Benefits Stemming from Space Exploration

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International Space Exploration
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Table of Content

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Executive Summary

More than fifty years of human activity in space have produced societal benefits that improve the quality of life on Earth. The first satellites, designed to study the space environment and test initial capabilities in Earth orbit, contributed critical knowledge and capabilities for developing satellite telecommunications, global positioning, and advances in weather forecasting. Space exploration initiated the economic development of space that today, year after year, delivers high returns for invested funds in space[1]. The challenges of space exploration have sparked new scientific and technological knowledge of inherent value to humankind, leading to better understanding of our Universe and the solar system in which we live. Knowledge, coupled with ingenuity, provides people around the globe with solutions as well as useful products and services. Knowledge acquired from space exploration has also introduced new perspectives on our individual and collective place in the Universe.

Future space exploration goals call for sending humans and robots beyond Low Earth Orbit and establishing sustained access to destinations such as the Moon, asteroids and Mars. Space agencies participating in the International Space Exploration Coordination Group (ISECG)[2] are discussing an international approach for achieving these goals, documented in ISECG's Global Exploration Roadmap[3]. That approach begins with the International Space Station (ISS), and leads to human missions to the surface of Mars.

Employing the complementary capabilities of both humans and robotic systems will enable humankind to meet this most ambitious space exploration challenge, and to increase benefits for society. These benefits can be categorized into three fundamental areas: innovation; culture and inspiration; and new means to address global challenges.

Innovation. There are numerous cases of societal benefits linked to new knowledge and technology from space exploration. Space exploration has contributed to many diverse aspects of everyday life, from solar panels to implantable heart monitors, from cancer therapy to light-weight materials, and from water-purification systems to improved computing systems and to a global search-and-rescue system[4]. Achieving the ambitious future exploration goals as outlined above will further expand the economic relevance of space. Space exploration will continue to be an essential driver for opening up new domains in science and technology, triggering other sectors to partner with the space sector for joint research and development. This will return immediate benefits back to Earth in areas such as materials, power generation and energy

[1] OECD Handbook on Measuring the Space Economy, March 2012.

[2] ISECG space agencies include, in alphabetical order: ASI (Italy), CNES (France), CNSA (China), CSA (Canada), CSIRO (Australia), DLR (Germany), ESA (Europe), ISRO (India), JAXA (Japan), KARI (Republic of Korea), NASA (United States of America), NSAU (Ukraine), Roscosmos (Russia), UKSA (United Kingdom).

[3] The Global Exploration Roadmap can be downloaded at www.globalspaceexploration.org

[4] Spinoff materials published by the National Aeronautics and Space Administration (e.g. Spinoff database, spinoff.nasa.gov/spinoff/database; Spinoff 2012, spinoff.nasa.gov/Spinoff2012);

storage, recycling and waste management, advanced robotics, health and medicine, transportation, engineering, computing and software. Furthermore, innovations required for space exploration, such as those related to miniaturisation, will drive improvements in other space systems and services resulting in higher performance and lower cost. These will in turn result in better services on Earth and better return of investment in institutional and commercial space activities. In addition, the excitement generated by space exploration attracts young people to careers in science, technology, engineering and mathematics, helping to build global capacity for scientific and technological innovation.

Culture and Inspiration. Space exploration offers a unique and evolving perspective on humanity's place in the Universe, which is common to all. Every day, space exploration missions fulfill people's curiosity, producing fresh data about the solar system that brings us closer to answering profound questions that have been asked for millennia: What is the nature of the Universe? Is the destiny of humankind bound to Earth? Are we and our planet unique? Is there life elsewhere in the Universe?

New Means to Address Global Challenges. Partnerships and capabilities developed through space exploration create new opportunities for addressing global challenges. Space exploration is a global endeavour contributing to trust and diplomacy between nations. Enhanced global partnerships and exploration capabilities may help advance international preparedness for protecting the Earth from catastrophic events such as some asteroid strikes, advancing collaborative research on space weather and protecting spacecraft by developing new means for space debris removal. Knowledge derived from space exploration may also contribute to implementing policies for environmentally sustainable development.

In summary, space scientists and engineers who overcame past challenges could not have predicted all the ways in which their innovations are now being used on Earth. Though the precise nature of future benefits from space exploration is unpredictable, current trends suggest that significant benefits may be generated in areas such as new materials, health and medicine, transportation, and computer technology**.** New opportunities for job creation and economic growth are being created by private enterprises that are increasingly investing in space exploration and seeking ways to make space exploration more affordable and reliable, and thus, more sustainable and profitable.

There is no activity on Earth that matches the unique challenges of space exploration. The first fifty years of space activity have generated benefits for people around the globe. This past record gives strong reason for confidence that renewed investments in space exploration will have similarly positive impacts for future generations.

1. Introduction

For more than fifty years, humans have explored space, and this has produced a continuing flow of societal benefits. By its very nature, space exploration expands the envelope of human knowledge and presence throughout the solar system, and this process has been accelerated by a combination of human and robotic activities. Experience has demonstrated that, as long as humankind addresses the challenges of exploring mankind's common frontier of space, many tangible societal benefits are produced, and in addition to those most commonly anticipated, a great variety of valuable innovations are generated serendipitously, for this is the nature of discovery.

From the early days of space flight, it became apparent that space exploration was an efficient driver for basic science and technology. The new challenges called for new approaches. The cost of launches drove designers to make spacecraft computers lighter, smaller and with the highest performance and dependability. Solar cells, batteries and fuel cells were driven by space needs and benefitted many sectors on Earth[5]. The first satellites, designed to study the space environment and test initial capabilities in Earth orbit, contributed critical knowledge for developing space telecommunications, global positioning, and advances in weather forecasting. The early missions also formed the technological basis for advanced space exploration, enabling the first robotic and human missions to the Moon, as well as highly capable planetary spacecraft and crewed space stations in orbit.

Over time, governments around the world increasingly cooperated to conduct complex space missions, demonstrating the power of international partnerships to amplify accomplishments in space.

The success has been impressive and space systems continue to drive innovation, support world-class science, provide vital services, and are part of the daily life of the common citizen. Service-driven space systems are the overwhelming part of space activity today[6]. Furthermore, the legacy of these historical efforts to develop sophisticated and useful capabilities and partnerships is evident in today's exploration programmes such as the International Space Station (ISS), which continues to contribute significant benefits to humanity[7]. The ISS supports

[5] Technology initiated by Space Exploration is often today driven by terrestrial mass market sectors. The space sector can then spin-in such technologies in effective ways. Renewed investments in achieving the ambitious future exploration goals promise to increase the innovation factor of space exploration.

[6] E.g. out of the 67 flights of Ariane 5 between January 2000 and July 2013, 59 launches (88%) were commercial.

[7] "International Space Station Benefits for Humanity", Ed. J.Robinson, developed by members of the Canadian Space Agency (CSA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), National Aeronautics and Space Administration (NASA), and Russian Federal Space Agency (Roscosmos), 2012. Accessed at http://www.nasa.gov/pdf/626862main_ISS_Benefit_for_Humanity.pdf.

investigations in life and physical sciences, as well as advancing research and technology to solve problems associated with long-duration human space flight that have many applications on the ground.

Future space exploration goals call for sending humans and robots beyond Low Earth Orbit (LEO) and establishing sustained access to space exploration destinations such as the Moon, asteroids and Mars. Space agencies participating in the International Space Exploration Coordination Group (ISECG)[8] are discussing an international approach for achieving these goals, documented in ISECG's Global Exploration Roadmap[9], that begins with the ISS and advances coordinated human and robotic exploration, leading, amongst other things, to human missions on the surface of Mars.

Achieving these ambitious exploration goals requires researchers to surmount new challenges and develop coordinated human and robotic exploration capabilities. As has been demonstrated in the past, deploying the unique and complementary capabilities of both humans and robotic space systems is not only essential for solar system exploration, but also promises to expand many benefits provided to people on Earth.

While early space scientists and engineers expected that space exploration would have positive impacts on humanity, they could not have foreseen all the specific social and economic benefits that have flowed from their work. So too, the current generation cannot predict in detail what benefits will eventually appear as a result of its efforts The unforeseen positive results of the past five decades indicate the great potential for space exploration to continue producing a wide range of applications and knowledge which will expand the space-based economy even further.

This paper, a collective effort by representatives of space agencies participating in ISECG, articulates a shared perspective on the nature and significance of the benefits of space exploration programmes, and on the potential for the future delivery of benefits. It summarizes the fundamental benefits to humanity (Chapter 2) which could arise as space agencies collectively work on achieving the ambitious future exploration goals outlined above. It also provides a perspective on potential specific benefits to be achieved over the next ten years (Chapter 3).

While this paper is not meant to provide a conclusive view on the societal relevance of future space exploration, it documents a strong commitment of space agencies to deliver benefits to

[8] ISECG space agencies include, in alphabetical order: ASI (Italy), CNES (France), CNSA (China), CSA (Canada), CSIRO (Australia), DLR (Germany), ESA (Europe), ISRO (India), JAXA (Japan), KARI (Republic of Korea), NASA (United States of America), NSAU (Ukraine), Roscosmos (Russia), UKSA (United Kingdom).

[9] The Global Exploration Roadmap can be downloaded at www.globalspaceexploration.org

society. It will aid space agencies in engaging relevant stakeholder communities in discussions on how the flow of benefits to society can be further improved.

2. Fundamental Benefits of Space Exploration

To a great extent, the benefits from space exploration are rooted in the generation of new knowledge, which is the first reward and which has inherent value to humankind. Technological knowledge, generated when high-performance space systems are developed to address the extreme challenges of space missions, yields many innovations that benefit the public. Scientific knowledge acquired from space expands humankind's understanding of nature and frequently unlocks creative and useful Earth-based applications for society. In the longer term, the knowledge accumulated over many missions and the expansion of human presence into the Solar System help people gain perspective on the fragility and rarity of life in the Universe and on humankind's accomplishments, potential, and destiny.

Space exploration stimulates the creation of both tangible and intangible benefits for humanity. Tangible impacts include all the innovation-related applications and benefits resulting from investments in these programmes, such as new devices and services that spin off into the marketplace. In addition, space exploration leads to advances in science and technology, and furthers workforce development and industrial capabilities, thus leading to an overall stimulation of private companies and industries, all of which contributes significantly to the economic progress of space-faring nations. Space exploration is also known to attract young people into careers in science and technology to the general benefit of society and the economy (see chapter 2.1). Space exploration also results in various intangible impacts due to the social and philosophical dimensions that address the nature and meaning of human life. Intangible benefits include the enriching of culture, the inspiration of citizens, and the building of mutual understanding as a result of international cooperation among space-faring nations.

The fundamental benefits generated by space exploration are grouped in this document as follows: (i) innovation; (ii) culture and inspiration; and (iii) new means to address global challenges. The delivery of these benefits to society provides the main rationale for investment in space exploration. An illustration on how these benefits are delivered by space agencies is given in the box below.

Space exploration’s capacity to continue delivering significant benefits to humanity was recognized by high-level government representatives from around the world when they convened in Lucca, Italy, in November 2011. They concluded that space exploration provides:

> *unprecedented opportunities to deliver benefits to humanity on Earth … These*

benefits include fuelling future discoveries; addressing global challenges in space and on Earth through the use of innovative technology; creating global partnerships by sharing challenging and peaceful goals; inspiring society and especially the younger generations through collective and individual efforts; and enabling economic expansion and new business opportunities. [10]

How Space Exploration Delivers Benefits

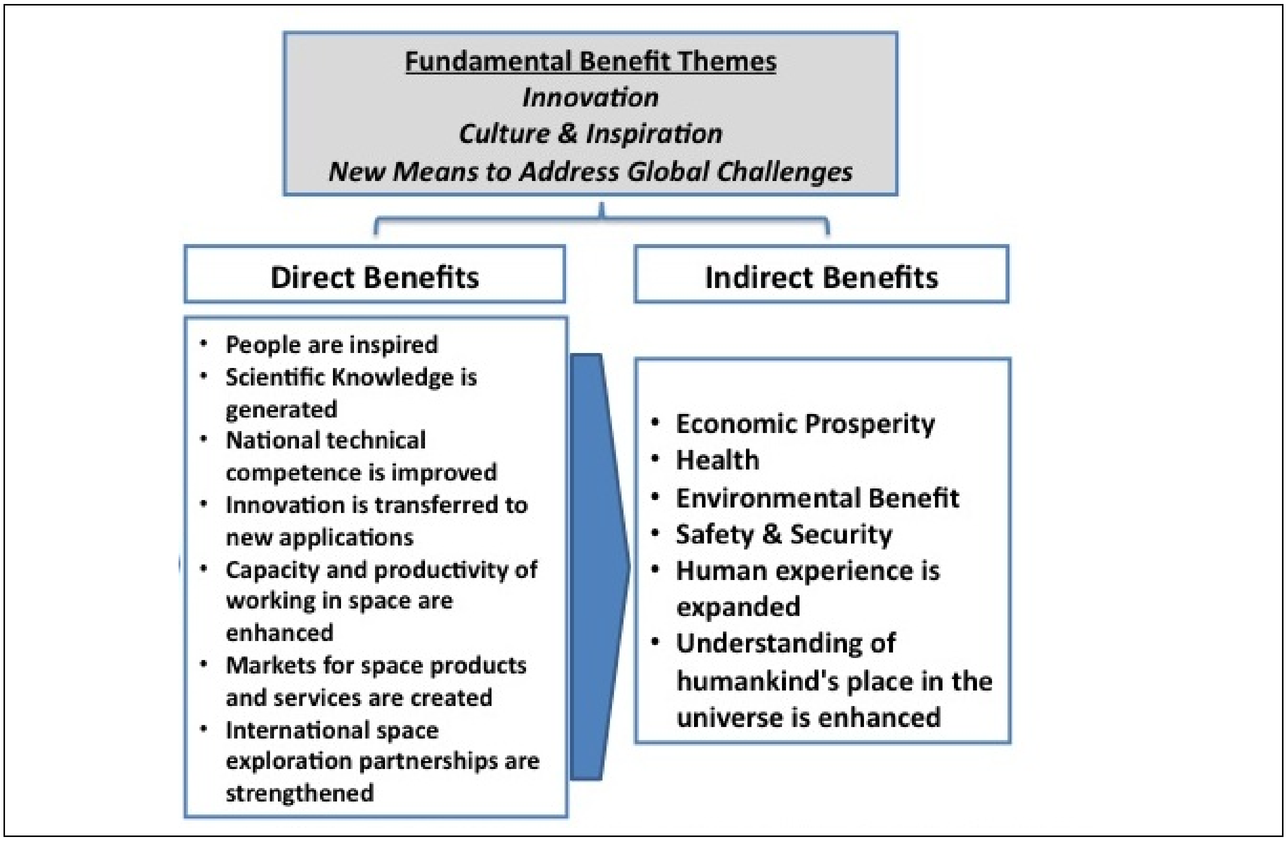
The benefits of space can be categorized as either direct or indirect. The direct benefits of exploration include the generation of scientific knowledge, the diffusion of innovation and creation of markets, the inspiration of people around the world, and agreements forged between the countries engaged in exploration.

Indirect benefits that result over time include tangible enhancements to the quality of life such as improved economic prosperity, health, environmental quality, safety, and security. They also include intangible philosophical benefits such as a deepened understanding and new perspectives on humankind's individual and collective place in the Universe.

Possibilities for benefit creation multiply rapidly when the products of space exploration interact with the imagination and creativity present in other fields of endeavour. Cultural benefits may depend on exploration mission stories and images spreading broadly across society. Educational organisations, the media and communications industries play a role in interpreting and amplifying exploration data, so that citizens may understand and appreciate their significance. To maximize societal impact, space agencies share space exploration results and collaborate with research institutions, businesses, universities, schools, museums, and other organizations.

The figure below represents a model of the links between space activities and ultimate societal benefits, and it helps space agencies explain and assess the unique contribution that space exploration makes to producing benefits for humanity.

[10] "Final Declaration of the First meeting of the High-level International Space Exploration Platform", Lucca, Italy, 2011, www.luccaexplorationconference2011.org.



2.1. Innovation

The challenge of space exploration drives a continuing effort to design ever more capable, reliable, and efficient systems requiring the utmost ingenuity. Space exploration missions use the unique capabilities of humans (e.g. on the spot decision-making, cognitive adaptability, versatility) and robots (e.g. precision, sensory accuracy, reliability and expendability) to achieve ambitious exploration goals. Maximizing the productivity of these missions by demanding an effective partnership between humans and machines drives progress in human health care, robotics, automation, and other domains.

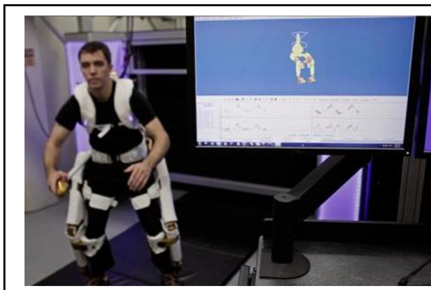


Figure 2. Exoskeleton to help paraplegics walk, derived from space robotic systems

Space exploration thus supports innovation and economic prosperity by stimulating advances in science and technology, as well as motivating the global scientific and technological workforce, thus enlarging the sphere of human economic activity.

Advances in Science and Technology

Overcoming the challenges of working in space has led to many technological and scientific advances that have provided benefits to society on Earth in areas including health and medicine, transportation, public safety, consumer goods, energy and environment, information technology, and industrial productivity.

> *People often ask, If you like spin-off products, why not just invest in those technologies straightaway, instead of waiting for them to happen as spin-offs? The answer: it just doesn't work that way. Let's say you're a thermodynamicist, the world's expert on heat, and I ask you to build me a better oven. You might invent a convection oven, or an oven that's more insulated or that permits easier access to its contents. But no matter how much money I give you, you will not invent a microwave oven. Because that came from another place. It came from investments in communications, in radar. The microwave oven is traceable to the war effort, not to a thermodynamicist.*
>
> Neil deGrasse Tyson, *Space Chronicles*, W.W.Norton & Company, 2012, p.210.

The wider list of technological benefits encompasses improved solar panels, implantable heart monitors, light-based anti-cancer therapy, cordless tools, light-weight high-temperature alloys used in jet engine turbines, cameras found in today's cell phones, compact water-purification systems, global search-and-rescue systems and biomedical technologies.[11][12][13][14][15].

Scientific research founded on data from space is also leading to discoveries with benefits for life on Earth. Ongoing research in the space environment of the ISS – in areas such as human physiology, plant biology, materials science, and fundamental physics – continues to yield insights that benefit society. For example, studies of the human body's response to extended periods in the microgravity environment of the ISS are improving our understanding of the aging process. Fundamental scientific studies of the Martian environment, its evolution and current state represent important benchmarks of terrestrial planetary evolution, and hence,

[11] *Down to Earth: Everyday Uses for European Space Technology*, European Space Agency, 2001, www.esa.int/esapub/br/br175/br175.pdf

[12] Spinoff materials published by the National Aeronautics and Space Administration (e.g. Spinoff database, spinoff.nasa.gov/spinoff/database; Spinoff 2012, spinoff.nasa.gov/Spinoff2012);

[13] Spinoff from Japan's Aerospace Technology, aerospacebiz.jaxa.jp/en/spinoff; *Aerospace Biz 2012*, Japan Aerospace Exploration Agency, 2012, aerospacebiz.jaxa.jp/jp/publish/data/aerospacebiz_2012.pdf

[14]"neuroArm: Robotic arms lend a healing touch", Canadian Space Agency, www.asc-csa.gc.ca/eng/iss/benefits_01_neuroArm.asp.

[15] "*From Space to Earth",* B. Feuerbacher and E. Messerschmid *,* Schiffer Publisher*,* March 2011.

provide a model that some scientists believe will aid our growing understanding of climate change processes on Earth.

Global Technical Workforce Development

Investment in the Apollo Moon exploration programme in the 1960s correlates with the level of technical education later attained by students (Figure 3), suggesting that the programme's high public profile and dramatic achievements had a widespread influence on the level of US technical education.

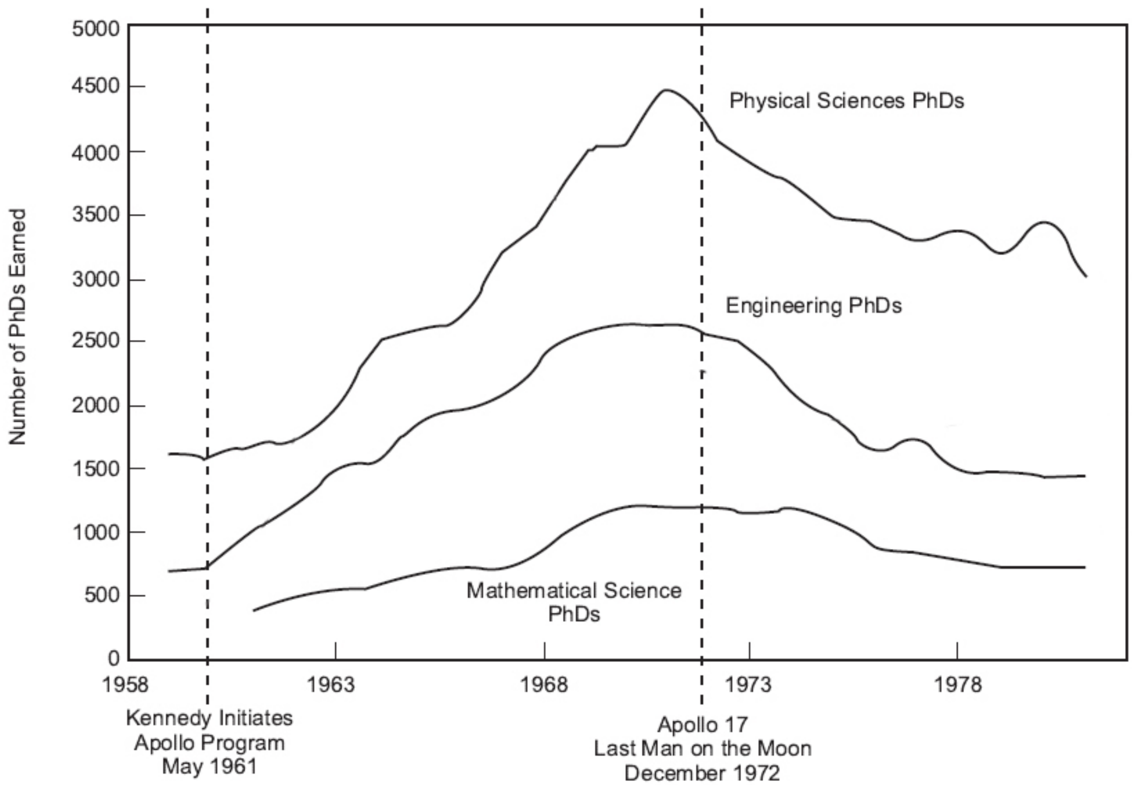


Figure 3. Space Exploration's Impact on Educational Achievement.[16]

A 2009 survey found that fifty percent of the internationally renowned scientists who published in the prestigious journal *Nature* during the previous three years had been inspired by Apollo to become scientists; 89 percent of the respondents also agreed that human spaceflight inspires younger generations to study science.[17]

One of the lessons from Apollo is that having a visible space exploration programme is important in encouraging young people to pursue science, technology, engineering, and

[16] Siegfried, W.H., "Space Colonization—Benefits for the World", Space Technology and Applications International Forum, 2003.

[17] Nature 460, 314-315 (2009); www.nature.com/news/2009/090715/full/460314a.html.

mathematics (STEM) fields. Such a programme will also send a message to students that they have the possibility of long-term exciting careers in science and technology.

Figure 4. Space exploration inspires students.

Today, many space exploration missions include components designed to stimulate young people's interest in STEM. More than 2 million teachers and 43 million students from 49 countries have participated in student experiments and activities associated with the International Space Station (ISS)[18]. In some cases, scientists enlisted the help of students to conduct their investigations aboard the ISS, and in other cases students designed space experiments themselves. For example, a programme inviting students to design scientific experiments for implementation on the ISS has attracted the interest of tens of thousands of young people[19].

Enlarged Economic Sphere

The early space activities have undoubtedly enlarged our economic sphere, which now extends into space, including the low Earth orbit up to geostationary distances. Recently private initiatives have been launched to extend the economic sphere even further, extending to the Moon, asteroids, and even Mars. This relies on space exploration, which drives the development of new technologies and capabilities (e.g. heavy lift launchers, human and robotic servicing, and autonomous space operations). By developing reliable space exploration systems that incorporate human decision-making, troubleshooting, and flexibility, possibilities are created for enhancing the economic development of space driven by private sector investments (e.g. new means to service in-space infrastructure for applications and science purposes can be envisaged).

Furthermore, by deepening our understanding of how humans and machines function in space, and developing technologies for space exploration, publicly funded space exploration has

[18] "Inspiring the Next Generation: ISS Education Opportunities and Accomplishments 2000-2012", ref: http://www.nasa.gov/pdf/696998main_ISS_Education_Publication_2012__final_100512.pdf

[19] Student Spaceflight Experiments Program, an initiative of the National Center for Earth and Space Science Education in partnership with NanoRacks, LLC and NASA, ssep.ncesse.org.

lowered the risks and costs associated with accessing and working in space. As a result private investment is increasing in space-based endeavours such as space transportation systems, Earth-orbiting habitats, space tourism and even planetary mining technologies to eventually harvest precious materials thought to be present in asteroids[20]. Investment in space-based endeavours is becoming sufficiently attractive to private entrepreneurs, so that humankind may be ready to "incorporate the solar system in our economic sphere"[21].

Enlarging the Economic Sphere

May 2012 saw the first resupply mission to the ISS by a privately-owned space vehicle[22]. Hundreds of millions of dollars of private capital have been invested in the development of human space transportation and habitation systems with relevance to potential future space-based industries such as tourism and resource mining. Apart from cargo vehicles to service the ISS, early-stage investments have also been made in the development of privately-crewed spacecraft and space stations. In the United Kingdom, private sector investment is targeting the development of engine technology for a reusable space-plane**.** International prize competitions have also been established which stimulate private sector investments in space exploration[23].

2.2. Culture and Inspiration

Space exploration missions offer a unique perspective on humanity's place in the Universe, satisfying our curiosity and inspiring wonder. They provide the best opportunities for addressing questions such as "What is the nature of the Universe", "Is the destiny of humankind bound to Earth?", "Are we and our planet unique?", and "Is there life elsewhere in the Universe?".

The first five decades of human activity in space had a profound impact on the social development of humankind. Yuri Gagarin's first moments in space and Neil Armstrong's first step on the Moon truly were "giant leaps for mankind" because they expanded our views about the limits of human travel and planted seeds for new thinking about where beyond Earth human existence might be possible. Stephen Hawking has argued that "to confine our attention to terrestrial matters would be to limit the human spirit"[24]. Understanding whether sustained human activity beyond Earth orbit is actually feasible will have a profound influence on cultural and intellectual life around the world and on humanity's views and expectations of itself.

[20] See initiatives as those of Planetary Resources (http://www.planetaryresources.com/) and Deep Space Industries (http://deepspaceindustries.com/team/)
[21] Marburger, J., keynote address, 44th Robert H. Goddard Memorial Symposium, American Astronautical Society, Greenbelt, MD, 2006.
[22] See: http://www.spacex.com
[23] For example, the Ansari X-Prize, space.xprize.org/ansari-x-prize; and the Google Lunar X-Prize, www.googlelunarxprize.org.
[24] Stephen Hawking, Foreword to *The Physics of Star Trek*, by L.M. Krauss, Basic Books, 2007.

There may soon be news about environments that could have harboured life elsewhere in the solar system. In early 2013 the Mars Curiosity Rover obtained preliminary evidence that the Martian environment once had conditions favourable to supporting life. Discovery of signs of past or present life in the solar system (or beyond[25]) would affect in unpredictable ways humanity's appreciation of life's uniqueness on Earth. The impact on philosophy, culture, religion, and politics could be comparable to that caused by Copernicus's heliocentric model of the Universe.

Impact of Space Exploration on Culture

Figure 5. Earthrise seen from lunar orbit (a) Apollo 8, and (b) Kaguya as well as (c) picture of Earth taken by NASA's Cassini probe from more than 1.4 billion kilometers away in orbit around Saturn.

An iconic symbol of space exploration's capacity to alter humankind's perception of its place in the Universe is the "Earthrise" photograph from the Apollo 8 mission in 1968 (Figure 5.a). Seen from lunar orbit, our home planet appeared fragile and isolated. The photograph caused many to develop a new perspective of our place in the cosmos and raised awareness of the need for global solutions to environmental challenges. Earth was seen as a seamless whole without national boundaries.

Space exploration has also inspired the development of various movies, bestselling books, songs, photographs and paintings. Cultural products are a very visible symbol for how society relates to space exploration.

2.3. New Means to Address Global Challenges

Partnerships and capabilities developed through human space exploration create new opportunities for addressing global challenges. Space exploration is an inherently worldwide endeavour that attracts broad international interest and affects people all across the globe by producing knowledge, capabilities, and relationships that help society deal with some of the most pressing long-term global challenges. Space exploration is a catalyst for nations to build

[25] Exploration beyond the solar system is discovering planetary worlds – "exoplanets" – with emphasis on finding Earth-like bodies that might support life.

mutual understanding and trust, and international partnerships that advance common exploration goals help to align interests among nations and promote diplomacy. As programmes become more ambitious, like the ISS (see text box below) and human missions to the Moon, asteroids, and Mars, they require more extensive international cooperation, and this creates opportunities to strengthen the capacity for peaceful, globally-coordinated activities in space and on Earth. Complex and demanding exploration missions will benefit from contributions by a wide pool of partners. Future partnerships for space exploration will build on existing partnership such as the one for the ISS, but will also be open to include new partners. Partnership opportunities can be adapted to the needs and resources of developed as well as of developing countries.

ISS and Global Partnerships

The ISS partnership, nearly thirty years old, is the pre-eminent example of successful, continuing international cooperation in space exploration. Fifteen nations signed the intergovernmental agreement that established the partnership framework (Figure 6), and cooperation has expanded over the years, resulting in 68 nations to date that have participated in ISS activities. The ISS partnership demonstrates the functional dimension of international cooperation in space as it enables partners with different levels of investments to gain access to this unique laboratory, not affordable for any partner alone, and thereby share into the benefits.

It also demonstrates the political aspect of exploration. To achieve its core mission, the ISS partnership has overcome political and economic strains. It has demonstrated the diplomatic value of international cooperation in space. An astronaut who served on the ISS has observed that it has been "as much a foreign policy … achievement as it is a technical one."[26]

Figure 6. International cooperation on the International Space Station builds trust among nations

International partnerships and technical capabilities for space exploration contribute to developing new options for dealing with global challenges for which space activities offer unique solutions. These include the challenges of dealing with hazardous near-Earth asteroids and managing the threat posed by solar storms to the people and equipment in space and on

[26] Payette, Julie, "Research and Diplomacy 350 Kilometers above the Earth. Lessons from the International Space Station," *Science and Diplomacy,* December 2012.

Earth. Enhanced global partnerships and exploration capabilities may also contribute to protecting spacecraft by developing new means for space debris removal. Furthermore, knowledge gained from space exploration can also contributes to implementing policies related to environmentally sustainable development. Earth can be regarded as a spaceship floating in our solar system. Many aspects of sustainability, recycling, or efficient use of scarce resources have to be tackled in the course of exploration missions and can be transferred to systems on Earth.

Advancing Capabilities for Global Protection

Figure 7. Chelyabinsk meteor

Capabilities developed and knowledge gathered from space exploration contribute to ongoing efforts to understand the threat to Earth posed by asteroids, and to devise means for protecting the planet. Scientists[27] believe that a collision between the Earth and one or more large asteroids about 65 million years ago caused the rapid mass extinction of most plant and animal species on Earth. Worldwide awareness of the dangers posed by asteroids was raised by the February 2013 close approach of a 40-metre asteroid and, on the same day, the unexpected explosion over Russia of a meteor (Figure 7) believed to be about 17 metres wide and weighing 10,000 tonnes. The blast injured over 1,000 people and damaged over 4,000 buildings. The asteroid that missed Earth by only 27,000 kilometres was large enough to have caused catastrophic damage if it had entered the atmosphere[28].

These events triggered public concern about how to protect Earth from asteroid collisions. They also underscored the significance of the work of the international space groups recently endorsed for creation by the United Nations Committee on the Peaceful Uses of Outer Space's Working Group on Near-Earth Objects[29].

Space-based systems that will be required to provide astronauts and exploration spacecraft with early warning of solar events also provide direct benefit to people on Earth. Geomagnetic

[27] Alvarez, LW, Alvarez, W, Asaro, F, and Michel, HV (1980). "Extraterrestrial cause for the Cretaceous–Tertiary extinction". Science 208 (4448): 1095–1108; “Time Scales of Critical Events Around the Cretaceous-Paleogene Boundary”, by Paul. R. Renne et. al., *Science,* Vol. 339 no. 6120 pp. 684-687, February 8, 2013; “Two large meteorite impacts at the Cretaceous-Paleogene Boundary,” by David Jolley, et. al., *Geology*, Vol. 38, no. 9, pp. 835-838, September 2010.

[28] "NASA Releases Radar Movie of Asteroid 2012 DA14",www.jpl.nasa.gov/news/news.php?release=2013-101.

[29] "Recommendations of the Action Team on Near-Earth Objects for an international response to the near-Earth object impact threat", United Nations Office for Outer Space Affairs, 20 Feb 2013, www.oosa.unvienna.org/pdf/misc/2013/at-14/at14-handoutE.pdf.

disturbances caused by solar storms can severely damage electrical and radio transmission grids on Earth. In 1989, a geomagnetic storm affected millions of people by knocking out the electrical power grid in Quebec, Canada, and causing power grid problems across the United States, including destruction of a key nuclear power plant transformer[30]. Adverse space weather causes disruption of space services for global communications, navigation and search & rescue on which society is ever more reliant.

3. Expected Benefits from Exploration Missions in the Next Ten Years

Benefits will materialize in the short-term as agencies prepare for implementing human missions beyond LEO. Space agencies have made public their collective intention to plan for human and robotic missions beyond LEO to destinations including the Moon, asteroids and Mars[31]. Agencies will conduct in the next ten years robotic missions to these destinations. They will invest in the development and demonstration of advanced technologies and new human transportation systems, conduct ground and space-based research for ensuring human health and performance in space and use the ISS for advancing global research and testing exploration technologies, systems, and operational concepts. Early human missions beyond LEO are expected to take place in the early 2020s. The next ten years will be essential for building the global partnership required for achieving the ambitious goals of space exploration.

With this outlook in mind, this section describes some social and economic benefits that are expected to result from space exploration in the near-term in the three fundamental benefit areas introduced in chapter 2.

3.1. Innovation

The challenges to achieving ambitious exploration goals are driven largely by the need to enable reliable, safe and sustained operations of crew and machines in the harsh environment of space. These challenges require solutions that will provide benefits on Earth even before being employed in orbit, and they include:

- Development of highly reliable human and robotic systems interacting with each other on Earth and in space with limited maintenance;
- Long travel time and operation in confined spacecraft and shelters;
- New transportation capabilities (e.g. launch, rendezvous, docking, refuelling, landing);

[30] "Severe Space Weather Events--Understanding Societal and Economic Impacts: A Workshop Report", National Research Council, National Academy of Sciences, 2008 (page 109). Accessed at www.nap.edu/catalog/12507.html.
[31] "The Global Exploration Strategy. The Framework for Coordination", 2007.

- Operations in extremely hostile environments;
- Autonomous operations with limited communications and logistical supplies from Earth;
- Miniaturization of components and development of new in-situ capabilities.

Closed Loop Life Support System

While recycling is critical for limiting the costs of sustaining human operations in Low Earth Orbit, it is an absolute requirement for enabling human missions beyond LEO. Life support systems for future deep space missions will need to have nearly 100 % recycling capability.

The European MELiSSA project (Micro-Ecological Life Support System Alternative[32]) is one example of a project which aims at gaining knowledge and know-how in the development a closed loop sustainable habitat. In collaboration with the industry, it has developed technology that purifies millions of cubic metres of water every day, in hundreds of towns[33]. Furthermore, sensors developed to monitor the MELISSA recycling processes are now used in the processes used by terrestrial food producers.

Many bacteria were studied for application within the MELiSSA project. One of those has been shown to cut levels of LDL cholesterol – the 'bad' cholesterol - and research on this bacterium has now been taken over by the private sector[34].

The very same solutions providing space exploration missions with improved technologies will in turn lead to more efficient solutions in the commercial satellite market and the enabling of new applications. Anticipated innovations include:

- miniaturization (mass, power, volume),
- increased lifetime and robustness for operations in a harsh environment,
- lower cost launchers,
- increased power efficiency,
- lighter and more efficient solar arrays and radiators,
- lighter structures, and
- higher energy-density storage devices.

A human space mission of several months will require innovative health care and medical diagnostic and therapy tools to work in confined spaces with limited in-situ medical expertise.

[32] http://www.esa.int/SPECIALS/Melissa/index.html
[33] http://www.veoliawaterst.com/biostyr/en/
[34] http://www.esa.int/Our_Activities/Human_Spaceflight/Research/Red_bacteria_fighting_cholesterol_for_you

Telemedicine

Maintaining the health of astronauts as they explore beyond Low Earth Orbit and conduct missions of many months or years will require increasingly sophisticated methods. Telemedicine provides medical care to patients who may be located far away from medical providers. It is critically important to the success of space exploration, and space agencies have led much of the innovation in this field since its very beginnings. Meanwhile, the public is using telemedicine capabilities more and more to send diagnostic images to doctors in other cities, to allow patients in rural areas to remain at home while hospital nurses monitor vital parameters such as heart rate or blood pressure, and to conduct interactive medical examinations and diagnostic procedures. The convenience and efficiency provided by telemedicine provides tangible benefits to society and is improving the quality of life for people around the globe.

The Advanced Diagnostic Ultrasound in Microgravity (ADUM) developed by NASA in partnership with a hospital in Detroit is one example of an exploration-driven telemedicine innovation. This portable ultrasound device being tested on the ISS may one day help crew members as far away as Mars, and may also be particularly useful for emergency medical personnel on Earth. The ADUM can diagnose a variety of ailments, including abdominal conditions, collapsed lungs, and tooth infections, and it promises to save lives while lowering health care costs.[35]

Figure 8. Astronauts aboard the International Space Station use a compact ultrasound device to capture and transmit to Earth high-quality images of internal organs and structures, demonstrating a technology that provides people in remote locations on Earth with efficient access to expert diagnosis and medical treatment.

[35] http://www.nasa.gov/mission_pages/station/research/experiments/133.html

The direct infusion of technological innovations from space into terrestrial markets will be ensured by industrial entities operating simultaneously in space and terrestrial markets as well as by the technology transfer programmes run by space agencies.

Continued missions on the ISS, as well as planned human and robotic missions beyond LEO to the Moon, asteroids, and Mars will be key to generating scientific knowledge in the fields of planetary science, astrobiology, astrophysics, fundamental physics, life sciences, and the social sciences. For example, the ISS will continue to host studies to understand the physiological and biological effects of space on humans, such as bone and muscle loss, diminished immune efficiency, slower wound healing, and poorer cognitive performance. The results are helping the medical community to provide better health care for remote communities and aging populations.

More broadly, the growing capacity to work in space for extended periods of time is likely to encourage further investment in the space economy – for example through mastery of sophisticated and delicate repair and construction tasks such as the servicing of the Hubble space telescope, and greater understanding of how to manage risks to human health and safety. Specifically, developments in propulsion, transportation, and infrastructure systems may lower the cost of space access and utilization, and thus enable expanded private investment in space cargo transport, space tourism, and resource utilization.

3.2. Culture and Inspiration

In recent years, a number of agencies have conducted robotic space missions[36] that have uncovered new knowledge about the solar system's past and present and are providing clues to help humankind understand how life began on Earth. In the coming decade, a variety of new missions to the Moon, asteroids, and Mars[37] will deepen that understanding and shed light on the possibility of past or present life elsewhere in the solar system.

Exploring Mars: Inspiration for Humankind

The possibility of past or present life beyond Earth continues to inspire people to reflect on humanity's place in the Universe. Since the 1970's, space agencies have sent a series of spacecraft to explore Mars in the search for answers. Scientists now believe that water may once have flowed on the surface and that early conditions on the planet could have supported life. NASA's Curiosity rover, which has been exploring the Yellowknife Bay area on Mars since 2012, has discovered new evidence that Mars could have supported ancient microbial life. ESA and Roscosmos plans for ExoMars missions in 2016 and 2018, and NASA's plans for a Mars 2020 rover will make further progress in the search for signs of life. These missions set the stage for what scientists agree will bring humankind even closer to revealing whether Martian life ever existed: a mission to return Mars samples back to Earth.

Figure 9. From NASA Curiosity Rover: Martian landscape looking toward Mount Sharp near Yellowknife Bay, an area where researchers have found minerals indicating the past presence of water.

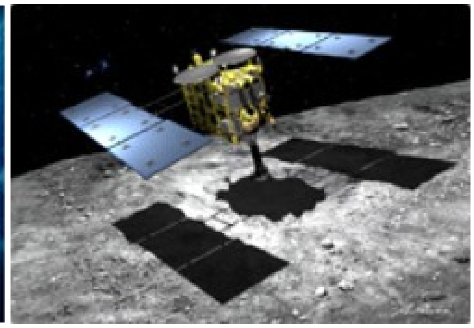
The renewed interest in space exploration, generated by work on human missions beyond LEO is deeply inspirational. These missions will accelerate solar system exploration and discovery by leveraging humankind's natural ability to analyze and adapt to unpredictable situations. Human

[36] Recent lunar missions include CNSA's Chang'e 1 and 2, ESA's SMART-1, ISRO's Chandrayaan-1, JAXA's Kaguya, and NASA's LRO, LCROSS, and GRAIL. Recent asteroid missions include ESA's Rosetta, JAXA's Hayabusa, and NASA's Dawn. Recent Mars missions include ESA's Mars Express, and NASA's Phoenix, Mars Reconnaissance Orbiter, and Curiosity.

[37] Planned lunar missions include CNSA's Chang'e 3, ISRO's Chandrayaan-2, NASA's LADEE, and Roscosmos's Luna-Glob (Luna-25 and 26)and Luna-Resurs (Luna-27). Planned asteroid missions include JAXA's Hayabusa-2 and NASA's OSIRIS-REx. Planned Mars missions include ESA-Roscosmos's ExoMars, ISRO's Mangalyaan, and NASA's MAVEN, InSight, and Mars 2020 mission.

missions to the lunar vicinity that are being considered for the next decade will lay the groundwork for exploration of more distant destinations.

Exploring asteroids: Inspiration for Humankind



© Twentieth Century Fox JAXA’s HAYABUSA-2

Figure 10. (a) Motion picture poster for the Japanese movie that followed the Hayabusa-1 mission (b) JAXA concept of Hayabusa-2 mission.

Public excitement in Japan reached new heights in 2010 after JAXA's Hayabusa mission became the first ever to return sample material from an asteroid back to Earth. After the spacecraft suffered several near-catastrophic technical problems, the public became enthralled with the heroic efforts to revive the mission, which was treated as a top news story of the year and the topic of 3 motion pictures. Samples returned from asteroid Itokawa are being analyzed by laboratories in Japan, the USA, and other parts of the world.

As the follow-on mission, Hayabusa-2 is targeted to be launched in 2014 to asteroid 1999JU3. It will carry an impactor to create an artificial crater on the asteroid and collect subsurface sample material. It will also carry Japanese rovers and a lander built by a German-French collaboration. It is scheduled to come back to Earth in 2020 with its sample. Hayabusa-2 will investigate the origin of organic matter and water in the solar system and how they are related to life and water in the oceans of Earth.

3.3. New Means to Address Global Challenges

The next ten years will be essential for building international partnership for exploration. This will offer opportunities to developed and emerging space nations to contribute according to their needs and capabilities.

The ability to operate and work with humans in the lunar vicinity will provide new means for protecting the planet and servicing space-based assets. NASA has begun planning for a robotic mission to redirect a small asteroid into lunar orbit to allow for a human to visit it. Space exploration missions such as this will contribute to already ongoing efforts to understand the threat to Earth posed by asteroids, currently mostly implemented through ground and space-based telescopes, and to devise means for protecting the planet. Furthermore, stronger cooperation in space exploration will create opportunities for enhanced international coordination and cooperation on topics such as space debris management and space weather monitoring

Cooperation between diverse nations on challenging space projects will showcase the ability to jointly advance common goals and help to improve diplomatic ties and understanding between nations.

4. Conclusion

Space exploration has produced an impressive record of benefits for humanity. This paper has distilled a body of evidence of such benefits into a few key observations about the capacity of future space exploration to contribute to innovation, culture and inspiration, and new means to address global challenges**.**

Space exploration has driven scientific and technological **innovation** that benefits people around the globe every day. Sending humans and machines into space presents challenges that are overcome only by the utmost ingenuity; this leads to new knowledge and technical innovations that are used on Earth in ways that can be dramatic and unpredictable.

Space exploration serves **a cultural and inspirational** purpose by fulfilling a deep need to understand the world, address questions about the origins of life and the nature of the Universe, and to expand the notion of what it means to be human.

Because space exploration stimulates significant global investment and international partnerships, and because of its extremely challenging nature, demands the development of cutting edge technical capabilities, it provides unique opportunities to address some of the **global challenges** facing society today. When nations work together on challenging space missions, this promotes international cooperation beyond the realm of space. It aligns interests and forges relationships that further peace and stability on Earth.

There is no activity on Earth that matches the unique challenges of space exploration. The first fifty years of space activity have generated benefits for people around the globe. This past record gives strong reason for confidence that renewed investments in space exploration will have similarly positive impacts for future generations.

Image Credits

Figure 2: Exoskeleton (NASA and the Florida Institute for Human and Machine Cognition); Figure 4: Astronauts: NASA; students: commons.wikimedia; Figure 5: Apollo Earthrise (NASA), Kaguya Earthrise (JAXA), Cassini (NASA); Figure 6: ISS Expedition 20 (NASA), ISS (NASA); Figure 7: Chelyabinsk meteor (AP Photo/Nasha gazeta, www.ng.kz); Figure 8: Advanced Diagnostic Ultrasound in Microgravity (NASA).; Figure 9: NASA; Figure 10: JAXA; Twentieth Century Fox.