacecraft
OST	Outer Space Treaty
PAC	Protected Antipode Circle
PSA	Planetary Science Archive
PDS	NASA Planetary Data System
PECB	Protecting the Environment of Celestial Bodies (IAA Cosmic Study)
PEX	Panel on Exploration (COSPAR)
PISCES	Pacific International Space Center for Exploration Systems
PPP	Panel on Planetary Protection (COSPAR)
PSR	Permanently Shadowed Regions
RFI	Radio Frequency Interference
RMS	Remote Manipulator System
Roskosmos	Russian Federation Space Agency
SCAR	Scientific Committee on Antarctic Research
SCOR	Scientific Committee on Oceanic Research
SMART-1	European Moon Orbiter
SMD	NASA Science Mission Directorate
SPI	Space Policy Institute Washington DC
SRF	Sample Receiving Facility
STEM	Science Technology Engineering and Mathematics
TGO	Trace Gas Orbiter
TNA	Europlanet Trans National Access
UN	United Nations
UNESCO	United Nations Educational Scientific and Cultural Organization
UNOOSA	United Nations Office of Outer Space Affairs
YH-1	Yinghuo-1 (YH-1) orbiter piggyback on the Russian Phobos-Grunt mission

Appendix A. Individual roadmaps of national space agencies

In the new millennium major spacefaring countries have developed plans for ambitious space exploration programs to explore the Earth–Moon–Mars space (see Table 2).

A.1. NASA/US

In February 2011, US President Barack Obama proposed, amid the economic crisis and overall freeze on discretionary spending, a five-year $94 billion budget request for NASA. This plan for fiscal years 2012–2016 cancels the Bush Administration's Constellation program and pursues a new "flexible path" strategy that focuses on technology development and on creating opportunities for the commercial sector to enable more ambitious exploration endeavors, including human space flight (Augustine Report, 2009). The US national space policy, released in June 2010 called for far-reaching exploration milestones, such as "By 2025, begin crewed missions beyond the Moon, including sending humans to an asteroid." and "By the mid-2030s, send humans to orbit Mars and return them safely to Earth". The utilization of the International Space Station (ISS) is supported until at least 2020 with efforts to encourage a balance of NASA and non-NASA research. An advanced heavy-lift launch vehicle—the Space Launch System—will provide an entirely new national capability for human exploration beyond Earth's orbit. The first developmental flight is targeted for the end of 2017.

Current and near-future lunar missions include the Lunar Reconnaissance Orbiter (LRO) in orbit since June 2009. In 2011 the twin spacecraft Gravity Recovery and Interior Laboratory (GRAIL) was launched in tandem orbits around the Moon to measure its gravity field in unprecedented detail. The Lunar Atmosphere and Dust Environment Explorer (LADEE) is a mission that will orbit the Moon in 2013 and determine global density, composition and time variability of the highly tenuous atmosphere and dust environment. Plans for an International Lunar Network (ILN) for geophysical studies are in development for possibly deployment after 2018. Mars is also a major target of US exploration activities. The Mars Science Laboratory (MSL) to be launched in November 2011 will explore the Martian surface, followed by the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft, scheduled for launch in late 2013. A long-term ESA–NASA cooperation on the exploration of Mars has been agreed upon with the ExoMars mission planned to be conducted in 2016 and 2018, respectively. The current scenario is to send a joint NASA–ESA rover to the Martian surface to search for biosignatures and cache samples for a future Mars Sample Return mission.

A.2. Europe

Europe (defined as the European Space Agency ESA and its Member States) has a long-standing tradition of space exploration, and has participated with great success in many activities on its own and in partnership with other spacefaring countries. It has made significant contributions to robotics missions and human spaceflight.

ESA expanded its robotic presence in the solar system with the visit of several bodies including Mars (Mars Express) and the Moon (SMART-1, European instruments on Chandrayaan-1). SMART-1, Europe first lunar mission demonstrated technologies for future science and exploration missions.

ESA has contributed three European instruments (C1XS, SIR2 and SARA) for the Indian lunar Chandrayaan-1 mission and a ground station control and data

Table 2
Top: Overview of space exploration capabilities of the major space actors (adapted from Ehrenfreund et al., 2010a). D: developed; UD: under development; NE: not existent. *Bottom:* Future planned space exploration missions and approximate launch dates are listed (as per July 2011). The Google Lunar X-Prize lander(s) are anticipated in 2015. The ExoMars mission is planned as NASA/ESA collaboration for 2016 and 2018, respectively.

	United States	Russia	Europe	Japan	China	India
Launch System	D	D	D	D	D	D
Human Transport Capabilities	UD	D	NE	NE	D	UD
Astronaut Corps	D	D	D	D	D	UD
Satellite Manufacturing Capabilities	D	D	D	D	D	D
Deep Space Network	D	D	D	D	UD	UD
Moon Missions	D	D	D	D	D	D
Mars Missions	D	D	D	D	UD	UD
Other Planetary and NEO Missions	D	D	D	D	NE	NE
ISS Participation	D	D	D	D	NE	NE
IMEWG, ILEWG, GES Participation	D	D	D	D	D	D

	United States	Russia	Europe	Japan	China	India	Launch
Moon Orbiters					Chang'E2		2010
	GRAIL						2011
							2013
	LADEE		ESMO			Chandrayaan-2	2014
				Selene 2			2015
Moon Landers and/or Rovers		Luna-Glob			Chang'E3		2013
		Luna-Res./1					2014
		Luna-Res./2					>2015
			Polar lander				2018
Small Moons and NEO missions		Phobos-Grunt					2011
				Hayabusa-2			2014
	OSIRIS-REx						2016
Martian Orbiters					Yinghou1		2011
	MAVEN						2013
	Trace		Trace				
	Gas		Gas				
	Orbiter		Orbiter				2016
Martian Landers	MSL						2011
			EDM				2016
Martian Rovers	ExoMars		ExoMars				2018
Mars Sample Return	planned		planned				>2020

reception and collaboration for the Chinese lunar Chang'E-1 mission. ESA is also looking at developing a lunar mission for potential landing towards the end of the decade. ESA has recently developed a long-term cooperation with NASA to use several opportunities to go to Mars, starting with ExoMars in 2016 and 2018 (Cf. NASA/US). Europe has recently demonstrated its willingness and capability to provide essential contributions to the International Space Station (ISS) through the Columbus orbital laboratory, the Automated Transfer Vehicles (ATVs), and other ISS infrastructures (MPLM, Node 2, Node 3).[33]

The political dimensions of space exploration and its economic and strategic applications are in the process of being fully acknowledged in Europe (Horneck et al., 2010). Several steps and milestones have been completed since the first European Space Policy adopted in 2007 by 29 European Union (EU)/ESA Member States, illustrating the growing political awareness of space exploration in Europe. In October 2009 the European Commission's (EC) President Barroso recalled that space exploration is one of the EC's priorities. An international exploration endeavour is part of the objectives of the European Space Policy with a strong potential to contribute to a knowledge based society and to stimulate innovation. Space exploration appears also in the orientations which resulted from the last Space Council, where the need to assess the possibilities offered by European Union policies to embed space exploration in a wider political perspective was reaffirmed. As first step towards the elaboration in due time of a fully-fledged political vision on "Europe and Exploration" encompassing a long-term strategy/roadmap and an international cooperation scheme, the first EU-ESA conference on Human Space Exploration was held in Prague on 23 October 2009. Ministers in charge of space from ESA and EU Member States, Members of Parliament and rep-

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[33] Harmony, also known as Node 2, is the "utility hub" of the International Space Station. NASA's module Node 3 is called Tranquility and was originally built by ESA and ASI.

resentatives from academia and industry met and converged on the concept that Europe should define a vision for exploration jointly with all stakeholders. A second conference was held under the Belgian EU Presidency on 21 October 2010. The two Space Exploration Conferences have laid the ground for the establishment of an enlarged, international mechanism of coordination and cooperation. The participants of the Brussels conference identified the need for policy discussions at international level and concluded that "A dedicated international high-level space exploration platform should be established. Complementing existing technical fora, it should promote strategic guidance and international cooperation". It called for the organisation of a first meeting of an international, high level space exploration platform by the end of 2011, marking the evolution from the two conferences, prepared by Europe, to a truly global platform. The third Space Exploration Conference/First High-Level Exploration Platform will take place in Lucca (Italy) on 10 November 2011 and launch high-level policy dialogues on space exploration.

A.3. Roskosmos/Russia

The Russian government adopted several years ago a new Federal Space Program (2006-2015). The 10-year plan includes as a major goal the development and maintenance of orbital space constellations in the interest of Russia's socio-economic benefits. Russia's Security Council approved also a draft space policy for the period until 2020. This policy aims at retaining Russia's status as a leading space power. The Phobos-Grunt mission was launched to the martian moon Phobos in November 2011 but was lost after an engine firing failure. The Russian lunar program encompasses Luna-Glob (a Moon orbiter and landing probe) in 2012/2013, and further in the decade Luna Resource/1 (a lunar lander in combination with the Indian Chandrayaan-2 orbiter and mini-rover), and the Luna Resource/2 mission that is currently defined as a multi-element mission (lander, rover, re-transmitting satellite). Following the decision of the United States to terminate shuttle operations in 2011, and the existence of a gap before the entry into operation of the next US, Chinese or commercial human space flight vehicle, Russia will play a crucial role in providing support to the ISS through its Soyuz and Progress vehicles.

A.4. JAXA/Japan

In the document "Basic Plan for Space Policy"[34] released in June 2009, it is stated that the Japanese government will continue to achieve world-leading scientific results, such as probes of Venus and Mercury and the astronomical observations by X-rays and strengthen cooperation in space science. Japan launched its lunar probe (Selene/Kaguya) that impacted on the Moon after successful operation in June 2009. The Japanese Hayabusa mission explored the near-Earth asteroid Itokawa and returned samples to Earth in June 2010. A new asteroid sample return missions Hayabusa-2 is planned for 2014. Moon orbiters Selene 2 and 3 are planned for this decade. Scientific investigation of the Moon remains a high Japanese priority. Japan's participation to the ISS focuses on the development and exploitation of the Japanese Experiment Module KIBO as well as unmanned cargo transportation using its HTV vehicle. Japan plans on participating in the utilization of the ISS until at least 2020. The overall organization of Japan's space organization and priorities continues to be under review by the Strategic Headquarters for Space Policy.

A.5. CNSA/China

China is currently building up a space program with high ambitions. Among the main targets are a robotic program for exploring the Moon and human spaceflight. In 2007, China launched its first lunar probe, Chang'E-1, as the first mission of the China Lunar Exploration Program (CLEP), with participation of ESA for mission support and ground station control and data collection. The Chang'E-2 orbiter was the first mission within Phase II of the overall Chinese Lunar Exploration Program and was launched in October 2010, aiming to create a more detailed survey on possible landing sites while all other scientific payloads remained the same as with Chang'E-1. The core mission of the second phase of CLEP is Chang'E-3, which consists of a lander and rover. It is currently under development and will be launched 2012–2013. Phase III of the CLEP is a sample return mission, which is planned for launch in 2017–2018.

In addition to their lunar-focused activities, the Chinese will send the Yinghou-1 (YH-1) orbiter with the Russian Phobos-Grunt mission in 2011 to conduct space-environment, atmospheric, gravity, and surface-imaging studies of Mars.

A taikonaut performed China's first extravehicular activity (EVA) in 2008. Further missions on manned spaceflight include demonstration of rendezvous and docking technology followed by space lab missions. The ultimate goal of the Chinese manned space flight program of this stage is to build up a permanent space station. In 2011 China launched Tiangong-1, the first space lab module. It will be followed by an unmanned Shenzhou-8 spacecraft. Docking tests are expected for November 2011.

A.6. ISRO/India

India is embarking on new space endeavors that include space exploration and human spaceflight. ISRO, which

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[34] http://www.kantei.go.jp/jp/singi/utyuu/basic_plan.pdf.

previously had focused on space application efforts, has developed new scientific programs and launched Chandrayaan-1 in 2008 to the Moon, as the first Indian planetary mission. International instruments on this mission include C1XS, SIR2 and SARA delivered by ESA, M3, mini-SAR by NASA, and RADOM from Bulgaria. A second robotic lunar mission in collaboration with Russia is in the planning stage for 2012. ISRO would contribute an orbiter – Chandrayaan-2 – and a mini-rover to the Russian mission. The combined mission Luna Resource/2 will be launched with an Indian rocket. Recent technological studies on human spaceflight scenarios have led to a proposal to the Indian government for a first manned mission in the 2016 timeframe and an ambitious program of human spaceflight to follow. The government has not yet accepted this proposal.

A.7. CSA/Canada

Canada is an active ISS partner and trains an astronaut corps. Canada has been involved in space exploration for more than 25 years with its robotics, science and astronaut corps contributions. As part of its space plan, the CSA objectives are to ensure full utilization of the ISS, to be active in on-orbit robotics servicing, to be a partner in the Mars Sample Return series of missions, to participate in human and scientific exploration of the Moon, Mars and asteroids. Canada views space exploration as a collaborative endeavour and aims at contributing key technologies and science expertise to international missions. These contributions should be critical, welcome and as much as possible visible. Canada contributes to the world space effort especially with NASA (i.e., participation to NASA's Phoenix mission) and ESA but also with other space agencies. In addition, the CSA is an active participant to international groups such as the International Space Exploration Coordination Group (ISECG) and the International Mars Exploration Working Group (IMEWG) and sees these groups as essential to engage the dialogue amongst spacefaring nations.

A.8. KARI/South Korea

Even though it started to be active in space later than its Asian counterparts, Korea is making notable investments and progress in developing its indigenous space capability. Although its first two attempts were failures, Korea continues to prepare for a third try at a successful launch of the Korea space launch vehicle-1 in cooperation with Russia. Although most past and future Korean satellites focus on Earth-oriented applications, Korea also plans to send spacecraft to the Moon including at some point a lunar lander. Korea's first astronaut, Yi So-Yeon went to the ISS aboard a Russian Soyuz in April 2008, but there has been no follow-up activity in human spaceflight. However, Korea has expressed interest in getting more involved in ISS utilization now that the facility will operate until at least 2020.

Appendix B. Roadmaps of national and international science and analysis working groups

B.1. ILEWG – The International Lunar Exploration Working Group

ILEWG is a public forum sponsored by the world's space agencies to support "international cooperation towards a world strategy for the exploration and utilization of the Moon – our natural satellite" (International Lunar Workshop, Beatenberg (CH), June 1994).

The Forum is intended to serve three relevant groups:

1. Actual members of the ILEWG, e.g., delegates and representatives of the participating space agencies and organizations - allowing them to discuss and possibly harmonize their draft concepts and plans in the spirit of the Beatenberg Declaration.
2. Team members of the relevant space projects - allowing them to coordinate their internal work according to the guidelines provided by the charter of the ILEWG.
3. Members of the general public and of the Lunar Explorer's Society who are interested and wish to be informed on the progress of the Moon projects and possibly contribute their own ideas.

ILEWG has several task groups that advance work in the areas of lunar science exploration, living and working on the Moon, key technologies, utilization of lunar resources, infrastructure of lunar bases, surface operations, society, law, policy and commerce, public outreach, education and also supports the Young Lunar Explorers. Regular declarations of ILEWG summarize findings and give recommendations that are summarized by a large community (ILEWG, 2009). ILEWG logical and progressive roadmap was defined in 1995 and is de facto implemented with the recent fleet of orbiter precursors for science, technology and reconnaissance. The second phase with a number of coordinated surface elements supporting its orbital assets will constitute the "Global Robotic Village". The third phase will see the deployment of large systems in preparation for astronauts. The fourth phase will see the transition from short missions to permanent human presence at international bases.

Working areas of ILEWG:

- Science of, on, and from the Moon.
- Living and working on the Moon.
- Key technologies.
- Utilization of lunar resources.
- Infrastructures for lunar bases.
- Surface operations.
- Society, law, policy, and commerce.
- Public outreach, education, multicultural aspects; and
- Young Lunar Explorers.

Website: http://sci.esa.int/ilewg.

B.2. LEAG – The Lunar Exploration Analysis Group

The Lunar Exploration Analysis Group (LEAG) is responsible for analyzing scientific, technical, commercial, and operational issues associated with lunar exploration in response to requests by NASA. The LEAG serves as a community-based, interdisciplinary forum for future exploration and provides analysis in support of lunar exploration objectives and their implications for lunar architecture planning and activity prioritization. It provides findings and analysis to NASA through the NASA Advisory Council within which the LEAG Chair is a member of the Planetary Science Subcommittee (PSS). LEAG has published in 2009 an extended document that incorporates previous efforts into an integrated plan for sustained lunar exploration. The Lunar Exploration Roadmap LER includes many investigations divided into three subthemes:

SCIENCE:	Pursue scientific activities to address fundamental questions about our solar system.
FEED FORWARD:	Use the Moon to prepare for potential future missions to Mars and other destinations.
SUSTAINABILITY:	Extend sustained human presence to the Moon to enable eventual settlement.

Overall the roadmap is intended to layout an *integrated* and *sustainable plan* for lunar exploration that will allow NASA to transition from the Moon to Mars (and beyond) without abandoning the lunar assets built up using tax payer dollars.

Website: http://www.lpi.usra.edu/leag/.

B.3. ILN International Lunar Network

The International Lunar Network (ILN), aims to provide an organizing theme for all landed science missions in this decade by involving each landed station as a node in a geophysical network. Several nodes are under discussion. In the ILN concept, each node would include some number of "core" capabilities (e.g., seismic, heat flow, laser retro-reflectors) that would be extant on each station, reflecting prioritized lunar science goals articulated in the National Research Council's study (NRC, 2007). Individual nodes could and likely would carry additional, unique experiments to study local or global lunar science. Such experiments might include atmospheric and dust instruments, plasma physics investigations, astronomical instruments, electromagnetic profiling of lunar regolith and crust, local geochemistry, and *in situ* resource utilization demonstrations. A lunar communications relay satellite is under discussion to support activities on the lunar farside.

Website: http://www.iln.arc.nasa.gov/.

B.4. NLSI – The NASA Lunar Science Institute

The Mission of the NASA Lunar Science Institute (NLSI) and its member investigators is to advance studies of the Moon by:

- Conducting collaborative research in all areas of lunar science, enabling cross - disciplinary partnerships throughout the lunar science community.
- Providing scientific and technical perspectives to NASA on its lunar research programs and missions.
- Exploring innovative ways of using information technology for scientific collaboration between geographically disparate teams.
- Training the next generation of lunar scientists with research opportunities for undergraduate and graduate students.
- Encouraging Education and Public Outreach (EPO) through formal education content development, informal student programs and participatory public events.

In order to advance the field of lunar science, the NLSI has assembled 7 US science teams along with a partnership program for international science organizations (currently involved are Canada, South Korea, United Kingdom, Saudi Arabia, Israel, Netherlands, and Germany).

Website: http://www.lunarscience.nasa.gov/.

B.5. MEPAG – Mars Exploration Program Analysis Group

MEPAG is NASA's community-based forum designed to provide science input for planning and prioritizing Mars future exploration activities for the next several decades. It is chartered by NASA's Lead Scientist for Mars Exploration at NASA HQ, and reports its findings at meetings of the Planetary Science Subcommittee of the NASA Advisory Council (NAC). Open to all interested members of the Mars exploration community, MEPAG conducts analyses of planning questions that are presented to it. MEPAG regularly evaluates Mars exploration goals, objectives, investigations and priorities on the basis of the widest possible community outreach. NASA's Mars Program Office, located at JPL, has been directed to manage the logistics associated with the operations of MEPAG on behalf of NASA's Space Science Enterprise. MEPAG holds open townhall-style meetings approximately twice per year. MEPAG's analysis efforts are discussed at regular meetings that are held approximately twice per year, and the results are documented in reports that are posted on the MEPAG web site. The cost of operating MEPAG is managed by the Mars Program Office at JPL.

MEPAG is managed by an Executive Committee consisting of the past and present Chairs, NASA's Lead Scientist for Mars Exploration, two Mars Chief Scientists, the chair of the MEPAG Goals Committee (the only standing committee currently maintained by MEPAG), and an ESA Mars liason.

MEPAG additionally maintains a mailing list of all currently active Mars scientists, and that mailing list is used to convey information about Mars-themed conferences and workshops, and other announcements of relevance to the community. As of February 2010, this mailing list had about 2000 names.

Website: http://mepag.jpl.nasa.gov/.

B.6. The NASA Astrobiology Roadmap

The NASA Astrobiology Roadmap provides guidance for research and technology development across the NASA programs in space, Earth, and biological sciences. This roadmap, updated approximately every five years, is prepared by scientists and technologists from government, academia, and the private sector. Research goals and objectives detailed in the roadmap address three basic questions:

- How does life begin and evolve?
- Does life exist elsewhere in the Universe?
- What is the future of life on Earth and beyond?

Science goals in this roadmap identify key paths of research: understanding the nature and distribution of habitable environments in the Universe, exploring for habitable environments and life in our own solar system, understanding the emergence of life, determining how early life on Earth interacted and evolved with its changing environment, understanding the evolutionary mechanisms and environmental limits of life, determining the principles that will shape future life, and recognizing signatures of life on other worlds and on early Earth. Science objectives outlined in the roadmap identify high-priority efforts for the next three to five years. The roadmap identifies four basic principles that are fundamental to implementing NASA's astrobiology program:

- Astrobiology is multidisciplinary in content and interdisciplinary in execution.
- Astrobiology encourages planetary stewardship through an emphasis on planetary protection.
- Astrobiology recognizes broad societal interest in its endeavors.
- Public interest in astrobiology warrants a strong emphasis on communication, education, and public outreach.

Astrobiology is an important and growing focus of planetary exploration.

Website: http://astrobiology.nasa.gov/.

B.7. IMEWG – International Mars Exploration Working Group

The International Mars Exploration Working Group (IMEWG) has representatives from all space agencies and major institutions participating in Mars Exploration. The IMEWG was conceived at a meeting at Wiesbaden, Germany, May 1993, and since then met regularly to discuss the general strategy for the exploration of Mars.

The present charter of the IMEWG (approved in 1996) is as follows:

- Produce and maintain an international strategy for the exploration of Mars.
- Provide a forum for the coordination of Mars exploration missions.
- Examine the possibilities for the next steps beyond the currently defined missions.

The intent of IMEWG is to lay out a broad long-range strategy for Mars exploration. The strategy must be sufficiently specific that intermediate and long-range goals can be identified, and yet sufficiently flexible that the means and schedule for achieving the goals can accommodate to programmatic and fiscal realities. The strategy must also be consistent with missions already funded or planned. The recommendations issued by IMEWG have been well met in various space organizations and led to actions that improve the complementarity of the planned and approved mission scenarios.

Website: http://www.atmos.washington.edu/~mars/IMEWG_strategy.html.

B.8. ISECG – The International Space Exploration Coordination Group

The International Space Exploration Coordination Group (ISECG) was established in response to "*The Global Exploration Strategy: The Framework for Coordination*" (GES, 2007) developed by fourteen space agencies and released in May 2007. This GES Framework Document articulated a shared vision of coordinated human and robotic space exploration focused on solar system destinations where humans may one day live and work. Among the many Framework Document findings was the need to establish a voluntary, non-binding international coordination mechanism through which individual agencies may exchange information regarding their interests, plans and activities in space exploration, and to work together on means of strengthening both individual exploration programs as well as the collective effort.

The goals of ISECG are: (1) to establish a voluntary, nonbinding international coordination mechanism that enhances information exchange concerning interests, objectives, and plans in space exploration; and (2) to strengthen both individual exploration programs and the collective effort (ISECG, 2008). The ISECG promotes and transmits non-binding findings and recommendations. Toward this end, the ISECG has established several dedicated working groups such as the International Space Exploration Coordination Tool INTERSECT which facilitates cooperation (ISECG, 2009) by integrating mission and capability information provided by participating agencies. These activities represent a useful first step toward globally coordinated exploration. In 2010, ISECG was able to advance the implementation of the GES by serving as the international forum where interested agencies continued to share their objectives and plans for human and robotic space exploration (ISECG, 2010). The recently published Global Exploration Roadmap (GER 2011) identifies two potential pathways for human exploration: “Asteroid Next” and “Moon Next.”

Website: http://www.globalspaceexploration.org/.

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