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Synergies of Earth science and space exploration

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Abstract

A more flexible policy basis from which to manage our planet in the 21st century is desirable. As one contribution, we note that synergies between space exploration and the preservation of our habitat exist, and that protecting life on Earth requires similar concepts and information as investigations of life beyond the Earth, including the expansion of human presence in space. Instrumentation and data handling to observe both planetary objects and planet Earth are based on similar techniques. Moreover, while planetary surface operations are conducted under different conditions, the technology to probe the surface and subsurface of both the Earth and other planets requires similar tools, such as radar, seismometers, and drilling devices. The Earth observation community has developed some exemplary tools and has featured successful international cooperation in data handling and sharing that could be equally well applied to robotic planetary exploration. Here we propose a network involving both communities that will enable the interchange of scientific insights and the development of new policies and management strategies. Those tools can provide a vital forum through which the management of this planet can be assisted, and in which a new bridge between the Earth-centric and space-centric communities can be built.

Keywords: Earth observation; Space exploration; Astrobiology; Space weather; Biodiversity; International space cooperation

1. Introduction

The global environmental situation is alarming and represents a major action-item on the agenda of international politics. Humanity faces a number of important environmental problems including global warming, climate extremes, depletion of natural resources, and pollution. Associated with those problems are global issues that include climate catastrophes, poverty, diseases, and their associated mortality.

For example, the oceans comprise nearly all the water on planet Earth, with fresh water in rivers and lakes, and trapped in polar ice caps and glaciers, only making up 3% of the overall total. By far the largest amount of fresh water is frozen; ground water makes up 0.28% and the water found in fresh water lakes and rivers, readily available for use, makes up only 0.009% of Earth's total. Not surprisingly, the quantity and quality of this water is stretched to the limit. Industrialization has modified also our atmosphere, affecting its ability to protect us from dangerous solar radiation. Resources on land and in the oceans are over-exploited, and all over the world unsustainable practices have led to environmental degradation that needs to be halted, such as desertification and deforestation. Pollution is ubiquitous and degraded air, water, and soil cause detrimental impacts on human health and living conditions. More than 1.2 billion people on our planet have no access to clean water, and drinking polluted water is the number one cause of death for children in Africa. Forests, deserts, wetlands, and mountains each provide habitat for numerous species and ecosystems. Forests contain 70% of the carbon of biological systems, but industrialization and modern technology have led to widespread habitat destruction. A critical goal must therefore be to halt this

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destruction of our own habitat, which is coupled to the overall decline of Earth's biodiversity. We have to ensure sufficient resources to account for the ever growing population (to 9 billion by 2050) and find solutions while balancing resource allocation among regions.

Increasingly, it has been shown that space technology can be applied to address problems on Earth (UNOOSA, 2006). For instance, satellite imagery can cover large territories over regular time periods and obtain information in different wavelength regions and thus deliver a comprehensive picture of planet Earth. However, while the "Mission to Planet Earth" enabled by Earth observation satellites has been recognized in the past decades, the role and potential contribution of space exploration activities to understanding and protecting our home planet has not been accepted to the same degree. Indeed, such a link may not be apparent at first thought: in fact, many believe that the exploration of our solar system brings only marginal benefits in improving and understanding life on Earth. Some of the space activities involved in investigating our solar system have nonetheless equally significant implications for understanding the evolution of life on Earth and how Earth has become—and remains—habitable. In particular, studies of the Sun and of the potential for life on other planets in our solar system provide examples of the linkages between space exploration and Earth sciences.

One facet of the new era of space exploration currently unfolding that may provide a further link is a global effort to investigate the Earth–Moon–Mars system that can be undertaken by many space-faring countries and new space powers. Moving human exploration to the next step, returning to the Moon with the objectives to build habitats, infrastructure, and initiate commercial exploitation are ways of coping with technological and intellectual evolution. Many philosophers and biologists have discussed the possible (and likely) short lifetime scenario of humans on planet Earth. In his recent book, Charles Cockell (Cockell 2006, p. 173) states: "*the fusion of environmentalism and space settlement is a unique opportunity in the emerging history of humankind: one that is now, for a relatively brief period, available for us to grasp*" which is an acknowledgement that synergies between space exploration and preserving our habitat do exist.

In order to provide direction in the use of those synergies, we have to understand some of the parameters such as the uniqueness of the Earth, what we know about the origin and evolution of life, what satellites can be used to support scientific efforts, and what management strategies are needed to bridge the two communities (Earth-centric and space-centric).

2. Current and future space activities in Earth observation and space exploration

Ambitious space projects that address Earth science and space exploration are currently in the planning and development stage. Satellites monitoring the environment and climate will play an ever increasing role in the near future and ambitious space exploration roadmaps to explore the Earth–Moon–Mars system are planned in worldwide coordination involving established and new rising space powers.

2.1. Space-based Earth observation

The ability to observe the Earth from space has transformed our view of our own planet. One clear example of that transformation is the "blue marble" view of the Earth seen first by the Apollo astronauts and the object of a revolutionary change in the way humans view their home in space. With the appreciation of the space vantage-point brought by Apollo emerged a greater appreciation of the more mundane but increasingly sophisticated views of the Earth brought through orbital spacecraft, which have evolved from returned photographic platforms to quantitatively oriented instrument platforms, capable of measuring variables such as temperature, concentration of atmospheric trace gases, and the exact elevation of land and ocean. These measurements have led to a new scientific understanding of the Earth system, which both represents a major intellectual accomplishment and provides important societal benefits through the improvement of the predictability of everyday life on Earth (NRC, 2008a).

Earth observation satellites provide the most straight forward example of how space technology contributes to overcoming environmental challenges on Earth. Close monitoring of environmental parameters, natural phenomena, and resources is crucial for effective management and to ensure future sustainability of the Earth's critical life support systems. Space-based systems comprise the centerpiece of future environmental monitoring. Where ground-based systems are limited in the frequency, continuity, and coverage of important ecosystems, satellites can provide essential Earth observation data on a continuous basis at a range of scales—from local to global. Increasingly, environmental measurements are most effectively or uniquely obtained from space. Satellite instruments can deliver images and measurements of various geophysical parameters of the atmosphere, land, ocean, ice, gravity, and magnetic fields. According to the Committee on Earth Observations Satellites (CEOS) space-based measurements can currently provide 25 out of the 45 Essential Climate Variables (ECV) identified by the United Nations Framework Convention on Climate Change (UNFCCC) (see CEOS, 2008). The implementation plan of the Global Climate Observations System (GCOS, 2004, p. 7) notes that "*a detailed global climate record for the future critically depends upon a major satellite component*".

An international effort in Earth observation is being made through the Group on Earth Observations (GEO), a voluntary partnership of governments and organizations currently comprised of 77 countries, the European Commission, and 56 participating organizations, collaborating to build the Global Earth Observation System of Systems (GEOSS). GEOSS will link together various types of existing and planned Earth observation systems to provide a unified environmental information service to support the multitudes of users around the world. GEOSS's 10-year implementation plan (GEO, 2005) addresses nine societal benefit areas (disaster, health, energy, climate, water, weather, ecosystem, agriculture, and biodiversity). CEOS coordinates the contribution of space-based systems to GEOSS (see UNFCCC, 2006).

Space-based systems are also being integrated into disaster monitoring and management schemes. The International Charter on Space and Major Disasters, established in 2001, mobilizes Earth observation capabilities of space agencies—upon disaster occurrence—to provide satellite-based information, such as the maps of disaster affected areas, to assist disaster relief activities. The United Nations are now working toward developing a more elaborate universal platform—the space-based Information for Disaster Management and Emergency Response (UN-SPIDER)—to support the disaster management community.

While space-based systems have successfully demonstrated capability in measuring key Earth environmental variables, the current capabilities do not adequately map all required parameters nor fully meet the quality and standards required by the user community (CEOS, 2008). In addition, there are also concerns of "satellite data gaps" from lapsed observing programs, which stand in stark contrast to the stunning and growing needs for space-based information by the world's users (NRC, 2008a; CSIS, 2008). Building a reliable Earth observation capacity relies strongly on the availability of inter-calibrated long-term data records, which can only be maintained if subsequent generations of satellite sensors overlap with their predecessors. The capability to observe Earth from space is jeopardized by delays and lack of funding for many critical satellite missions.

2.2. Space exploration in the 21st century

The term "*space exploration*" encompasses both robotic and human exploration activities. Using ESA's definition from the document entitled: European Objectives and Interests in Space Exploration (ESA, 2007), space exploration is defined as to "*extend access and a sustainable presence for humans in Earth–Moon–Mars space, including the Lagrangian Points and near-Earth objects.*"

Space exploration, an issue that used to be of marginal political interest in recent years, has returned to the top of the space policy agenda of many space-faring countries. Space exploration can provide many socio-economic benefits ranging from more influence on the international scene to increased industrial competitiveness. Human spaceflight is also a source of inspiration for the general public, and the youth in particular. Space exploration is thus not only seen as a destination, but also rather as a process driven by political and socio-economic motives. However, space exploration is a very demanding endeavor both in terms of financial and technological resources.

The challenge posed by the complexity of long-term, multi-destination exploration activities calls not only for a broad public support but also for a sustained political engagement in order to have a wide and resilient backing of space exploration plans. The current international space exploration environment is dramatically evolving due to two main trends.

- Following the changing geopolitics of space activities, new actors are increasingly becoming involved in space exploration. A growing number of space agencies have planned lunar and Martian orbiter and lander missions often in the context of preparations for future human exploration. New actors are demonstrating great interest in exploration, mainly for international reasons and the will to strengthen greater regional or even global (Science and Technology, S&T) leadership.
- International cooperation has become a central element of the strategy of most countries involved in exploration as symbolized by the International Space Station (ISS) but also the Global Exploration Strategy (GES) or the International Lunar Network (ILN) initiatives (GES, 2007). Recent (and future) geopolitical developments, combined with the funding constraints of the various space-faring countries, have made it clear that greater international cooperation will be important for future space exploration activities.

The major space powers—the United States, Russia, Europe, Canada, Japan, China, and India—have developed ambitious space exploration programs (Peter, 2008). In early 2004, the United States announced its Vision for Space Exploration (NASA, 2004), which includes development of a new space transportation system, a return to the Moon and construction of lunar bases, and eventual manned missions to Mars. Exploration System Architecture (NASA, 2005) has been studied by NASA and its component systems and technologies are currently under review.[1] Europe's long-term plan for exploration is pursued with the robotic and human exploration program, Aurora (Messina et al., 2006). Europe's Aurora program was actually initiated in 2001, several years before NASA's Vision document.[2] Russia approved the Federal Space Program 2006–2015 (SE Russia, 2005), in which it recognized that "*space exploration and research, including exploration and research of the Moon and other space objects, have the highest national priority in the Russian Federation*". In Japan, JAXA has announced its long-term vision, JAXA 2025 (JAXA, 2005), highlighting lunar and primitive body exploration that involves robotic missions to the Moon, human lunar system, and asteroid missions. China's space ambitions, as underlined in its 2006 White Paper (SE China, 2006) on space activities, includes a series of robotic

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[1] Augustine report: http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf.

[2] http://www.esa.int/esaMI/Aurora/SEMZOS39ZAD_0.html.

missions to the Moon and a joint mission to Mars with Russia. China intends to continue with its manned space program. India has also embarked on exploration endeavors, with a series of robotic missions to the Moon and the potential launching of astronauts into LEO by 2015. South Korea tested a space launcher without success, but announced its participation in lunar exploration (Cho, 2007). In view of these plans, the International Space Exploration Coordination Group (ISECG) was established in 2007 to act as a body to facilitate the coordination and collaboration in the exploration activities among different countries (see GES, 2007; ISECG, 2008, 2009).

Astronauts have spent short periods in Earth orbit and on the Moon, and relatively extensive periods in space in orbital stations such as Mir and the International Space Station (ISS). One ambitious plan for future space exploration includes even longer stays on the Moon and human journeys to Mars. The ISS is now coming to the end of its construction phase and accommodates six-person crews and gives them the time to fully utilize ISS's research capacities to conduct various research activities for science, commercial application on Earth, and preparations for future exploration.

Nonetheless, more advanced capabilities are needed. In order to carry out the future manned and robotic missions to Moon, Mars, and beyond, not only the existing technologies should be significantly advanced, but also new and innovative technologies must be developed to make the planned exploration missions feasible. For human missions to Moon and Mars, the development of new space transportation capabilities and long-duration human support systems are critical. Current time estimates for a travel to Mars are $\sim$6 months one-way. Such long journeys and prolonged stays beyond the Earth's radiation belts (and therefore exposure to proton storms and galactic cosmic radiation) add a new dimension to human space flight. Humans will be put under extreme stress during such long-term space voyages and be exposed to major risks and hazard. Survival of humans beyond Earth under such conditions, and their continued health upon return, must first be demonstrated. Space radiation, isolation, and medical problems such as muscle-loss and in particular bone demineralization require countermeasures if astronauts are to retain full functionality. Survival training in extreme environments and isolation studies in artificial habitats need to be extended and included in future astronaut training. Life support systems, energy production and advances in space materials are among the new technologies that have to be further developed to enable future exploration objectives. In robotic exploration, improving technologies for entry, descent, and landing (EDL), drilling and sample acquisition, are identified as one of the next major challenges. A recent assessment of NASA's Solar System Exploration Program (NRC, 2008b, p. 59) revealed that NASA has cut back the funding for its technology development programs. However, these enabling technology programs need to be adequately funded to guarantee future progress in implementing future exploration goals. A previous funding reduction for astrobiology research and related instrument technology development has also had impacts on future solar system exploration (NRC, 2008b, p. 5). For continuous improvement in technologies, these breaks in funding are extremely disruptive—but the real key to productive technology development activities is regular opportunities to employ them. Here both space missions and analog missions have proven to be important.

3. Where space meets Earth

Planet Earth is currently the only habitable world we know. Although life may have existed as early as 3.5 billion years ago, humans have lived for only a rather short time on Earth—about 2 million years. Nonetheless, we are (unfortunately) making up for lost time as a factor affecting the habitability of the planet. In the last 200 years humans have changed the Earth dramatically, calling into question how long the Earth and its natural systems can balance its limited energy and material resources against the effects of human-caused pollution.

Keeping Earth's natural "life support" processes operating, and the planet habitable by humans, has become a critical challenge. Space activities, particularly environmental satellites that monitor the biosphere, are becoming essential tools to help us to manage and sustain our very lives (Sadeh et al., 1996).

Space observations can tell us about our current biosphere, but the Earth as a system has not always been hospitable to human life. For approximately half of its existence, there was virtually no free oxygen in the Earth's atmosphere, and a completely different set of biogeochemical cycles operated to keep the Earth relatively stable in that state. Fundamental knowledge of the Earth is of more than casual interest—it is essential that we understand how to keep it from changing back to a stable state with conditions that would not support human life.

Astrobiology, the study of life in the universe, seeks answers to fundamental questions on the origin, evolution, distribution and future of life, wherever it may exist. As an interdisciplinary science field that unites astronomers, biologists, physicists, chemists, geologists and many of their subdisciplines it addresses many questions that are relevant for sustaining life on planet Earth—and in particular, the relationships between a planet (especially the Earth) and life, and how each affects the other. Astrobiology provides both the knowledge and perspective to inform us about how to maintain the Earth as a long-term habitable home for humanity. Originally a creation of NASA (under the titles, "exobiology" and "planetary biology"), astrobiology has grown worldwide as a multi- and interdisciplinary endeavor. Together, astrobiologists have collaborated in writing down a "NASA Astrobiology Roadmap" (Des Marais et al., 2008) now in its third iteration that covers seven main goals, given in temporal, and not priority, order. Of particular interest here in joining Earth sciences and space studies is roadmap goal number 6, which states that astrobiology, as a field, should work to,

> Understand the principles that will shape the future of life, both on Earth and beyond. Elucidate the drivers and effects of microbial ecosystem change as a basis for forecasting future changes on time scales ranging from decades to millions of years, and explore the potential for microbial life to survive and evolve in environments beyond Earth, especially regarding aspects relevant to US Space Policy.

Here "US Space Policy" is a reference to the specific US interest in returning to the Moon and going on to Mars, as mentioned above. Astrobiology, and particularly the desire to understand the origin, evolution, and distribution of life in the universe, is one of the chief motivators for expanded human capabilities to conduct science on other worlds (Fig. 1).

3.1. Lessons from astrobiology: conservation of biodiversity and life in extreme environments

Over the course of the last 4.5 billion years, Earth has created an ideal environment to sustain life of an astonishing variety. Dynamic processes in the Earth's interior have established a magnetosphere that protects the Earth from harmful cosmic ray particles. The Earth's atmosphere, in turn, shields life from harmful ultraviolet radiation and allows for a stable climate and temperature cycle by providing a "greenhouse effect" that retains some of the infrared radiation that is emitted from the Earth's surface.

A brief look at our planetary neighbors shows that Venus, with an average surface temperature of 500 °C (as a result of a "runaway" greenhouse effect), and Mars, with a surface temperature from −60 °C to +10 °C and a thin atmosphere (with an insufficient greenhouse effect), are both unable to sustain life as we know it at the surface.

The combination of Earth's physical and chemical processes (e.g. ocean circulation, atmospheric flows, plate tectonic recycling of the crust, etc.) and living processes, together, form biogeochemical cycles that transform the elements and compounds related to life (the bio-elements such as H, C, O, S, N, P). While humans originally were part of these natural cycles, the discovery and proliferation of human-discovered technology have caused major disruptions to these bio-cycles in many, if not most, parts of the globe. As a consequence, and with the orders-of-magnitude rise in human population over the last 200 years, humans are coming to dominate and destroy the natural cycling of the elements with unpredictable consequences. While it is well known that natural processes have led to extinction of species, other life forms arose over time. Regrettably, the effects of modern human activities are rapid on the evolutionary timescale, and consequently are

Fig. 1. Astrobiology connects space and Earth science to answer fundamental questions about life in the universe (Des Marais et al., 2008).

impacting climate, ecosystems, and other species at a rate that does not allow for natural replacement of ecosystems in the same time-span. Consequently, the loss of ecosystems on which we depend is affecting human habitats adversely, all over the planet.

Biodiversity is a measure of the variety and numbers of life found at all levels of biological organization. As a concept, biodiversity can embrace all forms of diversity in biological systems: in genetics, species, and ecosystems. The conservation of biodiversity has become a global concern because different species contribute in essential (and often uncharacterized) ways to the functioning of the Earth's life support systems, on which we all depend. Effectively, the loss of biodiversity results in the loss of valuable ecosystem services that we take for granted, and which we (if we care to continue to inhabit the Earth) can ill-afford to lose.

The ongoing loss of biodiversity is of concern to astrobiologists, in particular, they realize that the Earth, as a system, is quite capable of operating without it—but that it can operate as a system that does not provide essential support (e.g. oxygen in the atmosphere) for human life. In fact, the most critical difference between today's Earth, and that of 2.5 billion years ago, is biodiversity. The effects of other living systems have made the Earth the extremely habitable planet that it is today, and it would be ironic if humanity's influence were to destroy those systems on which we all very much depend. Scholes et al. (2008) note that unlike climate change there are no widely accepted and globally available set of measures to assess biodiversity and critical information that can aid in the preservation of biodiversity. Thus, challenges lie in integrating biodiversity data that are diverse, physically dispersed, and in many cases, not organized in a way that makes them accessible to modern researchers.

The threat to biological diversity was among the topics discussed at the UN World Summit for Sustainable Development in 2002. At the Summit, the governments adopted the "Convention on Biological Diversity" to conserve biological diversity. "Biodiversity" is one of the nine 'societal benefit areas' identified by GEOSS.

The Biodiversity Observation Network (BON) (Scholes et al., 2008) is an initiative within GEOSS which establishes a framework for data collection, standardization, and information exchange in biodiversity studies (BON, 2009). NASA and DIVERSITAS, an international program of biodiversity science, is leading the planning phase of GEO-BON, in collaboration with the GEO secretariat. Nine other organizations and programs are participating in this initiative.

In a sense, the astrobiological interest of life in extreme environments is complementary to the study and appreciation of biodiversity. Life on Earth is extremely adaptable, and has been shown to overcome extremes in temperature, pH, and pressure in abundance (see Table 1). Equally interesting is the fact that some microbes depend exclusively on abiotic processes for their existence, including organisms in deep mines that survive on the products of radioactivity and organisms at deep sea vents. While it is encouraging that life is so tenacious, it is also humbling in a sense. While these microbes live in "extreme" environments quite successfully (and thus would not be hurt if the Earth, itself, were to become "extreme") the word "extreme" is used because it connotes an environment where humans could not live, at all.

Table 1
Examples of parameters constraining life processes.

Parameter	Limiting conditions	Type of organism
Water	Liquid water required	
Temperature[a]	Minimum −2 °C	Psychrophiles
	50–80 °C	Thermophiles
	80–121 °C	Hyperthermophiles
Salinity	15–37.5% NaCl	Halophiles
pH	0.7–4	Acidophiles
	8–13.2	Akalophiles
Atmospheric pressure	Up to 130 MPa	Barophiles
Energetic radiation	Up to 3 kGy	Radiophiles

[a] Note that the lowest temperature known to allow microorgansms to metabolize is ∼−20 °C and the highest ∼121 °C.

The study of extreme life is important in determining both where life may be found elsewhere, and in understanding the functioning and adaptability of life that we have here on Earth. Both NASA and the US National Science Foundation have had or currently have programs to study "extremophiles" and recently, the European Commission has initiated within its "Framework 7" 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 (ESF, 2007). 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, 2008).

By relating information on both biodiversity and extreme life, this synergy of Earth and space science can help to provide concepts (based on recent scientific data) on how ecosystems respond to rapid rates of change and determine possible directions by which the Earth and its biosphere (including humans) will survive and co-evolve in the future. This approach requires applying the principles and perspectives of astrobiology to identify options that might allow humanity to halt the destruction of its own habitat as well as the decline of biodiversity on Earth, while addressing a variety of related economic and energy-related scenarios associated with those options.

3.2. Space weather and its impacts on anthropogenic activities

Space weather and space climate (Mursula et al., 2007), in analogy to conventional weather and climate of the Earth, conceptualizes variations of environmental conditions in outer space. Space weather on Earth is primarily determined by the solar activity and interplanetary magnetic field and their interaction with the Earth's atmosphere, magnetosphere, and ionosphere. The Sun's activity undergoes dramatic changes, both short- and long-term, with a range of regular and irregular phenomena. A stream of ionized particles is enduringly emitted by the Sun. This component increases in solar luminescence with the sunspot cycle while the galactic cosmic rays are anti-correlated with the sunspot cycle.

More galactic cosmic rays cause a radiation risk for satellites and trans-polar aviation. Solar eruptive events occur generally in phase with the sunspot cycles, and consist of solar flares, coronal mass ejections and solar energetic particles. Those events can cause ionospheric storms, which can disrupt Global Navigation Satellite Systems as well as communication. Increased radiation affects also the health and safety of astronauts and airplane passengers (WMO, 2009).

The United States National Space Weather Program Council defined space weather as "conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health" (NSWP, 1995). Historical records reveal that unusually large space weather events occurred in the past such as the geomagnetic superstorms in 1859 and 1921. Moreover, in 1989 a power blackout in Canada caused by a geomagnetic storm left millions of people without electricity for several hours. Such extreme events, though rare, can occur again. Since modern society depends heavily on a variety of complex technology infrastructure, a possible loss of core functions (e.g. communication, navigation, and power supply) due to a severe space weather event poses serious socio-economic and security implications (see NRC, 2008c).

The study of solar activity, solar wind, and their effects on the near-Earth environment has been shown to have important implications both for life on Earth and for human space exploration. Space weather can interfere with astronaut operations in space, and because humans now reside in low Earth orbit on the ISS, and may soon travel to further destinations within the solar system, the significance of these studies is growing. While the influence of space weather on global warming is still uncertain, it is the subject of ongoing scientific investigations. A number of space-based probes monitor solar activity and provide data for space weather predictions. The variety of measurements enabled by space-based instruments is summarized in Table 2. The ESA–NASA Solar and Heliospheric Observatory (SOHO) spacecraft and NASA's Advanced Composition Explorer (ACE) provide near real-time coverage of space weather data from the L1 Lagrangian point. Monitoring from L1 point is particularly important to providing early warning of geomagnetic storms. A number of Earth-orbiting satellites as well as ground-based facilities provide data for space weather services. A recent addition to space weather monitoring is the NASA–ESA Solar-Terrestrial Relations Observatory (STEREO), which performs stereoscopic imagery in the region between the Sun and the Earth. And for "customer service", the United States provides various space weather services through the Space Weather Prediction Center (SWPC) operated by the National Oceanic and Atmospheric Administration (NOAA). A space weather hazard scale provides guidance to its users by quantifying the severity of the anticipated events, and an effort is underway at WMO to facilitate an international collaboration in operational space weather services (see WMO, 2009).

Table 2
Space-based instrument measurement requirements for space weather studies (adapted from Hapgood and Oliver, 2001, p. 9).

Space instrument measurement types
Solar images
Auroral images
Solar X-ray and UV fluxes
Solar wind plasma properties
Interplanetary magnetic field
Magnetospheric magnetic field
Cross-tail electric field
Bulk plasma properties
Electron and ion fluxes
Debris and meteoroid properties
Interplanetary radio emissions

4. Exploiting synergies of Earth science and space exploration

While there are areas of common interests and identified synergies between Earth science and space exploration, such potential synergies have not been fully recognized and exploited. The importance of an interdisciplinary approach to bring together both Earth and space communities has been recognized in the 2003 decadal survey of NASA's heliophysics program (NRC, 2003).

Future settlements on other planets require the construction of habitats, life support systems and access to resources such as water, oxygen and other elements. Permanent settlement of the human race beyond Earth may result in terra-forming of the new habitat. Although the goals and objectives have changed, synergies are given in this scenario, in particular concerning operations in extreme environments and space hazards. Commercial application has a much stronger involvement in human exploration. National space agencies do not have sufficient funding to cover the costs for human space exploration and need the commercial sector as reliable partner. New legal frameworks will be required including planetary protection guidelines to exert control over extended and more frequent space activities (Kminek and Conley, 2008; Williamson, 2003). Furthermore, the general perspective of society will change. Leaving Earth for extended periods to explore other solar system objects and eventually settle on another planet in the far future augments technical requirements but requires evolving policy aspects that impact governance, society and the commercial sector.

Fifty years of Earth observations from space has accelerated the cross-disciplinary integration of analysis,

Table 3
Synergy matrix between planetary space exploration and Earth science activities.

Life on Earth	Science	Instruments	Data and predictions	Technology
Space	Solar-terrestrial connection Cosmic effects Planet dynamics	Particle sensors Dust collection Sky surveys Radiation sensors	Solar flares Cosmic rays NEO impacts Space weather	Launchers Satellites Space probes Platforms
Planets	Atmosphere Surface Subsurface Interior	Remote sensing Surface probes Radar/drill Seismometer	Greenhouse Geological history Volcanism Quakes	Orbiters Rovers Balloons In situ instrumentation Automated systems
Earth	Atmosphere Surface Subsurface Interior	Remote sensing Surface probes Radar/drill Seismometer	Climate Oceans Volcanoes Quakes	Orbiters Ground segments Balloons In situ instrumentation Ocean drills Autonomous systems
	Governance	Education	Commerce	Society
Space	Space treaties International space cooperation	Perspectives Origins of Solar System	Transportation systems	Communication Positioning Weather
Planets	Planetary protection	Geology Origin of life Habitability	Resources, Preparation for human space flight	Exploration Inspiration Knowledge
Earth	Environmental policies Pollution Disaster control	Global warming Biodiversity Long-distance education	Satellite services (environmental, communication, security)	Climate control Humanitarian aid information

interpretation, and ultimately our understanding of the dynamic processes that govern the planet; this new approach plays a critically important role in helping society manage planetary-scale resources and environmental challenges (NRC, 2008a). The exploitation of synergies in Earth science and space exploration provides opportunities for both communities to further this achievement. Both scenarios, Life on Earth and Life beyond Earth not only share similar goals but also need similar information to conduct a successful program. Table 3 portrays the synergies of robotic planetary exploration and Earth science activities aimed to protect the environment and life on Earth. Table 3 indicates that science goals and the required instrumentation for Earth observations and planetary science are often similar. There are obvious synergies in technology and data handling that could lead to a fruitful exchange of scientists and engineers. The synergy matrix addresses not only science and technology but also socio-economic issues. Table 4 summarizes the synergies between the human exploration of the Earth–Mars–Moon system and Earth sciences. The challenge of building new infrastructure for planetary environments and new human transport systems and cargo vehicles has a strong impact on the stakeholders, such as the space sector and society at large and requires an interdisciplinary approach.

In order to successfully explore another planet we need a thorough understanding on the limits for life on Earth and how to survive in harsh environments. The Earth observation community has developed exemplary tools and successful international cooperation in data handling and sharing that could be applied to robotic planetary exploration as well. Education and awareness of the society will benefit from the knowledge of habitability in our solar system including aspects of planetary protection.

Earth and space communities should join in order to exploit the synergies in the form of collaborations. Such synergies can arise on technical, managerial, and political levels. Technical synergies can result from sharing scientific knowledge, data, and experiences, as well as common infrastructures, technologies, and skills. Managerial synergies can arise from sharing institutions, governance structure, and learning from management knowledge and skills of the other community.

At the political front, coalitions can be formed to address common policy goals and strategies that could be shared to address common issues. The following subsections identify specific areas of synergies that could be exploited by the two communities.

4.1. Sharing of scientific knowledge, instrument technologies and data

Synergies of the instrumentation and data handling concerning planetary objects and Earth observations are evident. Remote sensing instruments on planetary orbiters have been modeled after instruments that study the Earth atmosphere (cf. as the proposed MATMOS instrument for Mars atmospheric studies, derived from the ATMOS

Table 4
Synergy matrix between human space exploration and Earth science activities.

Life beyond Earth	Science	Instruments	Data and predictions	Technology
Space	Solar-terrestrial connection	Particle sensors	Solar flares	Launchers
ISS	Cosmic effects	Dust collection	Cosmic rays	Satellites
	Planet dynamics	Sky surveys	Impacts	Space probes
		Radiation sensors	Space weather	Platforms
Moon	History	Surface probes	Geological history	Rovers, robots
Mars	Geology	Radar/drill	Radioactive dating	Autonomous systems
Asteroids	Conditions for life resources	Robotic tools	Composition	Impactors
		Penetrators	Constraints for life	In situ instrumentation
				Life support systems
Earth	Atmosphere	Remote sensing	Climate	Ground segments
	Surface	Surface probes	Oceans	Balloons
	Subsurface	Radar/drill	Volcanoes	In situ instrumentation
	Interior	Seismometer	Quakes	Ocean drills
				Autonomous systems
	Governance	Education	Commerce	Society
Space	Space treaties	Perspectives	Human transport systems	Advanced access to space
ISS	International space cooperation	Human expansion	Cargo vehicles	Technology advances
		Survival in space	Space tourism	Space rides
Moon	Planetary	New territories	Habitats	Lunar base
Mars	Protection	Habitability	Resources	Human transport to Mars
Asteroids	Moon treaty	Humans and robot synergies	Exploitation	Future settlements
	Rescue agreement		Space suits	
Earth	Environmental policies	Global warming	Satellite services (environmental and communication, security)	Climate control
	Pollution	Biodiversity		Humanitarian aid information
	Disaster control	Long-distance education		

instrument that flew on the Space Shuttle, or EPOXI,[3] a mission that studies comets, exoplanets and Earth). Planetary surface operations are conducted under different conditions, but with a number of technological similarities to systems used to investigate both the surface and subsurface of the Earth's surface and oceans.

Both environments feature autonomous systems, power conservation, and the use of radar instrumentation, seismometers and drilling devices to probe below the surface. Data characterizing space weather and space climate (short-and long-term variations, respectively) can serve both communities.

Adoption of common standards and calibration is important in Earth observations because the data obtained from various systems and instruments must be compared or stitched together to make the information more useful and comprehensive. In Earth observations, such effort is under way. As part of a solution to calibration problems, a Global Space-based Inter Calibration System has been proposed to allow calibration of various different instruments to assure comparability as well as quality of data. GEOSS also adopts and promotes standardization and processing of data.

Full and open access to satellite data is crucial—as only when a sufficient number of scientists are trained in the effective use of these data, will the analysis tools mature to the benefit of all parties. In addition, training and maintaining the required workforce is possible only if the data are continuously accessible to the broad scientific community. The concept of open data access was adopted by the International Geophysical Year some 50 years ago when establishing the World Data Center System. It required decades for the analysis tools used in Earth observation to mature.

In space exploration, standardization of planetary data is also important—ISECG has started the standardization effort with the Space Exploration Coordination Tool INTERSECT (see ISECG, 2009). In lunar exploration, common standards and interfaces are being considered and developed through the International Lunar Exploration Working Group (ILEWG) from coordination. Data processing algorithms, data package formats, software tools are among the intellectual properties that could be mutually exploited. To summarize, it is highly desirable that knowledge on the standardization process concerning data analysis and archiving of remote sensing data should be exchanged for cross-fertilization between both communities.

4.2. Combining efforts in education and public awareness

Over the past years, there has been an increasing awareness in environmental impact and climate change. However, the crucial role played by space systems in delivering environmental data has not been fully recog-

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[3] http://epoxi.umd.edu/#.

nized. Moreover, in the case of space weather, ignorance in potential hazard caused by severe space weather is profound. Space exploration programs may be more visible but equally suffer from lack of public support. The amount of budget on space programs often puts them under doubt: "*Why go into space when we have so many problems here on Earth?*" or "*What does the space program do for me?*" Such questions largely originate from the lack of awareness how space activities contribute to daily life. Both communities Earth and space-centric could benefit from awareness campaigns highlighting spin-offs from space activities.

Making the public aware how strongly they are dependent on satellite communication controlling phone and television transmission and dominating the daily life and routine is an important endeavor (Grimard, 2008). Promoting "spin-offs" that have originated from space programs including computer technology, manufacturing, health and medicine, safety, and transportation is an important tool to win public support. Some of the spin-offs have proven to be useful in meeting environmental challenges, e.g. to harness solar energy originated from the need to generate electric power in outer space before being adopted as clean energy source. To reverse the current public opinion about space activities will require a strong effort in public outreach and education involving interactive technologies to reach young people (Ehrenfreund et al., 2010).

4.3. Forging a common policy for long-term commitment and planning

Assuring the availability of continuous and comprehensive Earth observation data is the biggest challenge faced by the Earth observation community. Continuity is especially important for monitoring long-term phenomena such as climate change. Currently most of the Earth observation satellites are being developed for scientific or experimental purposes, and transition of these systems into operational phase is perceived critical in assuring long-term continuous availability of Earth observation data. Europe has committed itself to the development of the Global Monitoring for Environment and Security (GMES/Kopernikus) program, an operational Earth observation constellation to be functional for the next 25 years.[4] In contrast, the United States lacks long-term commitment and planning in Earth observation and this is considered a serious problem. For example, in space weather monitoring, the fragility and lack of robustness of the US's current capabilities have been perceived as problematic. Not only is there a lack of a dedicated system of space weather monitoring, but also there are no immediate backups or replacements for the spacecraft that space weather prediction services currently rely on.

Long-term sustainability of human exploration has also been championed but its feasibility remains uncertain. The retirement of the Space Shuttle will limit crew access to ISS using Soyuz rockets only, unless otherwise enabled by a COTS (Commercial Orbital Transportation Services) system. In robotics, the US Mars program has been conducting a mission every 26 months, but the future roadmap (along with programmatic missteps and budgetary issues) indicates gaps in that schedule.

A program for international Mars cooperation between ESA and NASA is currently under review that would focus on space missions to Mars in 2016, 2018 and 2020. The Russian Phobos-Grunt mission is scheduled to bring back a sample from the Martian moon in 2011. Since space systems take a long time to develop, it is important to plan ahead and secure a long-term commitment. However, due to high costs, complexity in technology, and the nature of politics, it is very difficult to plan and commit to any long-term roadmap in space programs. A common effort to establish a space network related to the conservation of biodiversity and the study of life in extreme environments (or the search for life) may capture the attention of the public and lead to larger governmental support. Within a more stable funding system, such a program could be implemented by current space powers and new rising space-faring countries, alike.

4.4. Developing a private sector participation strategy

While private actors are increasingly relying on the Earth observation data, their participation in the domain has been very limited. For example, there was no sufficient input to the set of Earth observation requirements from the industry as from the scientific community, which may inhibit private sector use and support of space system development (CSIS, 2008). Space weather data are crucial for a number of industries that are operating airlines and electric power grids.

Input from the private industry is essential for making the data useful to them. In addition, business opportunities of the private sector in both Earth observation and space weather services should be explored. Solar and geospatial imaging instrumentation could be transitioned into operational programs for the public and private sectors. Public–private partnerships in space exploration are evolving and governments are likely to rely more on commercial space services in the long-run. NASA has invested and committed to purchase potential COTS crew and cargo services to the ISS.

The successful launch of the Falcon 1 in September 2008 is seen as a key milestone. Entrepreneurs are finding market opportunities in space tourism and starting to play unique visionary roles. For example the X PRIZE Foundation (X-Prize, 2009) and Google announced a new cash prize competition aiming to start a commercial race to the Moon. Looking two decades ahead, in conjunction with the recent progress of the private sector the situation, may shift strongly toward more involvement of space entrepreneurs and the private sector. The rise of new space partners and environmental and social responsibility

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[4] http://ec.europa.eu/gmes/index_en.htm.

should enhance more public private partnerships in space exploration and Earth sciences.

4.5. Implementing an international cooperation strategy

In the past years, various international collaborating and coordinating efforts in Earth observations have been formed (see Section 2.1). The international definition of space exploration defined by the Global Exploration Strategy (GES, 2007) may be read as "*a global, societal project driven by the goal to extend human presence in Earth–Moon–Mars space.*" The main international coordination mechanism for space weather has been the International Space Environment Service (ISES), which shares models and research results with a limited partner base. Although there is no global framework for space weather monitoring architecture currently in place, there is a strong case for space weather monitoring activities to be organized in a global context as events occur at global scale and it naturally embraces an array of international issues.

While international efforts increasingly become a norm in both Earth and space activities, challenges in international cooperation still remain. Cooperation is often hindered by US export regulations, including International Traffic in Arms Regulations (ITAR). These regulations apply not only to the space system hardware but also to space-obtained data, personnel exchange, and informal discussions. The sensitivity of relying on satellite assets controlled by foreign governments could also become an issue. For example, national security implication of relying on China on monitoring at L1 for space weather has been addressed in the United States (NRC, 2008c, p. 89).

The existing international coordination mechanisms are all on a voluntary-basis, thus there is no enforcement mechanism or legal framework supporting cooperation schemes. In addition, the existence of various international organizations and coordination mechanisms adds layers of bureaucracy and complexity, and dilutes the resources available for cooperation. Thus, the role and responsibilities of various cooperative bodies should be clarified in order to effectively manage cooperation. Sharing of international legal frameworks and, for example an international environmental regime that includes the concept of planetary protection will be a future asset to sustain our global protection of environment on Earth and beyond.

5. An interdisciplinary approach to bridge the Earth and space communities

An interdisciplinary approach is needed for all initiatives to bridge activities in Earth observation, space weather, biodiversity, and space exploration. Bringing different groups (international, private/public, provider/user, space/non-space, raw-data to operational service) together to work on a common challenge is difficult. However, networking and sharing of data, knowledge and experience is crucial to exploit synergies.

Cross-boundary sharing of information, coordination, and collaboration among the space and Earth science community will be necessary to address key questions for our future such as sustainability of our biosphere. For example, in space weather, the concept of Earth–Sun as a system has been successfully adopted over the past years. However, both communities, Earth and space-centric, suffer from similar drawbacks, such as lack of coordination, resources, long-term strategies, standardization and of public support. A synergy between two different communities can only be achieved by bringing the communities together in a suitable environment to exchange ideas and expertise. And that exercise alone might not be successful. Exchange of expertise during short conferences (with both communities present) will not lead to a strong collaborative effort, and may even result in a culture clash. The Earth observation community has the Earth-centric approach, whereas the space community is driven by desire to explore, innovate and push boundaries.

In order to align members of both communities team building exercises will be necessary as used in large companies. The team structure suggested to enable collaborations between Earth and space communities is *a global problem-solving team* that develops potential solutions (Hellriegel and Slocum, 2008). Team members should include experts from science, technology, the private sector, politics, law, information technology as well as public representatives and teachers. A mixture of task related members and relationship oriented members will bring balance to such teams.

Task-oriented problem-solving teams can elaborate concrete action plans that can be discussed with a larger part of the community and later be implemented in policy documents and governmental roadmaps.

Examples for specific goals that could be addressed by such teams are:

- Conduct space endeavors in synergy with Earth sciences and develop satellites or instruments that help to solve imminent problems on Earth; e.g. use the ISS for Earth observations.
- Conduct an enhanced program for field tests of planetary exploration in extreme environments on Earth (antarctic stations, dry deserts, ocean drilling ships, etc.) including rover operation, catastrophe training, and drilling exercises.
- Prepare activities for human space travel in science and related technology (material science, medical science, life support, and isolation/habitats).

The activities of cross-cultural, interdisciplinary and problem-solving teams may pace a successful way to find a consensus strategy between the Earth and the space communities. Governments have to provide such teams with sufficient resources and an environment that enables creative thinking. Carpenter et al. (2009) have recently discussed networked social–ecological research that should support a better understanding of the relationship between humans and the ecosystems on which they rely.

Often space agencies are hosting both the "Earth" and "planetary" science communities within the same institution. NASA, for example, hosts both groups under the Science Mission Directorate (SMD). This makes a space agency an ideal place for a cross-disciplinary approach. Not only should the communication barrier between the two groups be comparatively low, but also there are many opportunities for the groups to interact, both formally and informally, within the institutional setting. However, currently their work is narrowly divided. The two communities often compete for the limited budget allocated to the science programs. Managerial separation within the organization (in addition to academic disconnection) is a challenge when bringing the two communities together, so understandings of the benefit of interdisciplinary work can be promoted and institutionalized. Any joint activity or establishment of working or coordination groups, such as the one described above, may be facilitated within a space agency.

Another possible way to encourage important personal interactions, and thus understanding and cooperation, would be to set up an exchange program where scientists from each group are exchanged for a certain period of time. Space agencies could allocate a special budget for such interdisciplinary effort within their organization. Charles Cockell, in his book *Space on Earth* (Cockell, 2006, p. 115), notes that "*Space faring environmental ethics provides a completely new reason for ecosystem preservation and conservation—an understanding that ecosystems have universal value as unique examples of life and evolution*". He makes a number of suggestions to help to bridge the Earth and space-centric communities. For instance, he proposes a new alliance such as a "Department of Earth and Space Affairs" on governmental level. In the academic environment, study programs of "Environmental and Space Studies" should be offered.

Cross-disciplinary publications can certainly improve the education of society and new academic generations. Furthermore, companies that are both Earth and space-aware and that develop products that are useful for both Earth and space applications could play an important role in bridging the Earth and space communities.

The lack of space awareness has a negative effect on the public opinion of space activities and consequently there is no force on governments to increase the space budget. New participatory strategies to engage the public as major stakeholder need to be elaborated. The role of environmental satellites in climate control, disaster management, education and security is immensely powerful (ESPI, 2007). Benefits and spin-off from space technology have to be widely publicized. The younger generations that should be more concerned about the sustainability of planet Earth need to be targeted with new media technology such as interactive tools in the form of reality shows and computer games. Worldwide awareness campaigns (e.g. entitled "Space for Earth") will support governments in assuring long-term funding and planning. We have to recognize that the public has a strong influence on the decision-making process of future space endeavors.

Williams Burrow, in Survival Imperative (Burrows, 2006, p. 317) notes, "*The most daunting obstacle to a permanent program to use space for the protection of Earth is not financial or technical. It is political*". He argues that "*Planetary defense should become normative like military defense*" (Burrows, 2006, p. 247). The lack of coordination structures that possess budgetary authority as well as scattered responsibilities among several agencies has been identified as a major risk for effective cooperation. Protecting Earth should be institutionalized and financed accordingly. To solve humanitarian and environmental problems on Earth or to embark for exciting new human space endeavors and to exploit synergies among those two goals requires innovative concepts and brainstorming. Implementing such concepts would provide an impulse for new collaborations within the space sector, opportunities for international collaboration and give new insights how the human race can efficiently protect its habitat.

6. Conclusion

Synergies of Earth science and space exploration were explored. Without doubt space technology has strongly contributed to our understanding of planet Earth and helps continuously to improve environmental issues, communication and in areas like disaster management. Future human space exploration endeavors to Moon, Mars and beyond target the expansion of human presence in space. Both scenarios share similar goals—the protection and evolution of humanity—and need similar information to conduct a successful program. Synergies between both communities can arise on technical, managerial, and political levels. Commonality in data products and software in space technology is essential. Education and awareness of society can benefit tremendously from knowledge of the overall habitability of our solar system. For a long-term planning a clear management structure and a stable and protected budget by the individual space-faring countries are essential in order to make the global coordination effort between space and Earth science meaningful. International cooperation and sharing of international legal frameworks that include the concept of planetary protection will be a future asset to sustain the global protection of the environment on Earth and beyond.

A network bridging both communities and advancing the exchange of information on biodiversity, space weather and other areas of common interest will allow the development of new policies and management strategies to effectively exploit synergies of Earth science and space exploration.

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[X-Prize 2009] http://www.googlelunarxprize.org/.

Related websites

Convention on Biological Diversity. http://www.cbd.int.

GCOS Global Climate Observing System (GCOS). http://www.wmo.int/pages/prog/gcos.

GEO Group on Earth Observation (GEO). http://www.earthobservations.org.

CEOS: Committee on Earth Observation Satellites (CEOS). http://www.ceos.org.

GEOSS Global Environmental Observation System of Systems (GEOSS). http://www.earthobservations.org/geoss.

ILEWG International Lunar Exploration Working Group (ILEWG). http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=34125.

NOAA Space Weather Prediction Center. http://www.swpc.noaa.gov.

United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER). http://www.oosa.unvienna.org/oosa/en/unspider.

Further reading

International Charter on Space and Management Disasters. http://www.disastercharter.org.