

A composite image of space featuring the Sun, Earth, Moon, and Mars. The Sun is a bright white orb with a red corona on the left. The Earth is a blue and green planet with clouds, showing Europe and Africa on the right. The Moon is a gray, cratered sphere in the lower-left foreground. Mars is a smaller reddish-brown planet visible between the Earth and the Sun.

# Report of the UK Space Exploration Working Group

13 September 2007

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The Group was set up in January 2007 as an *ad hoc* committee to:

- review current global plans for space exploration;
- assess what opportunities and benefits exist for UK participation; and
- provide advice to BNSC and partners as to which areas the UK should focus on if it wishes to engage in space exploration.

This analysis is on behalf of BNSC partners for input to UK Space Board, BNSC Space Advisory Council, PPARC Science Committee (or its successor), BNSC Space Technology Advisory Board and other relevant advisory committees. The views expressed are those of the members of the Group and not necessarily of their institutions.

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## 1 Executive summary

**The UK Space Exploration Working Group recommends that the United Kingdom takes maximum advantage of the unique opportunities presented by the Global Exploration Strategy. It should play a full and active role in these programmes and the endeavours that will define space exploration in this century.**

**Involvement in both robotic and human elements of space exploration should be strategically targeted to develop new capabilities by building on existing UK strengths. Such activities will generate scientific knowledge and return value to the UK economy through technological challenges, innovations and new commercial ventures. Furthermore they will engage British society in the full excitement of space exploration and help to inspire a new generation of scientists and engineers.**

**We recommend early investment in a demonstration programme that would build both on current areas of strength and engage in preparatory human spaceflight activities. This will in due course enable the UK to judge the value of a stronger involvement up to a level commensurate with our GDP.**

The recently published Global Exploration Strategy<sup>1</sup> outlines the ambitions of the world's space-faring nations and their part in a new era of space exploration: one that will see humans and robots working in partnership on the surfaces of the Moon and Mars, while unmanned probes venture out across the far reaches of our solar system. These efforts will seek answers to fundamental questions including the nature and origin of life in the universe.

Participation in the 'grand challenge' of space exploration provides key opportunities for the UK to:

- shape and participate fully in programmes of space science;
- build on its history of excellence in science, technology and innovation;
- form valuable new collaborations with international partners;
- inspire the next generation of scientists and engineers; and
- exploit the direct and indirect commercial opportunities that will be created.

Studies of the solar system may be divided into four stages with increasing levels of sophistication: observation from Earth; observation from spacecraft (including fly-by); robotic landing and exploration; human space exploration *in situ*. The increasing levels of technical challenge have inevitably set the order in which these activities have been tackled. Observation from Earth has a history that is as old as astronomy, while remote observation from spacecraft has been used to great effect during the last 40 years. These endeavours will continue to offer excellent returns by making use of advances in technology.

So far all four stages have been applied to exploration of the Moon, though somewhat superficially given its relative accessibility. In contrast, exploration of the other planets and their moons with landers has begun only recently, and a natural next step, rich in opportunity, is to extend this strategy to Near Earth Objects. Exploration of extraterrestrial surfaces using humans is a goal for the future. While offering the most profound impact for scientific knowledge and human culture, it is also the most costly. It is however a challenge that reaches beyond just science: human exploration of space promises to impact society, medicine and commerce and when the economic assessment is made, these wider issues will have to be taken into account.

Mission planning for a detailed lunar exploration programme involving both machines and humans is already underway. Human space exploration of more remote sites, such as Near Earth Objects and Mars, may be carried out in a longer timeframe, but a return to the Moon will come first. This is the context that has inspired the Global Exploration Strategy and created both opportunities and challenges for the UK.

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Having considered these issues, we recommend that the UK should maintain and extend its significant roles in planetary science and robotic exploration through its participation in relevant ESA programmes and in collaboration with other international partners. It should build on its strengths in these areas through international collaboration in a programme of space exploration, taking an active role in selected aspects from the outset.

Further, we recommend that the UK should initiate a technology demonstrator programme focused on current areas of strength, consider joining ESA's microgravity programme, build capacity in relevant science communities across the UK and engage in preparatory human spaceflight activities. These will enable the UK to evaluate the benefits of increasing our involvement in space exploration to a level commensurate with our GDP.

In order to gain maximum benefit from these programmes the UK should develop a formal strategy for exploiting the substantial, wider benefits of space exploration to science education, commerce and culture. This should include funded programmes of public engagement and education.

We believe that space exploration is a strategic activity, with both tangible and intangible benefits across a range of areas. Until now, this has been driven by pure science, but the human exploration of space is a broader ambition. This will require new funding mechanisms to which the science budget should only contribute where appropriate and justified.

## 2 Recommendations

In order to make the most of emerging opportunities in the field of space exploration, maintain existing standards of excellence and develop new capabilities that ensure a prominent role in future international space activities the UK should:

1. Pursue a programme of space exploration in which an active role is played in both the robotic and human elements of the Global Exploration Strategy.
2. Develop a strategy for exploiting the substantial, wider benefits of space exploration to science, education, commerce and culture. This should include co-ordinated, properly funded and sustained programmes of public engagement and education.
3. Maintain leading UK involvement in planetary science within ESA Programmes and, where appropriate, in collaboration with other international partners. This must include continued involvement in the robotic exploration of Mars, especially through ESA's Aurora programme.
4. Initiate a targeted UK robotic lunar programme based on the use of low cost satellites, rovers and resulting operational services, ideally in collaboration with other partners while keeping control of some key technologies.
5. Identify and exploit opportunities for mutually beneficial, bilateral activities with NASA and other prospective partners. The Global Exploration Strategy and the recently signed NASA-BNSC Joint Statement of Intent create narrow windows of opportunity during which agreements of high value might be secured.
6. Take appropriate early steps to prepare for a future role in human space exploration efforts by securing flight opportunities for British astronauts within the next decade to conduct science research and advance science education.
7. Build capacity in relevant UK scientific and technological communities by funding and establishing academic chairs, fellowships, post-doctoral and doctoral positions at UK centres of excellence. These positions should cover the full range of life and physical sciences relevant to the exploration programme, and would expand upon the success of the existing Aurora Fellowship scheme.
8. Engage with research and industrial communities across a broad range of sciences and technology to assess the opportunities that may be raised in the new era of space exploration. This should extend beyond the existing BNSC core partners (DIUS, STFC, NERC) to include MRC and EPSRC and industrial sectors such as mining, prospecting, media and entertainment.
9. Investigate the current opportunities offered by a modest focused subscription to ESA's life and physical sciences programme (ELIPS) which could facilitate UK access to ESA's microgravity facilities in order to build up the UK life and physical sciences microgravity community in preparation for the longer term opportunities that will arise from participation in the GES.
10. Initiate a substantial and sustained national technology R&D and demonstrator programme focused on those areas of technology which underpin the UK's goals within the GES and strengthen the UK position in related ESA programmes. Knowledge exchange opportunities should be embedded in the programme from the start.
11. Survey and identify customer commitments, and quantify value added business for the exploration-related services identified in this report – from near term (e.g. lunar communications relay) to long term (e.g. exploitation of planetary mineral rights).
12. Review and update the UK licensing regime to encourage high value added activities such as space tourism and related activities such as inexpensive, regular and reliable launch of scientific payloads and small spacecraft which build on existing UK strengths and support proposed UK efforts in exploration.

These strategic recommendations would allow maximum benefit to the UK by focused incremental funding in national, ESA and other international bilateral initiatives. The proposed programme represents a broader ambition than the current science-driven exploration of space and so additional funds will be needed to promote the necessary activities in education, science, technology and knowledge exchange.

We believe this will generate new scientific knowledge, increase excitement for science and technology in the young to help build the workforce of the future, and provide a grand challenge to invigorate the UK economy.

### 3 A UK vision for space exploration

The recently published *Global Exploration Strategy: The Framework for Collaboration* outlines the future ambitions of the world's space-faring nations and their part in what promises to be one of this century's most ambitious programmes of science and discovery. This is the dawn of a new era in space exploration; one that will see humans and robots working in partnership on the surfaces of the Moon and Mars, while unmanned probes venture out across the far reaches of our solar system. These efforts will seek answers to questions of fundamental importance to science.

Humanity faces many challenges at the beginning of the 21<sup>st</sup> Century. The exploration of the solar system offers a much-needed opportunity for the peaceful co-operation of all the nations of the world, which in addition to bringing technological advancement and economic growth, may also help to build a sense of global solidarity and fellowship.

We envisage a programme of space exploration in which this country plays a prominent role in the activities described by the Global Exploration Strategy. This will generate new scientific knowledge, increase excitement for science and technology in the young to build the workforce of the future, and provide a grand challenge to invigorate the UK economy.

While science and technology lie at the core of such activities, the wider benefits span the boundaries between society, commerce, culture and education and appeal to the sense of discovery and inspiration experienced by ordinary people from all backgrounds.

In our opinion it is important that the UK investigate new opportunities to collaborate with other nations that exploit our strength in planetary exploration. Our objective should be to target our participation on areas that have the greatest potential to yield benefits to science, technology, industry and the wider public. We believe that this balanced approach will benefit the UK economy and our quality of life through increased scientific knowledge, commercial opportunities, novel technologies, and inspiration in the field of science education. Cultural benefits will also flow from our collaboration in what seems set to become one of the international grand challenges of the 21st Century.

It is important that a commitment, in principle, to the long term programme of human and robotic exploration is made now, and that preparatory programmes should commence immediately, since many of the key international players are actively developing plans and offering partnership opportunities that may not remain open for long. By being involved in this first wave of development, the UK will secure a position of influence. This will enable us to take our full share in both scientific discoveries and in any commercial developments which exploit opportunities in the neighbourhood of Earth that may take place in both the near and more distant future. The UK has a long and noble tradition for exploration across our planet. It is now time for a new vision and a more distant voyage.

<b>Recommendation:</b>	<b>Our key recommendation is that the UK should pursue a programme of space exploration in which an active role is played in both the robotic and human elements of the Global Exploration Strategy.</b>
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## 4 Background

### 4.1 Introduction

The UK Space Board asked us to review global plans for space exploration, to assess the opportunities and benefits for UK participation and to advise on a suitable focus for UK activities should it decide to engage in space exploration. For the purposes of this report, ‘space exploration’ is taken to mean

*the systematic exploration by robotic and human means of solar system destinations upon which in the foreseeable future humans will live and work.*

The Terms of Reference and membership of the UK Space Exploration Working Group are set out in Appendix B (p78).

Four sub-groups assessed the potential benefits to science, technology, commerce and society respectively, taking into account the plans of the main space-faring nations (summarised in this chapter).

The Science sub-group considered the scientific rationale for space exploration, *focusing especially on questions that require spacecraft or humans to land on other planets, but also considering areas of science that could be enabled if outposts were established on the Moon or elsewhere.* Whilst key questions of interest concern the search for life beyond Earth, many other areas could benefit. These include understanding the origin and evolution of the solar system, studying the behaviour of planetary environments (including that of the Earth), and creating new opportunities in astronomy, fundamental physics and the life and medical sciences. (**Chapter 5**)

The Technology and Knowledge Transfer sub-group considered suitable goals for the UK to make best use of its technological strengths. The UK has clear strengths in many technologies that could be used to serve the needs of a space exploration programme. The group also considered the most effective use of investment, from the perspective of technology and knowledge exchange, at various levels and looked at the benefits to the UK through the ‘grand challenge’ of space exploration in the transfer of technology to other sectors and stimulation of the engineering skills base. (**Chapter 6**)

The Commerce sub-group considered the short and long term opportunities for UK industry. The early stages are most likely to include support to international exploration missions (for example communications and navigation services), whilst longer-term opportunities may include exploitation of extra-terrestrial resources (e.g. through robotic assisted mining) and delivery of media services to cater to public interest in space exploration. A supportive UK government licensing and regulatory regime is crucial to enabling all such opportunities. (**Chapter 7**)

The Society sub-group considered the wider benefits to society, including the political benefits of increased collaboration with international partners in new and challenging endeavours. The group also evaluated the opportunities for human spaceflight to inspire students to take up careers in science and technology, as well as to engage the public at large. (**Chapter 8**)

We bring together the collective conclusions of the sub-groups (**Chapter 9**), and present a set of scenarios for implementation including various levels of robotic and human involvement. In order to illustrate these scenarios, we suggest a range of missions in which the UK could play a leading role, whilst collaborating with other nations (**Chapter 10**) and present our recommendations (**Chapter 11**).

### 4.2 International context

There is renewed global interest in space exploration, as evidenced by the development of the NASA Vision for Space Exploration (VSE), the ESA Aurora programme, and robotic lunar missions under development in India, China, Russia and Japan.

In particular, NASA’s space exploration programme is gathering momentum and was at the centre of bilateral discussions with Administrator Griffin at Farnborough 2006. The National Academies in the US have recently published a comprehensive report<sup>2</sup> addressing the scientific goals of lunar exploration.

NASA has placed industrial contracts for key elements of the system to return astronauts to the Moon in 2020, and will launch a robotic lunar exploration mission, LRO, in 2008/09. NASA has announced that its objective is the construction of a permanently crewed lunar outpost at one of the poles. BNSC has in April 2007 signed a Memorandum of Understanding with NASA to enable the two agencies to work together more closely on space exploration.

## UK Space Exploration Working Group

The UK (through the Science and Technology Facilities Council) has joined the first phase of the ESA Aurora exploration programme and is focused on the science-driven robotic exploration of Mars leading up to a future robotic Mars sample return mission. In the preparation to this decision, the UK undertook a systematic analysis of the scientific, technological and knowledge exchange goals of robotic Mars exploration. However, it is felt that this work now needs to be expanded to address other aspects of space exploration.

As part of the ESA Aurora work plan, BNSC/PPARC hosted a two-day exploration workshop of European experts in Edinburgh in January 2007. Nationally, the UK has undertaken in 2006 a small study of science-driven lunar robotic missions, and has proposed a lunar sample return mission to ESA in response to a Call for Ideas for the proposed NEXT mission. In 2005 the Royal Astronomical Society published an independent scientific assessment of the case for human space exploration and concluded that the UK would derive substantial scientific and other benefits from participation.<sup>3</sup>

Through the ESA science programme, UK industry is undertaking a preliminary study of a robotic asteroid sample return science mission, while through the ESA General Studies programme, UK industry is involved in studies of a possible mission to mitigate the threats from Near Earth Objects, Don Quijote. UK scientists are strongly involved across the full range of proposals to the 2007 Cosmic Vision competitive call for proposals for new missions in the ESA Science Programme. This includes proposals relevant to space exploration (lunar science, Mars science and asteroid sample return).

### **4.3 Global Exploration Strategy**

Starting with an international exploration workshop in Spring 2006, NASA initiated a process to create a ‘Global Exploration Strategy.’ This involves fourteen space agencies from China, India, Italy, France, Germany and the UK, as well as ESA. The group met four times and via weekly teleconferences in order to:

- prepare an overarching framework for space exploration;
- identify mechanisms for collaboration; and
- detail scientific, technological and societal themes and objectives for robotic and human space exploration.

Although initiated by NASA, the process has established a collegiate, international flavour. The goals of this activity were reflected in the high level ‘Spineto Declaration,’<sup>4</sup> drawn up by agencies at the Second Spineto workshop on ‘International Cooperation for Sustainable Space Exploration’ hosted by ASI in May 2006.

The resulting document, *The Global Exploration Strategy: The Framework for Coordination* was reviewed by Heads of Agencies and published in May 2007. The document is supported by a large database of possible exploration objectives. These have not been sorted in terms of priority or time-phasing by the GES group, but NASA has taken these objectives to inform the strategy for its lunar architecture, which was announced in public on 4 December 2006 at the Second Exploration Conference in Houston.

The Framework for Coordination envisages, among other things, an International Coordination Mechanism which is likely to include a standing committee tasked with sharing the plans of participating nations and seeking ways to improve collaboration, reduce duplication and maximise benefits. It will also advise on how to reach agreements where needed – for example in deciding the correct bodies to deal with issues concerning commercial exploitation.

China, Russia, India and Japan are all undertaking reviews of space exploration and have published plans or are consulting with their communities. Most recently, the Indian space agency, ISRO, has announced a preliminary plan to land an astronaut on the Moon by 2020. It is in this international context in which the present review has been conducted.

### **4.4 United States**

In January 2004 President Bush announced a Vision for Space Exploration,<sup>5</sup> the main elements of which were to:

- Complete the International Space Station.
- Safely fly the Space Shuttle until 2010.

- Develop and fly the Crew Exploration Vehicle no later than 2014 (with a goal of 2012).
- Return to the Moon no later than 2020.
- Extend human presence across the solar system and beyond.
- Implement a sustained and affordable human and robotic programme.
- Develop supporting innovative technologies, knowledge, and infrastructures.
- Promote international and commercial participation in exploration.

According to the NASA Authorization Act of 2005, ‘The Administrator shall establish a program to develop a sustained human presence on the Moon, including a robust precursor program to promote exploration, science, commerce and U.S. pre-eminence in space, and as a stepping stone to future exploration of Mars and other destinations. [...] The fundamental goal of this vision is to advance US scientific, security, and economic interests through a robust space exploration program.’

The NASA vision for lunar exploration has been built up from elements in six themes: human civilisation, global partnerships, scientific knowledge, economic expansion, exploration preparation and public engagement.

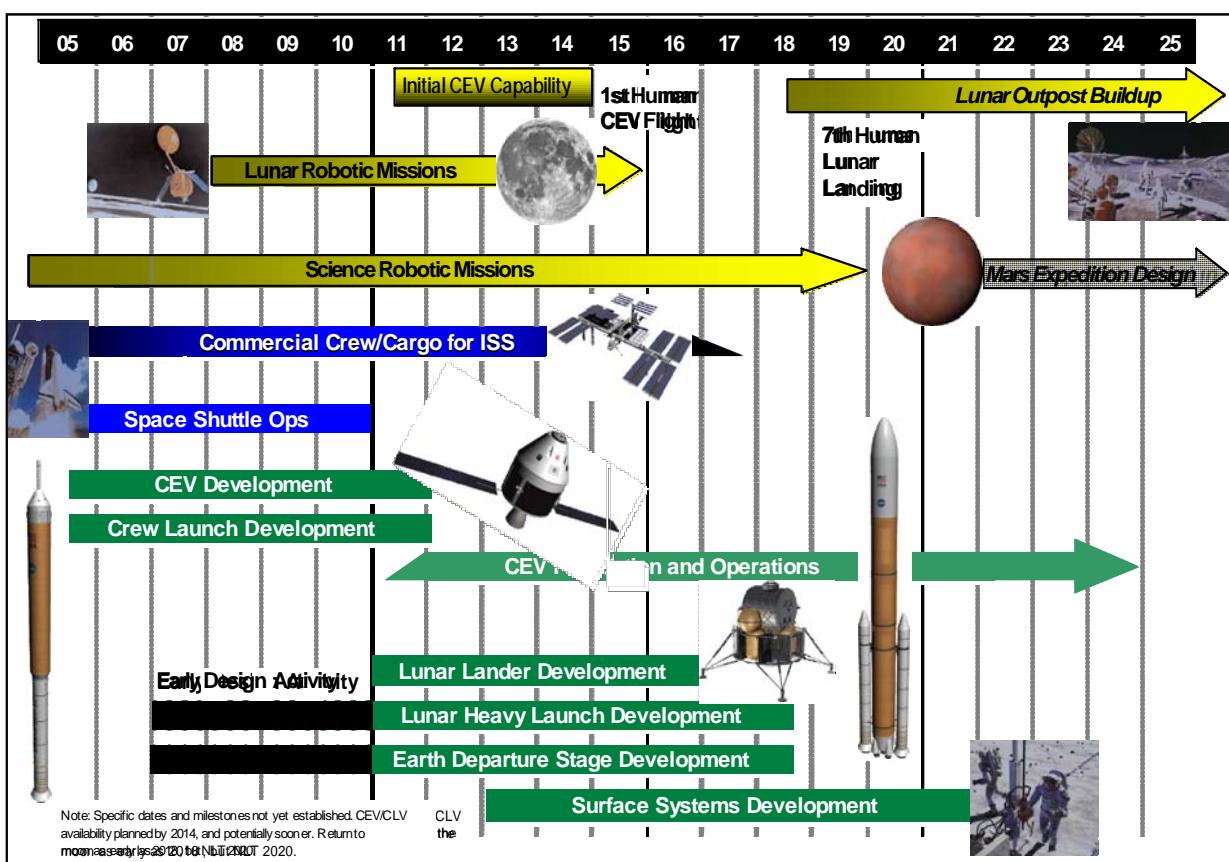


Figure 1 Timeline for US Space Exploration Programme

Despite the ambitions of the US to return to the Moon by 2020, this will be hard to achieve on the existing NASA budget, especially in view of the funding required to maintain the Shuttle until 2010. For this reason it seems clear that they cannot achieve their goals alone.

Indeed NASA has drawn up a list of technologies that will be needed to achieve their aims and have identified a few areas that they regard as strategically important to US national interests. However for the bulk of these technologies NASA has stated that it is open to offers of external collaboration – for example in the development of lunar surface infrastructure.

To this end NASA has been in discussion with BNSC on the possibilities for working together more closely and a joint statement of intent in the field of space exploration was signed on 19 April 2007.<sup>6</sup> A joint US-UK working group is being set up to propose collaborative activities in the field.

## **4.5 Europe (ESA)**

ESA has had a hugely successful history of exploring the solar system – from the Giotto mission which visited Halley’s Comet in 1986, through the Cassini-Huygens mission which landed a probe on the surface of Saturn’s moon, Titan, in 2005, and onto the Rosetta mission which is three years into its journey to land on the surface of a comet in 2014. Another ESA mission, SMART-1, successfully tested new technologies for future planetary missions, orbiting the Moon from 2004 to 2006. The Mars Express mission is still in orbit around Mars and sending back exceptional scientific data and images while Venus Express is currently studying the evolution of the atmosphere of Venus. The UK has had a major involvement in all of these important missions.

In addition, ESA is cooperating with other nations on planetary missions – for example on the Indian Chandrayaan-1 lunar mission, due for launch in 2008, and the Chinese Cháng’é-1 mission, due for launch to the Moon later this year. Its future ExoMars mission will include collaboration with the USA and Russia, and the BepiColombo mission to Mercury will include major involvement from Japan and Russia.

ESA continues to be a major player in the building and operation of the International Space Station. It has built a range of infrastructure, from various components of the main structure of the ISS, to a range of facilities for scientific experiments. These have given rise to a large number of hi-tech businesses throughout the participating states in Europe, as well as access to microgravity facilities to conduct scientific research in life and physical sciences.

In 2001, ESA set up the Aurora programme, the objective of which is first to formulate and then to implement a European long-term plan for the robotic and human exploration of solar system bodies holding promise for traces of life. The UK is the second-largest contributor to this programme after Italy.

In 2003, an ESA strategic study<sup>7</sup> recommended that ‘in 2025, Europe will begin to operate a permanently manned outpost on the Moon as part of a multi-decade, international exploration effort to serve humanity, thus increasing our knowledge and helping us to address the global challenges of the future.’

In 2005, a further ESA strategic study<sup>8</sup> recommended that ‘Europe will implement a visible, affordable and robust space exploration programme, driven by the long-term goal of the in-situ exploration of Mars by humans, which creates benefits for society, engages other space-faring nations through collaborative activities and, thereby, contributes significantly to societal development.’

Among ESA’s Medium-Term Objectives are two that are relevant to space exploration:

- Support implementation of International Mars Sample Return mission.
- Ensure that Europe acts as a significant player in global space exploration through:
  - development of enabling capabilities;
  - implementation of European-led international robotic mission (ExoMars); and
  - promotion of broad international and societal engagement.

The UK is also participating in long term exploration scenario studies within the Core Programme element of Aurora. These activities are intended to help develop European strategy for the next ESA Ministerial and beyond. They embrace various destinations including the Moon, Mars and asteroids, and are considering three drivers or rationales for exploration: scientific, technological and societal.

## **4.6 Europe (complementary to ESA)**

In order to gain the maximum value from their participation in ESA programmes, many ESA member states are formulating their own national plans for involvement in space exploration.

In particular, Germany, France and Italy are all contributing to a study of the Russian Crew Space Transportation System - a replacement for the Soyuz capsule.

German spending is presently focused on completion and exploitation of the ISS, but it is also undertaking a national study of lunar activities and has held a series of workshops on exploration. A national lunar orbiter mission ('LEO') is seen as the first objective.

France is mainly focused on robotic Mars exploration at present but is holding a national workshop to consider the wider aspects of exploration in the Autumn of 2007.

Italy is the leading contributor to Aurora and has funded 16 national studies on lunar science and

supporting technology. It has a national budget of €900M earmarked for lunar exploration.

#### **4.7 Russia**

Russia may be thought of as the ‘sleeping giant’ of space activities: after a long period of post-Soviet decline, the Russian Federal Space Agency ‘Roscosmos’ is now in a period of rapid growth as its annual budget has increased by 33% to €900M in 2006, as part of ten year plan costing \$11 billion.

Planned new projects include: several astronomy missions; a sample return mission to Phobos, one of the moons of Mars; and an ambitious lunar mission, Lunar Glob, including an orbiter, lander and penetrators. The Soyuz vehicle is to be upgraded in stages to become capable of lunar flyby and perhaps then replaced by a winged crew return vehicle. Cooperation with ESA is underway through the study of the Crew Space Transportation System. The most recent announcements set out plans for a human mission to the Moon in 2025, and a permanent operational station on the surface of the Moon in 2028-2032. A human mission to Mars is said to be possible after 2035.

At \$21M each, all space tourism flights to the Russian part of the ISS on Soyuz launches are booked through to 2009.

#### **4.8 Japan**

Japan plans an energetic programme of space exploration and indeed has recently renamed its space agency the Japan Aerospace Exploration Agency (JAXA).

Its near-term aims are focused on Moon exploration and possible utilisation:

- Promote studies of the Moon and possible utilisation of the Moon.
- Expand the scope of activities of Japan.
- Challenge to develop cutting-edge technologies such as robotics technologies, nanotechnologies and micro machines, and solar power technologies.
- Prepare for the establishment of a human lunar base.
- Develop complementary relationships with other nations for effective exploration.

Within about 10 years:

- Further moon exploration with Moon-orbiting satellites (SELENE, etc.).
- Studies of possible utilisation of the Moon and development of innovative future technologies.
- Seek a decision by the government on whether to take significant steps towards the utilisation of the Moon.

Within about 20 years:

- Contributions to the international community by taking roles in the implementation of international lunar initiatives.
- Development of enabling technologies for long-term stay on the Moon.

The SELenological and ENgineering Explorer ‘SELENE’, Japan’s first large lunar explorer, will be launched by the H-IIA rocket in 2007. It will investigate the entire moon in order to obtain information on its elemental and mineralogical composition, its geography, its surface and sub-surface structure, the remnant of its magnetic field, and its gravity field. The results are expected to lead to a better overall understanding of the Moon’s evolution.

At the same time, the observation equipment installed on the orbiting satellite will observe plasma, the electromagnetic field and high-energy particles. The data obtained this way will be of great scientific importance for exploring the possibility of using the moon for human endeavours.

#### **4.9 China**

China has a demonstrated capability in launch vehicles and in space applications (telecoms satellites, Earth observation, weather, microgravity via recoverable satellites, navigation), and is currently becoming involved in space science (e.g. the Double Star mission, in collaboration with ESA).

The growth in China’s space programme is shown by the recent increase in the number of satellites launched: between 1970 and 2000, 47 satellites were launched, whereas between 2000 and 2005, 22 satellites were flown. China has also commenced a programme of human space exploration, and has

launched three ‘Taikonauts’ into low Earth orbit aboard the Shenzhou spacecraft. Its political priorities, stated in ‘China’s Space Activities in 2006’<sup>9</sup>, include:

- continuation of Shenzhou human missions;
- 3-step robotic lunar programme (Chang’e I, II, III); and
- new heavy launcher using green propellants.

There are occasional reports on plans for a human space station and/or human lunar missions.

## **4.10 India**

ISRO, the Indian Space Research Organisation, has a long history of using space as a tool in its national development and has gained impressive competences in launch vehicles and applications satellites. It has now set planetary exploration as its next long-term goal. It is in the process of building the Chandrayaan 1 lunar orbiter which is due for launch in 2008. This mission is being carried out in collaboration with ESA and carries a UK spectrometer which will conduct a geochemical survey of the surface of the Moon. A possible second mission is planned for 2012.

In addition, India is laying independent plans for human spaceflight which it considers essential to its goals. The first phase which will put an Indian in orbit by 2014 is expected to cost in the region of \$2.2bn. The proposed second phase would land an astronaut on the Moon.

## **4.11 Canada**

Canada has taken a strategic decision not to develop its own launch capability. As a consequence Canada is a champion of international collaboration in space and in the past has achieved flight opportunities for Canadian astronauts through infrastructure contributions to international programs, most notably the contribution of the robotic Canadarms on the Space Shuttle and the International Space Station. The first robotic arm was built by Canada as its contribution to the US Space Shuttle programme, and it has since built and delivered a further six under commercial contracts directly from NASA to Canadian industry. Canada has also contributed the Mobile Servicing System (MSS) to the International Space Station programme that includes a mobile base, a large arm (Canadarm2), and a dextrous manipulator (Dextre). As part of the international agreement between ISS partners, Canada also has a responsibility in ground operations and training for the MSS on ISS. This contribution to ISS allows access for Canadian science payloads as well as Canadian astronauts. This highly successful programme is a useful example of effective bilateral arrangements that could serve as a model for UK engagement in exploration.

In order to meet the goals of Canada’s Space Science and Exploration Strategy, and as part of a broad consultation process, the Canadian Space Agency (CSA) held a workshop with members of its space community in 2006. Participants were asked particularly to identify within their proposed programs ‘the next Canadarm’ as a means of securing further human access to space. The timeframe given for the proposed program was 2007-2027. CSA will undertake a series of studies to support a draft plan and will continue consultations as it enters the process of getting agreement for its plans at government level.

## **4.12 Summary**

All of the existing and emerging space powers have made the decision to engage in space exploration, at present mostly with robots coupled with technological preparation for human exploration. However, the US decision to implement a human return to the Moon in 2020 and the establishment of a permanent lunar outpost has provided the stimulus to the preparation of a coordinated long term vision known as the Global, Exploration Strategy. This identifies a range of drivers for space exploration, including science, technology, commerce and societal benefits. In the following chapters, we have addressed these possibilities from a UK perspective.

## 5 Science

### 5.1 Overview: Why do we want (or need) to explore space?

Curiosity about what other worlds are like inspires public interest in space exploration. For the scientist there is the additional motivation that the exploration of other worlds can teach us about our own. Studying other planets can be compared to an experiment where you can vary the parameters: we can learn about how features such as the geology, atmosphere and magnetic fields of other planets have evolved and deepen our understanding of planetary dynamics in general. Thus we may learn about our own origins and possibly gain lessons for planning our future. Finding the answers to such questions will be greatly aided by exploration with robotic landers and humans.

Questions about the nature and origin of life are ones that literally concern our origins and have fascinated all cultures throughout history. Cosmology and particle physics are motivated by the search for cosmic origins in the aftermath of the Big Bang, with the hope of determining the nature of that singular event. Such investigations have explained how the elements formed, but how atoms gathered to become self-aware is the great mystery of life. Knowing whether it has happened only here on Earth or more widely would have great cultural impact.

Strategies for answering this question include looking for Earth-like planets around other stars, seeking evidence of pre-biotic molecules in space, or of life itself on Mars. There is also the tantalising prospect that if life on Earth was seeded by cometary bombardment, there might also be evidence in the lunar regolith (the layer of loose material covering the bedrock).

We recognise that space exploration will necessarily be a cooperative endeavour, but the UK has specific skills and strengths in many areas that will enable us to benefit from, and contribute to, any future global exploration strategy. The optimum approaches are varied.

We have achieved much in the search for the origins of life through experiments undertaken on Earth, and by the remote exploration of the Sun, Moon and planets. Examples of significant advances include:

- The detection of planets and debris discs around other stars, indicating that planetary systems other than our own are likely to be common. But because of technical limitations imposed by Earth-based experiments we have as yet been unable to detect Earth-mass planets.
- The detection of prebiotic molecules in interstellar space. To date, about 140 different compounds have been detected; all those with six or more atoms are organic i.e. contain carbon atoms. Many of the complex molecules in space are also found in laboratory experiments specifically designed to produce prebiotic molecules under assumed primordial Earth conditions, which suggests that a universal pre-biotic chemistry is at work in space. An ever increasing area of research is to determine how amino acids, complex sugars and other important bio-molecules are formed in space.
- The recognition that water played an important role in sculpting the surface of Mars and that its atmosphere must have been very different in the past – and was perhaps conducive to the emergence of life.
- The recognition, based on over 30 years of experience with the Apollo samples and subsequent remote-sensing studies, that the lunar surface provides a unique record of the history of the early solar system, much of it directly relevant to understanding the cosmic conditions under which life first arose on Earth.

Studies of planetary geology and the search for life require direct access to planetary surfaces, and this forms the principal planetary science case for engaging in a programme of space exploration. With regard to astronomical studies, ground-based observations have been limited by the constraints of the atmosphere and gravity. In order to make further gains, it is essential that we climb above the atmosphere, and the lunar surface offers some significant advantages over orbiting spacecraft (e.g. a large stable platform). In contrast to astronomical research, the discipline of Earth Observation (EO) has capitalised on the presence of the atmosphere, and has made significant gains in understanding atmospheric circulation, weather patterns, etc through a series of satellite-borne instrumentation. However, EO studies may also benefit by

monitoring the planet at a greater distance from a lunar platform, for example through the ability to observe space weather effects in the magnetosphere on a global scale.

With regard to a search for life's origins we need to consider the following questions:

- What is the origin and distribution of the atomic elements and molecules from which life arose?
- What were the physical and chemical environments in which life arose and evolved?
- How do planetary systems form and evolve?
- How is life affected by its external environment?

These questions encompass a range of disciplines, from planetary sciences, through astronomy to fundamental physics, medical and life sciences. While a prime goal of space exploration is to understand the origins of life and how life evolved as planetary systems developed, we recognise that investigations of the Moon, Mars and asteroids are major components in reaching that goal. We also recognise that the lunar surface is important as a platform from which other studies (e.g. astronomy, medical) can be undertaken. To reflect this diversity of subject matter, we start with a discussion of the science goals that we would attempt to achieve through direct study of the Moon, Mars and Near Earth Objects. We then consider the different disciplines that would benefit from studies based on a lunar platform, starting with observation of the Earth, and then the Sun, followed by astronomy and fundamental physics. Finally, we consider some of the opportunities for studies relating to human health

## **5.2 Moon, Mars and Near Earth Objects**

The discipline of planetary science seeks to understand the origin and evolution of planetary systems (in general) and the solar system (in particular), and the co-evolution of life with its planetary hosts. Results are obtained through observation and analysis of bodies within the solar system (and, increasingly, through study of extrasolar planets). Solar system bodies include asteroids, comets, planets and their satellites and the grains of dust that permeate the entire system. Studies involve remote observations by orbiting spacecraft, *in situ* measurements on planetary surfaces and laboratory analysis of returned samples, as well as theoretical modelling. So far, data from all but the nearest objects in the solar system have been acquired by remote techniques. *In situ* measurements have been made on the surface of the Moon, Mars, Venus and Saturn's satellite Titan, and material from asteroids, a comet, the Moon and Mars have been analysed directly in laboratories. These last-mentioned materials have almost all arrived by serendipity, only the Apollo and Luna samples from the Moon have been obtained from known locations on the surface of a planetary body. Such geological context is essential if the scientific benefits of sample analysis are to be maximised.

In order to progress in our studies of the solar system, and in understanding how life has been affected by its planetary environment, we need to make more detailed measurements at a number of locations on specific objects. In the next 20 – 30 years these investigations will be confined to the Moon, Mars and the asteroids, as they are the objects that can be reached with current and developing technologies. While an ultimate goal of this phase of a space exploration programme is a detailed investigation of Mars to look for signs of life, this can only be accomplished by a careful, long-term, programme of robotic and eventually human spaceflight missions. As well as building towards the search for life on Mars, the Global Exploration Strategy also calls for missions designed to explore the Moon and near-earth asteroids.. The Moon, in particular, contains a wealth of information directly relevant to the planetary context in which life evolved on Earth, and lunar exploration will also help us develop the operational expertise that will eventually be needed if human exploration of Mars is to follow. Specific science goals that will be enabled by an exploration programme can be considered in terms of the relevant target body.

### **5.2.1 The Moon**

The origin of the Moon is not completely understood. It differs from the satellites of Mars (thought to be captured asteroids or comets) and the giant planets (combinations of captured planetesimals and local aggregations of material). The most widely-accepted hypothesis for the origin of the Moon is from the catastrophic impact of a Mars-sized body (known as Theia) with the proto-Earth a few million years after the Earth originally aggregated. Although we have Apollo and Luna samples returned from specific regions of the lunar surface, and lunar meteorites ejected from random parts of the Moon by asteroid impact, we by no means have full coverage of the range of material present on the Moon, or a full

understanding of material at depth.

The lunar surface maintains a complete record of the history of collisions in the inner solar system. The number, size and distribution of craters on the Moon can be used as a calibration for the rate and timing of cratering throughout the solar system; this, in turn, is then used to provide a relative chronology for surface processes (volcanism, fluvial and glacial action, etc) on other planetary bodies. In order to have a well-defined chronology from lunar cratering records, it is necessary to have absolute ages from a complete suite of rocks from the Moon.

Unfortunately, Apollo and Luna samples were not obtained from all the different terrains, and so only a small percentage of the cratering record is calibrated. This has implications for understanding the evolution of Mars and the other rocky planets, where cratering records are more incomplete.

As well as preserving craters on its surface, the Moon also retains material from the impactors: small fragments of meteorite have been identified in drill cores from the Apollo missions, and recent UK-led work suggests that meteorites can survive impact on the lunar surface in favourable circumstances (e.g.

when landing close to the lowest possible velocity of 2.4 km/s, and/or at oblique angles). This is an exciting prospect, because it is possible that, just as lunar and Martian meteorites land on Earth, terrestrial meteorites (i.e. meteorites from the Earth) might land on the Moon. It is feasible that the lunar surface is keeping a record of ancient terrestrial rocks that are no longer present on Earth. In the same way that Martian meteorites contain pockets of Mars' atmosphere trapped during shock-induced melting of the rocks on ejection from the surface, terrestrial meteorites could contain analogous samples of the terrestrial atmosphere, possibly providing an opportunity to investigate Earth's atmosphere prior to the evolution of life. Moreover, the lunar surface is not just a repository for rocky materials: it also preserves volatiles trapped during aeons of bombardment by asteroids and comets, as well as abundant hydrogen from the solar wind (a potential fuel for future human utilisation).

It is clear that although the Moon is lifeless, it is an enormously important body in terms of understanding the Earth-Moon system and the development of the local environment in which life evolved on Earth. This, by itself, makes the Moon an important target for exploration. However, the Moon has a wider role to play in a space exploration programme, as it acts as an accessible platform on which to site instrumentation and, eventually, human habitation.

The main scientific goals of lunar exploration are to:

- determine the origin of the Moon and how that affected the development of the early Earth and life on Earth; and
- investigate the record of solar and collision histories embedded within the lunar regolith (soil layer, probably several metres deep).

These scientific goals require detailed characterisation of the Moon at all depths from surface to core. In order to achieve these goals, there will be requirements for:

- Emplacement of geophysical networks (e.g. seismometers, heat-flow probes, magnetometers<sup>10</sup>) required for studies of the lunar interior.
- Collection of a more diverse range of samples from larger geographical areas than has so far been achieved.
- *In situ* and laboratory-based geochemical analyses (including radiometric dating) of lunar samples, both from the surface and depth.
- Search for, and retrieval of, ancient regolith deposits containing samples of ancient solar wind



**Figure 2 The Shackleton Crater on the lunar South Pole. The lunar surface preserves a record of the history of the solar system. (Image ESA/SMART-1)**

and, possibly, terrestrial meteorites.

- Material from the Moon to be returned to Earth for analysis.
- A dedicated curation facility for the preliminary analysis, distribution and storage of material.

Some of these goals may be achieved robotically (e.g. seismometer emplacement and limited sample return), and these might form the basis of a near-term (2008-2012) UK contribution to a robotic lunar programme. See section 9.1.2 for further details.

However, some of the other goals could benefit from, and perhaps might even require, a human presence (see Appendix E and references 2, 3 and 43). Specifically, a renewed human exploration of the Moon will:

- Permit much more efficient collection of a more diverse range of samples from larger geographical areas than is possible robotically;
- Facilitate large-scale exploratory activities;
- Facilitate the landing of much more bulky and complex geophysical and other equipment than is likely to be feasible robotically;
- Increase the opportunities for serendipitous discoveries;
- Gain operational experience on a planetary surface that will be of value for the later exploration of Mars;
- Facilitate a number of other, non-planetary, science activities on the Moon; e.g. (i) life sciences investigations under reduced gravity conditions (see section 5.8); and (ii) maintenance and upgrading of astronomical instruments placed on the lunar surface (the value of a human presence for which has been one of the main lessons of operating the Hubble Space Telescope).

### 5.2.2 Mars

For almost 40 years, observations of Mars by orbiting satellites have shown the surface of the planet to be crossed by features thought to be produced by water or ice. There are also huge volcanoes and deep valleys. So the landscape of Mars indicates that it has had active thermal and fluvial histories. On Earth, where there is water and heat, life usually flourishes; for this reason, Mars has been the focus of attention in the search for life beyond Earth. The most compelling scientific drivers for the exploration of Mars are:

- Is there or has there been life on Mars?
- How has Mars evolved as a planet?

The two scientific drivers are inextricably linked, because life requires a stable platform in order to evolve, protection from harmful radiation to survive, and access to nutrients to flourish. To understand fully the complexities that might constrain a Martian ecosystem, we need to understand the origin and evolution of the Martian lithosphere (its rocky surface), hydro-cryosphere (its (mainly frozen) volatile reservoir) and atmosphere, and the interplay between these reservoirs and a Martian biosphere.

Although there have been many missions to Mars, and we now have detailed high-resolution images of features both from orbit and from the surface, there have as yet been no geophysical studies of the planet. So we still do not know the internal structure of Mars or the state of its core. Although we know that there are huge volcanoes, and believe they are extinct, we do not know what residual volcanic activity might still be occurring. There has been no detailed mapping of magnetic or gravity anomalies, which are pointers to sub-surface activity. The surface of Mars has been mapped at the 10 – 100m scale by orbiting satellites, and this, together with spectroscopic data, has helped us to recognise rock types. But there is no absolute chronology for the surface features, so we can only infer, based on crater counts, a relative timescale for different events. Such events might include periods of intensive volcanic activity, catastrophic flooding of large regions by melt-water and the presence of surface water as rivers and lakes.

It is clear that at times in the past, Mars has had an active fluvial history, but the hydrosphere no longer exists as a significant global reservoir. It has been replaced by a cryosphere, in which mixtures of water and carbon dioxide ice act as the bridge for cycling of volatiles between lithosphere and atmosphere. Ice occurs in the ice caps at the two poles, and as a sub-surface permafrost layer overlying icy regolith (soil layer) and bedrock many kilometres deep. Mars must have had a more substantial atmosphere at an earlier epoch in its history. The composition and pressure of this atmosphere are unknown, as is the timing and mechanism of its loss. The disappearance of the atmosphere altered the hydrological cycle on Mars, and thus reduced the potential for evolution of life in surface habitats. The trigger that initiated such a major change in conditions is unknown, but the coincidence in timing with the decline of the planetary magnetic

field is likely to be significant. Mars is a clear example of how geological changes have affected the habitability of a planetary body.



**Figure 3 Residual water ice in Vastitas Borealis Crater.**  
The presence of water may improve the prospect of finding signs of life on Mars. (Image ESA/DLR/FU Berlin (G. Neukum))

Despite the apparent lifelessness of the planet, and the sterile nature of the Martian surface (resulting from the unattenuated ultraviolet radiation from the sun), it is not certain that Mars is a dead planet. Studies of organisms on Earth have shown that micro-organisms can survive in the most unlikely of habitats. One specific example is the colonisation of Antarctic rocks by lichens, a symbiotic relationship between fungi and bacteria that is successful in its exploitation of a cold, dry and windy environment with limited nutrient supply. Analogous sub-surface niches on Mars might be inhabited by similar micro-organisms. The problem will be in locating and identifying such an ecosystem. One set of measurements that has not been made successfully, despite the recent spate of spacecraft visiting Mars, is the detection of organic compounds in surface and sub-surface locations. The

ExoMars mission, ESA's flagship astrobiology mission, currently scheduled for launch in 2013, has on board an instrument that will undertake this experiment, and will determine the nature and abundance of organic molecules present. Results (whether positive or negative) will help guide additional measurements of carbon at and below Mars' surface.

Once we have a better understanding of the composition of the three global reservoirs on Mars (the lithosphere, hydro-cryosphere and atmosphere), and the way in which they interact in the cycling of volatiles, it will be possible to begin comparative planetology in earnest, with a comparison between Earth and Mars. We need to understand why Earth, Mars and Venus have evolved so differently given the same starting materials. This will then inform studies of exoplanet evolution, and the search for life beyond the solar system.

Recent investigations of early life on Earth have highlighted the problem of the evidence on which the identification of preserved micro-organisms should be based. It is proving difficult on Earth to identify, with certainty, the remnants of fossilised bacteria on the basis of morphology alone. More sophisticated analyses than can be carried out on the surface of Mars might be required for unequivocal identification of fossilised Martian organisms (witness the debate surrounding potential identification of putative microfossils in Martian meteorite ALH 84001 in 1996 by McKay and co-workers). We will need advances in several technological areas if we are to return Martian rocks to Earth. The question of planetary protection (both of Mars by Earth, and vice versa) will need to be addressed, as will the issue of a curation facility for storage and distribution of returned material.

One of the most significant and important aims of robotic exploration of Mars will be to demonstrate the need for human exploration in order to settle definitively the question of whether or not there is extant life there. Ultimately, the human exploration of Mars will yield similar advantages in terms of the scale and efficiency of exploration as those identified above in the case of lunar exploration, and obtaining a definitive answer as to whether Mars has ever been inhabited may not be possible otherwise. However, the ability to return rocks to Earth from Mars is a necessary step in a programme that eventually intends to send humans to Mars. Moreover, preparation for human exploration of Mars will require additional information on environmental hazards (including knowledge of global circulation to forecast dust storms, and measurements of the UV and cosmic radiation flux at the surface) which may be addressed by precursor robotic missions, and studies in human physiological responses to long-term exposure to the space environment that will be required to deliver human crews to Mars and safely return them to Earth.

Thus, the principal scientific goals of Mars exploration are to:

- determine whether there is evidence for extant or extinct life; and

- determine the interaction between the lithosphere, hydro-cryosphere and atmosphere in order to evaluate how changes in one reservoir impact on the others.

In order to achieve these goals, there will be requirements for:

- Direct imagery and analysis of surface and sub-surface regions. This will require precision landing.
- In situ analysis of different rocks and ice. This will require the ability to move around the surface.
- Monitoring and measurement of the atmosphere, climate and weather (dust storms).
- Assessment of in situ resource utilisation: regolith composition, surface radiation levels, depth profile of radiation penetration, etc.
- Material from Mars to be returned to Earth for analysis.
- A dedicated sample curation facility for the preliminary analysis, distribution and storage of the material.

### 5.2.3 Near Earth Objects (NEOs)

The major bodies in the solar system are the Sun, the planets and their satellites. In addition there are many small bodies: asteroids (most of which orbit the Sun in a belt stretching between Mars and Jupiter), Kuiper Belt objects (KBOs, with orbits beyond Neptune; Pluto is now believed to be a KBO) and comets. KBOs and comets, along with some classes of asteroids, are believed to be primitive objects that have changed little since they aggregated from the protoplanetary disk some 4.56 billion years ago. In addition to these small bodies, there is a class of objects that orbit the Sun within Earth's orbit, the Near Earth Objects (NEOs), which are a combination of asteroids and captured comets.

NEOs are an accessible source of the primitive material from which the solar system was formed, and they carry within them records of early solar system history. NEOs are also a potential threat: collision between Earth and an NEO would be hazardous to life, as the consequences of such an impact would be global environmental changes unprecedented since the dinosaurs became extinct 65 million years ago. The Tunguska event of 1908 shows that significant collisions are not restricted to prehistoric times.

NEOs are an important target for a UK space exploration programme since understanding their composition and structure will not only give insights into the chemical and mineralogical ingredients from which the solar system formed, but will also give a window onto subsequent planetary evolution.

Although a rendezvous mission with an NEO would yield valuable data, a prime goal is to return a sample from an NEO back to Earth. There are many scientific drivers for such a mission, which include investigation of:

- the initial conditions and subsequent evolutionary history of the solar nebula (aggregation, melting, aqueous alteration, collision, etc);
- the composition of the building blocks of the terrestrial planets (Mercury, Venus, Earth and Mars), especially the nature and origin of organic compounds; and
- the role of asteroid impact in the origin and evolution of life on Earth (delivery of water and organic compounds; impact frustration of biological evolution; etc).

There are approximately 35,000 meteorites that come from asteroids in collections throughout the world. It could be argued that returning a sample from an NEO would not add much to results already gained from study of these meteorites. However, that is a false argument. Meteorites are derived from the surfaces of main belt asteroids, where they



**Figure 4 Asteroid Itakawa.** Asteroids are thought to be made from the primitive material which formed the solar system. (Image JAXA)

have been modified by collision and cosmic irradiation. As a meteorite passes through Earth's atmosphere, a significant percentage (over 90% in some cases) of the material is lost through ablation. And on landing, even if collected immediately, the meteorite is contaminated by the dust and organics carried by our atmosphere. A sample collected from the subsurface of an NEO would contain organic species that had not been compromised by terrestrial contaminants or cosmic radiation. This would, for the first time, allow analysis of pristine extraterrestrial organic molecules by the full range of high precision laboratory instrumentation. One specific measurement would be determination of the optical characteristics of the molecules, since life on Earth has a very specific optical signature (it is 'left-handed'). Measurements of organics in meteorites suggest that these molecules also are left-handed, but it has not been clear whether this is because the meteorites have been contaminated with terrestrial species, or whether this is a primordial signature. If the latter is the case, and is verified by analysis of uncontaminated material collected directly from an NEO, then it would be consistent with the hypothesis that the building blocks of life were delivered to Earth by asteroids and comets.

There are technical advantages to an NEO sample return mission: it would act as a pathfinder mission for future sample returns from Mars (identified as a major priority in the ESA's exploration programme). And looking even further to the future, returning a sample from a low gravity body will assist in the development of technical expertise for potential utilisation of asteroid resources.

The scientific goals of NEO investigation are to:

- provide insight into the materials from which the solar system aggregated, and the subsequent processes of melting, alteration and collision that they have experienced through 4.56 billion years of evolution;
- identify and characterise the organic materials that were the precursor molecules from which life eventually arose;
- determine the structure, coherence and rigidity of asteroids in order to inform hazard mitigation studies;
- investigate the record of solar and collision histories embedded within asteroidal regoliths; and
- provide technical experience for the return of samples (and humans) from Mars.

In order to achieve these goals, there will be requirements for:

- material from an NEO to be returned to Earth for analysis; and
- a dedicated sample curation facility for the preliminary analysis, distribution and storage of the material.

### **5.3    Earth observation**

Climate change brought about by global warming has been highlighted as the most significant problem that humanity faces in the coming decades, with enormous physical, economic and social consequences. Its accurate prediction is essential. The role of solar variability in climate change is identified in the Intergovernmental Panel on Climate Change Report (2001)<sup>11</sup> and in NERC's *Science for a Sustainable Future 2002-2007*<sup>12</sup> as a key science problem. The near-side of the Moon is a place from which we can make novel observations that will advance our understanding of the Earth and its surroundings.

Lunar observations can make important contributions to climate change studies, especially in helping to understand solar drivers of climate change so that the anthropogenic component can be more clearly identified. Examples include accurate and sustained measurements of the energy flowing in and out of the climate system: the solar spectrum (input); earthshine, i.e. sunlight reflected by Earth (output); infrared emission from the Earth (output). The measurements of Earth outputs require a view of the whole Earth and one that changes only slowly so that we can clearly identify temporal changes in those outputs. These measurements will therefore benefit from the perspective provided by location on the Moon. The Moon is at an ideal distance from the Earth for such observations and the view changes slowly over the course of each month. In addition, the inclination of the Moon's orbit (between 18° and 28° with respect to the Earth's equator) means that instruments on the lunar surface have a much better view of the Earth's polar regions than is available from geostationary orbits. In particular, observations around new moon will have a good view of the sunlit polar regions and thus allow measurements of the sunlight reflected by the polar ice and snow, which is an important factor in climate studies. In addition, a human base on the Moon will provide the long-term commitment that is critical to observing changes in solar activity and Earth outputs; this may offer long-term advantages over equivalent measurements at other locations in space.



**Figure 5 'Earthrise' photographed from the Command Module of Apollo 11 (Image NASA)**

Another benefit from a lunar perspective will be the ability to take images of the Earth's magnetosphere (the region of near-Earth space dominated by the planetary magnetic field) and magnetosheath (the region surrounding the magnetosphere where the solar wind is heated by its encounter with the magnetosphere). This region extends to distances of about 100 000-150 000 km from the Earth. Its observation requires a view from a slightly greater distance; the Moon at 400 000 km from Earth is thus ideal. The magnetosphere is the region in which space weather affects the operation of space-based systems on which human civilisation now critically depends, e.g. communications, navigation and weather satellites. We now make spot measurements from spacecraft in this region

but the future ability to image space weather phenomena has the potential to revolutionise the field in the same way that satellite imagery has revolutionised meteorology over the past forty years. Work is underway, in the UK and elsewhere, to develop instruments that can take images over a range of wavelengths (X-ray, ultra-violet, radio) and by imaging energetic neutral particles. A prototype system for X-ray observations is being developed by the University of Leicester, together with NASA Goddard.

The lunar surface is an excellent location to deploy large instruments that require a stable platform, for example radar interferometer observations of the Earth using antennas spread over many kilometres. These enable observations with higher spatial and temporal resolution than can be achieved with current satellite-based radars, which synthesise large antennas by combining measurements along the spacecraft's orbit. This will advance studies in areas that already exploit space radars such as surface topography, vegetation cover and ionospheric structure.

#### **5.4 Solar and solar-terrestrial physics**

Solar and solar-terrestrial physics are closely allied science disciplines; the former seeks to understand the operation of the Sun, whilst the latter is concerned with the Sun-Earth connection. Both disciplines rely on continuous observation of the Sun, monitoring its behaviour, coronal mass ejections, sunspots, and so on. Both ground- and space-based instrumentation have allowed major advances to be made in comprehending the dynamics of the Sun. As discussed in the previous section, global climate change is now a leading concern across all sections of society. Understanding the Sun, and how variations in solar output affect the Earth (its magnetosphere and its atmosphere), leading to changes in our climate, is therefore an essential subject for detailed study.

There is an enormous range of investigations that can be undertaken from the Moon, using it as a large, relatively stable platform in an environment free from atmospheric interference. A lunar platform for astronomical observations benefits from:

- the relative thermal stability that permanent sunlight offers for instruments; and
- the potential for human operatives to adjust, maintain and upgrade instruments.

A possible drawback of astronomical observations from the lunar surface is the presence of dust. Observations from Apollo and its robotic precursors showed that dust can be lifted up to 100 km above the surface.<sup>13</sup> Thus studies of dust mitigation will have to be addressed in early missions before astronomical instruments are placed on the surface. On the other hand, lunar-based equipment will have the major benefit of maintenance and upgrade supported by a future lunar base – the benefits of the presence of a human infrastructure for the support of astronomical facilities has been demonstrated by the successive servicing missions to the Hubble Space Telescope, and lunar-based observatories may be expected to benefit in a similar way.<sup>14</sup>

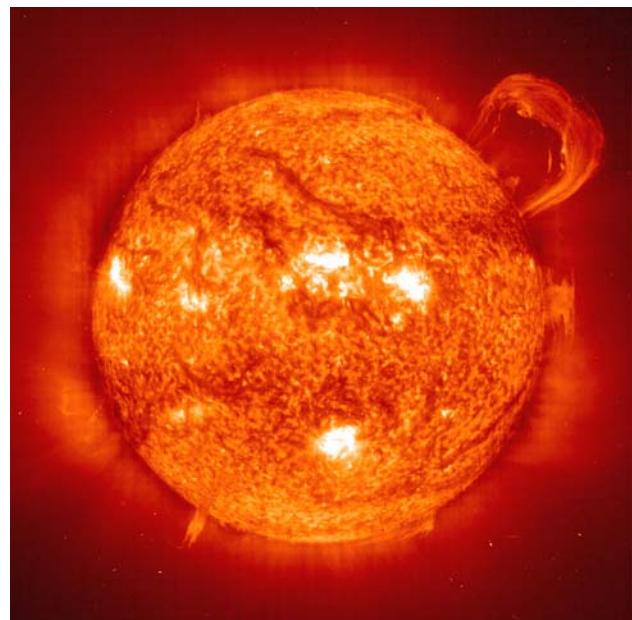
The main strengths of UK solar observers lie in instrumentation for and exploitation of optical, UV and EUV imaging and spectroscopy. There is also significant UK involvement in data from X- and gamma-ray observations of the Sun. This observational work is complemented by strong theoretical programmes modelling the solar atmosphere and interior. The UK also has strong observational skills in solar wind and interplanetary space measurements and space weather studies – both in-situ measurements from spacecraft and remote sensing using radio techniques. Here we list some key investigations that would require a lunar telescope for success.

*High-energy X-ray and gamma-ray solar astronomy:* the Sun produces X-rays in major events such as solar flares, but also in the continuous micro-flare events that are a possible source of coronal heating. X-rays are diagnostics of accelerated electrons, and gamma-rays are diagnostics of accelerated protons and ions. The requirements of stability in telescope design and large detector areas make high-quality X- and gamma-ray observations hard to do from orbiting platforms. High resolution imaging above about 40 keV requires collimating optics in which grids and detectors are aligned very stably and separated by long distances. For example, the thermal stability of the Peary Crater could provide an ideal environment for detection of high energy events.

*Low-frequency radio observations:* the outer solar corona and heliospheric plasma are sources of low frequency radio emission, impossible to observe from Earth because of the ionospheric cut-off. The emission arises from particles accelerated in flares and in shocks associated with coronal mass ejections. Radio emission provides plasma diagnostics including electron number density and magnetic field strength in these energetic structures, and can be used also for interplanetary space measurements of the solar wind. In addition, the magnetised planets (e.g. Earth, Jupiter, Saturn) produce low frequency radio signals by cyclotron maser emission from their auroral regions. These signals reveal much about the dynamics of their magnetospheres. An array of antennas is required for imaging, laid out over multiple sites. Radio instrumentation is simple and robust, and therefore very suitable for a lunar environment.

*Solar wind composition and solar energetic particles:* The Moon is an excellent location to collect solar wind material (e.g. through deposition in exposed metal and semi-conductor foils) and thereby infer the chemical composition of the Sun. Foil collectors were first deployed on the lunar surface during the Apollo landings, but the power of those measurements was severely limited by the short duration of the landings and the technology then available to manufacture and analyse the foils. Advances in foil technology and long duration exposure will enable much more comprehensive estimates of solar composition. This will allow scientists to make more stringent tests on models of the origin of the solar system - and was the motivation for NASA's recent Genesis mission. Unfortunately many of the foils exposed on that mission were damaged when the spacecraft crash-landed. Thus this is a well-proven and valuable technique that could easily be deployed on the lunar surface as part of a human return to the Moon. In a similar vein we can exploit the Moon itself as an object that has been exposed to the space environment over billions of years. The lunar regolith contains a record of that bombardment. Thus examination of drill cores from the regolith will yield a historical record of how the space environment has changed with the evolution of the Sun, the motion of the solar system around the galaxy and the exposure of the solar system to bursts of radiation from supernovae. This will be invaluable in providing a context for the evolution of life on Earth.

*Space weather monitoring:* This will be a safety-critical activity once humans spend long periods outside the protection provided by the Earth's magnetosphere - for example with a human presence on the Moon. But that presence will help us to sustain the observations that monitor space weather. The lunar surface is a great place to make co-ordinated observations across a range of wavelengths at very high spatial



**Figure 6 The sun seen in extreme UV showing a coronal mass ejection (Image ESA, NASA, SOHO/EIT)**

resolution throughout the entire solar cycle. This will allow identification of the conditions preceding solar eruptive events. In turn, this will lead to the development of predictive models, enabling forecasting of solar ‘weather’, such as the coronal mass ejections and solar flares. These events produce streams of radiation that are potentially hazardous to astronauts and equipment on the Moon, or on interplanetary flights, and also to power transmission and communications on the Earth. Space-weather monitoring on the Moon (hard radiation, particle, and magnetic environment, X-ray flux, UV/EUV sensors) can also be exploited for non-lunar space weather applications and for solar physics.

## 5.5 Other planets and planetary bodies

We cannot understand how the solar system formed and evolved without the study of the other planets and planetary bodies, nor can we hope to interpret measurements from extra-solar planets, orbiting other stars, unless we fully understand our own planetary system. Missions sending spacecraft to the other planets or on rendezvous with asteroids and comets are vitally important. But they are expensive and limited; missions to Jupiter, the giant of the solar system, for instance are restricted to one-per-decade events, or even less frequently. (Galileo reached Jupiter in 1995; JUNO will get there in the middle of the next decade.) So around the world, much of the work in planetary science is carried out using ground-based telescopes, such as those sited in Las Palmas, Hawaii, Australia and Chile. The Earth’s atmosphere limits what can be observed, however, because large parts of the spectrum are absorbed, and ‘seeing’ limits the spatial resolution of our observations. Great efforts have been made to overcome and minimise these problems: in Hawaii and Chile, high altitude observatories minimise atmospheric absorption; adaptive optics programmes battle to counter scintillation (twinkling) by the atmosphere.

All of the advantages of a lunar observatory alluded to in the previous section on solar and solar terrestrial physics apply equally to the study of our planetary siblings. And like the Sun and its interaction with the Earth, the processes amenable to our planetary studies are taking place in real time on objects that we can resolve spatially, such that we can understand the dynamic coupling involved: for example, solar *planetary* physics – a logical extension of solar terrestrial physics, and which is a particular strength in the UK – is providing deep insights into the interactions between the solar wind and bodies that are magnetised (e.g. Jupiter and Saturn) or unmagnetised (e.g. Venus and comets).

Among areas of planetary science that would make extensive use of lunar-based facilities are atmospheric physics and chemistry. The atmospheres of planets carry signatures that tell us about their origins and how they have subsequently evolved, which helps to develop our overall picture of solar system evolution. High resolution spectroscopy (particularly from the infrared right through to the microwave regions of the spectrum that suffer from absorption by the Earth’s atmosphere) is required to identify trace elements that can tie down the evolution of atmospheres. It is also required to measure winds generated by internal energy sources or – at the top of the atmosphere – by coupling to the planetary magnetosphere or the solar wind, a process that feeds fundamental parameters into solar planetary physics studies. Recent advances in measuring and modelling both persistent and variable auroral features on Jupiter and Saturn has enhanced our understanding of their magnetospheres and the plasma physics going on there.

However, much more needs to be done and the need to for detailed measurements is paramount: for instance, we do not understand why the atmospheres of giant planets are hundreds of degrees hotter than they should be, given the limited solar radiation they receive. Similarly, measurements of the erosion of the atmosphere of Venus by the solar wind pose the question as to why it still has an atmosphere at all. To understand the enormously dynamic and varied weather systems that planets exhibit needs spectroscopy to be combined with detailed global imaging; overcoming the restrictions of seeing will provide the opportunity to get measurements at the distance scales on which weather systems are forming and dispersing on a regular basis.

Some of the most dynamic objects in the solar system are the large moons of Jupiter and Saturn: Io is the most volcanic body we have ever come across; Titan and Europa are potential environments where life may have evolved. Specific missions to these bodies have included the Cassini-Huygens mission to Titan and more are being planned under the Cosmic Visions programme – the Jupiter-Europa Mission, for example. Inevitably *in situ* space missions will be relatively rare events. In the past, they benefited enormously from data obtained from Earth prior to the mission, as in the case of Titan: measurements of its atmospheric parameters were critical to the success of the Huygens landing. The opportunity to carry out monitoring at higher spatial resolutions and across the electromagnetic spectrum will greatly enhance the return on costly mission investment in the future.

## 5.6 Beyond the solar system

The solar and solar terrestrial physics section lists the advantages of using the Moon as a platform for siting a telescope that can make solar observations. Related arguments apply for instrumentation looking beyond the solar system, the most notable addition being that, as well as places in permanent sunlight, there are also regions of the Moon in permanent darkness, essential for successful astronomical observation. There will again also be the option for maintenance and upgrade supported by a future lunar base.

Telescopes on Earth are limited in their observations by many factors, practically all of which result from the presence of the atmosphere. Observational limitations arise from cloud cover and wind, the absorption of specific wavelengths by constituent atoms and molecules and the scintillation caused by temperature variations through the atmospheric column. It was an obvious step to place telescopes in space. Many significant discoveries over the past 20 years have resulted from observations using the Hubble Space Telescope (operating in the visible to near infrared regime); more recently the Spitzer Space Telescope (mid- to far-infrared) has added to the catalogue of findings. These telescopes have been inordinately successful, and replacements and complementary systems are in the planning and build phase, in particular the James Webb Space Telescope.

The telescopes named above are all single aperture instruments, and for such telescopes, there would be little advantage in siting them on the lunar surface. An alternative design of telescope is multi-aperture – or an interferometer – in which several (or many) collecting elements are spread over an area and the signals detected at each are combined together. It has been suggested that an interferometer could be deployed in space, as individual free-flying telescopes each communicating with a hub<sup>15</sup>. However, the technological requirements of maintaining the relative positions of the separate telescopes, to within the fraction of a wavelength required for interferometry, are very challenging. It seems likely, therefore, that Michelson interferometers, operating in wavelength ranges that are seriously affected by the Earth's atmosphere and ionosphere and hard to deploy as free-flyers in space, will produce their best astronomical results from the lunar surface. For example, a lunar interferometer, with a maximum baseline of ~100 m, would offer resolutions almost twenty times better than the James Webb Space Telescope and almost fifty times better than the Hubble Space Telescope. Such an instrument would be ideally suited for a range of exciting and challenging objectives associated with planets, stars and black holes.

Stars, and the possibility that there may be planets around them, have always been a prime focus of astronomers. While much has been discovered from a combination of the integrated properties of starlight and basic theory, the limitations of the Earth's atmosphere have prevented us from making detailed images of any star other than the Sun. Even the resolution offered by the Hubble Space Telescope is much too poor to see details corresponding to 1 AU (the radius of the Earth's orbit around the Sun) in stars and star-forming regions at a distance of 100 parsec (1 parsec, or pc, is about  $30 \times 10^{12}$  km, or 205,000 AU). Imaging stars and their environments in the optical and infrared, with the exceptional resolution provided by a lunar interferometer, is certain to lead to a deeper understanding and is likely to uncover new phenomena.

High resolution images of nearby stars will be dramatic. For example hot, massive, rapidly rotating stars can be expected to show oblate disks with dark, cooler, zones around their equators; such stars will follow different evolutionary paths from their slowly rotating cousins. Cool red-giants, on the other hand, are expected to show large convection cells appearing as dark 'star-spots' on the disk. As important in providing new information on stellar physics, such detailed multi-pixel images of our stellar neighbours will touch the public imagination in the way that Hubble Space Telescope images of galaxies and gas clouds have done.

One of the most challenging objectives of current astronomical research is the detection and characterisation of Earth-like planets orbiting within the 'Habitable Zone' of Sun-type stars. The Habitable Zone is the region where liquid water may exist on the planetary surface and is therefore favourable to the emergence or existence of life approximately as we know it. Therefore if this planet-star combination could be found, it would immediately be a focus for origin of life studies. The first extrasolar planet was reported in 1995; since then, over 200 additional planets have been discovered using ground-based telescopes and it is obvious that a sizeable fraction of all stars have planetary companions. Unfortunately, because of limitations in the various techniques employed to detect the planets, most of the bodies discovered so far have been 'hot Jupiters' – gas giants circling in orbits closer to the central star than Mercury is to the Sun. It is clear that planets like these are unlikely to host life. Most recently, the

Spitzer Space Telescope has observed a planet approximately 5-6 times larger than the Earth, and inferred a composition for its atmosphere. This measurement was pushing extant technology almost to its limit. In order to make major advances in the detection and study of extrasolar planets, we must turn to interferometry.



**Figure 7 The Moon may make a useful base for high-resolution telescopes to detect Earth-like planets beyond the solar system (Artist's impression NASA)**

The Sun is about ten billion times brighter than the Earth at visible and near-infrared wavelengths. In order to stand any chance of success in the search for other ‘Earths’ one must minimise the effects of this ‘glare’ by concentrating the light of both the planet and the star into the smallest possible points, thereby allowing them to be detected separately. This is the enormous advantage of space-based systems operating in the absence of atmospheric scintillations. But the technical challenges referred to above make it clear that interferometry from the Moon is likely to be the most fruitful way by which the study of extra-solar planets can progress. Only the resolution offered by ~100 m baselines provides the critically important potential to discover terrestrial planets by direct imaging and subsequently to characterise them by spectroscopy of their atmospheres. A 100 m instrument may allow the detection of Earth-like planets around hundreds of solar-type stars at distances up to 100 parsec. This is an undertaking of the utmost scientific and philosophical importance.

Beyond the Milky Way Galaxy high resolution imaging is also urgently required to transform our knowledge of massive black holes (MBHs) in the nuclei of galaxies. It is widely accepted that active galactic nuclei are powered by accretion of matter onto MBHs, and the observed evolution of the space density of Active Galactic Nuclei implies that a significant fraction of *all* luminous galaxies must host MBHs in their nuclei. These MBHs have masses in the range  $10^6$ - $10^{10}$  times that of the Sun and are relics of past activity. With the advent of the Hubble Space Telescope and ground-based telescopes with adaptive optics, advances have been made in our understanding of the nuclear regions of galaxies – and in recent years there has been a progression from MBHs as a theoretical requirement for the energetic phenomena in active galactic nuclei to direct estimates of their masses. Currently there are roughly 40 galaxies where a MBH has been detected and correlation with other physical attributes of the host implies that the history of MBHs is tied to the history of the formation of the galaxy. To get a complete view of galaxy evolution we therefore need to understand the role played by the central MBHs.

The reason MBHs remained a theoretical requirement rather than an observational reality for so long was because of a lack of resolving power. To detect a MBH with confidence, we need to probe the region – the *sphere of influence* – within which the MBH dominates the galactic dynamics. A typical scale for the sphere of influence is ~10 pc, tiny compared with the size of galaxies. It is important to note that of the

~40 MBH mass measurements so far, for only two of these galaxies (our Galaxy and NGC4258) is a massive black hole *the only option*. For all the other cases it is still possible to construct a model where the central mass consists of combinations of other dark objects – for example stellar mass black holes and neutron stars. A lunar interferometer offering tens of times the resolution of the Hubble or the James Webb Space Telescopes will allow us to constrain the distribution of the dark mass to within volumes so small that a black hole is the only physical possibility and would probe their mass function 1-2 orders of magnitude further down than existing facilities can.

We believe, therefore, that an optical/infrared interferometer on the lunar surface will provide transformational science and should be the highest astronomical priority. There are, however, many other astronomical projects that would benefit greatly from interferometric observations from a lunar platform. And in two other wavelength regimes the technology is already feasible.

*The sub-millimetre or terahertz regime (~500 GHz to ~5000 GHz):* in which the radiation is absorbed principally by water vapour in the Earth’s atmosphere. Here the science goals range from the physics of cold matter at a few Kelvin (e.g. the Cosmic Microwave Background Radiation) to the physics and chemistry of cool (tens of Kelvin) dust and gas in the Galactic interstellar medium and in star and planet-forming regions in our own and distant galaxies. The lack of atmosphere and the possibility of passive cooling of receiving systems and optics to tens of Kelvin are advantages of lunar over Earth-based systems but competitive interferometer systems will be large and complex. There is also much high resolution sub-mm science to be done with the ground-based ALMA, operating up to ~1 THz, and lower-resolution exploration of the higher frequency part of the regime with single apertures such as the aircraft-borne SOFIA and the space mission Herschel. For these reasons we think that planning a lunar-based sub-mm interferometer is premature.

*The very low frequency radio regime (<20 MHz):* this is close to, or below, the ionospheric plasma frequency and hence this radiation is largely inaccessible from the Earth’s surface. An exciting cosmological goal is to image the 21 cm line emission of atomic hydrogen at very high redshifts ( $z \sim 60$  to  $z \sim 300$ ) to probe the growth of structure in the universe following the decoupling of the Cosmic Microwave Background Radiation at  $z \sim 1000$ . The lunar far-side is free of any artificial interference or ionosphere and is therefore the ideal location for such an instrument. Major hurdles to overcome are: a *minimum* collecting area of ten square kilometres; the need to subtract out both the diffuse Galactic emission and the emission from discrete sources; and an extreme dynamic range ( $>10^8:1$ ) requirement on the overall system. Major ground-based systems (e.g. LOFAR and later the Square Kilometre Array) are now being deployed to explore wavelengths down to a few tens of MHz and it will be sensible to gain experience with these systems before proposing the next step onto the Moon.

## 5.7 Fundamental physics

In addition to being a base for an astronomical observatory, the Moon might act as a site for testing certain principles of fundamental physics, and there are at least three areas where a lunar base might help to advance the field. A lunar observatory could be employed to test Einstein’s theory of gravitation, as well as to carry out projects in high energy cosmic radiation and neutrino physics.

### 5.7.1 Gravitation

The huge interest in dark matter should not obscure the fact that there are alternative ‘explanations’ built around attempts to modify gravity on cosmological scales which also attempt to account for the apparent acceleration of the Hubble expansion. Cosmologically motivated theories that explain the small acceleration rate of the universe via the modification of gravity at very large, horizon, or superhorizon distances, can be tested by precision gravitational measurements at much shorter scales, such as the Earth-Moon distance. Precision measurements of the Earth-Moon distance may also be used to test Einstein’s theory of General Relativity. Laser-ranging devices, in which pulses of light sent from Earth are reflected back from a mirror on the Moon’s surface (placed there by the Apollo astronauts) enable precise measurement of the distance between Earth and the Moon. One of the shortcomings of the present set-up is that the reflector arrays on the Moon are limited in size, and thus the amount of light reflected back greatly reduced. The presence of a lunar base would allow banks of reflectors to be placed in several locations, giving orders of magnitude improvement in precision – not least because robotic (or human) operatives could keep the arrays clear of dust.

### 5.7.2 High energy cosmic radiation

Cosmic rays include protons, with energies up to around  $10^{10}$  eV (solar) or  $10^{15}$  eV (galactic). There are also families of ultra high energy cosmic rays (UHECRs) that are thought to be from heavier nuclei, with energies to at least  $10^{20}$  eV. The exact sources of these extragalactic UHECR are unknown. On Earth primary UHECRs are attenuated by interaction with the atmosphere, producing showers of secondary particles that are detectable at the Earth's surface. The Moon can be used for the detection of UHECRs – it can act both as a giant collector of primary cosmic rays, and also as an observatory for cosmic rays striking the Earth's atmosphere. Detection of an UHECR hitting the surface of the Moon will not be assisted by the formation of air showers (as there is no atmosphere), so extended arrays will be needed to detect the faint Cerenkov radiation emitted as the particles penetrate the lunar regolith. On Earth, Cerenkov radiation is generated within enormous tanks of ultra pure water, and then detected by sensitive photomultipliers. On the Moon, the lunar surface itself would act as the dielectric for production of Cerenkov radiation, and so arrays of photosensitive detectors could be arranged in shadowed areas.

### 5.7.3 Neutrino observations

Neutrino astronomy would benefit from being carried out in a location where interferences from atmospheric neutrinos are eliminated, so, for example, a lunar observatory might be used to search for neutrinos from supernovae. Other potential projects include study of the neutrino complement to UHECRs: ultra high energy (UHE) neutrinos, which should also be detectable at the Moon's surface. In the same way that UHECRs produce Cerenkov radiation (emitted in the visible region of the electromagnetic spectrum) when they impact the lunar surface, muons from UHE neutrinos produce radiation in the sub-millimetre to radio region of the spectrum. This is the Askaryan effect, which has been predicted, but not yet detected on Earth because the pulses of radiation are too small. Experiments are presently underway to improve the sensitivity of the Earth-based experiments, but a suitably-sited radio telescope (or interferometer array) on the lunar surface should also be able to pick up the signals.

While it is unrealistic to suppose that any of the above experiments would be proposed as motivation for a lunar base, were such a laboratory to exist, then it is probable that it could inspire serious research in these areas.

## 5.8 Space life and medical sciences

Space life sciences must be an integral part of any future space exploration programme because, eventually, there will be human outposts on the Moon and Mars. There is a whole suite of experiments that can be undertaken in the low gravity of the Moon, as well as in the microgravity environment of the International Space Station (ISS) that are to the benefit of human health on Earth. The field of space life and medical sciences has developed rapidly over the last decade. As the number of astronauts flown increases, so too has the biomedical science database and with it our understanding of the true value of microgravity as a tool and the space environment as a test facility. The UK boasts many world-class facilities in medical research. If properly interfaced with the existing wider international programme of space life sciences, there is no reason why these UK centres of excellence should not play a leading role in the future of space medicine. Of the disciplines related to space exploration, space medicine and programmes of human spaceflight have perhaps the greatest potential to yield tangible benefits to everyday healthcare.

Medical science advances through a different process from that of the other disciplines more traditionally



**Figure 8** Medical experiments on the ISS will prepare the way for human space exploration and will have benefits for patients on Earth (Image NASA)

associated with space research. The interactions of behavioural, environmental, biological and pathological variables complicate the study of all living systems. Because of this, unusual stimuli are valuable in generating new hypotheses. Reduced gravity and microgravity represent unusual stimuli for several biological systems. Significant advances have been made in the field of neurovestibular (balance and locomotion), cardiovascular and musculoskeletal physiology (bone and muscle loss or gain) through the study of the interaction of these systems with the space environment. The perturbation of physiological systems can now be analysed and modelled, identifying the fundamental properties of systems at the level of the whole body, as well as at the cellular and sub-cellular level. At the cellular level there have been many important discoveries, including contributions to research in the field of Human Immunodeficiency Virus (HIV), immune function, the spread of tumour cells, the artificial synthesis of organs and the cell signalling mechanisms involved in the remodelling of bone through osteoporosis.

A programme of microgravity experiments allows physiological systems to be looked at in new ways, yielding unique data. In turn this generates new hypotheses that are then tested through extensive ground campaigns. Much of medical science relies upon advances of this type, with hypotheses generated by study of pathological changes in small sub-populations followed by larger scale studies and extrapolation to the general population. There are several areas of scientific research that would benefit from being carried out in a low gravity environment such as the Moon:

- In biology, the ability to conduct experiments with normal, low and zero gravity allows the cellular, genetic and molecular basis of signal transduction to be studied since this gives the unique possibility of being able to switch on and off one signal without the interference of side-effects. It seems that cells interact differently in weightless conditions – microgravity will therefore help provide fundamental understanding of inter-cellular signalling.
- Studies of bone growth and loss reveal similar chemical markers in cultures held in microgravity to those found in patients with osteoporosis on the ground. The unique environment of microgravity provides a new variable with which to investigate all of these processes. The need to survive long journeys will spur this research, which may help to reveal fundamental processes related to aging (such as bone loss) and muscle deconditioning (with applications to critical care).
- Studies of human physiology in the space environment are also of fundamental importance in the context of the future human exploration of the Moon and Mars. As noted in the sections above, the human exploration of the Moon and Mars is expected to yield significant scientific results not obtainable in any other way. However, from the point of view of planetary field geology, it is essential to have *healthy* human crews operating in these environments, and this will necessitate research into developing whatever countermeasures to long-term exposure of human beings to the space environment may prove necessary. Much of this work can be performed in the near future on the ISS, and in the longer term would further benefit from access to a lunar base and associated infrastructure.

## **5.9 Exploration with robots or humans**

A pivotal technical question is, ‘Why do we need humans; why not just use robots?’

For science the concern is whether, as a result of investing in a human space infrastructure, fundamental questions can be answered that would otherwise be impossible. Thus the challenge is to decide what questions need to be answered and then determine what combination of humans and robots is best. Different classes of questions are optimally tackled by different approaches – some can be answered by robots *in situ*, often interacting with humans on Earth; others might require human presence at the site.

A single well-defined task at a single well-defined location can generally be automated successfully, but as the task becomes more complex, the time for autonomous operation before human intervention is required decreases dramatically. Defining issues for using stand-alone robots are: (i) how long can autonomy be given to the robot; (ii) how big a perturbation from the norm can be tolerated? The answers to these questions determine whether human presence is needed. Qualitatively one can summarise that ‘machines are not good problem solvers’.<sup>16</sup>

Humanity has evolved to be a highly flexible problem solver, optimally adapted to dealing with the unexpected by drawing upon a huge database of personal and collective knowledge: pattern recognition skills; libraries of information gathered over decadal time-scales; rapid acquisition of samples and an

ability to recognise data to be of importance which were not part of the original programme. When searching for unusual objects on the Moon or Mars, humans can think and act laterally in ways that robots cannot.<sup>3</sup> Automation can be much more sophisticated and the tasks much more complex if there are humans on site to guide real-time operations and act as problem solvers. The longer that it is necessary to maintain autonomy, the greater is the probability of encountering a problem that needs to be solved.

A more detailed comparison of the relative efficiencies of human and robotic exploration of planetary surfaces is given in Appendix E.

## **5.10 *What are the consequences of not undertaking the programme?***

Throughout this chapter, we have identified several key areas in which UK science has special strengths and skills enabling UK scientists to take leadership roles. However, this would only happen if we were a partner in the Global Exploration Strategy of which the UK has so far been a prime mover. We consider it essential to retain that position, and capitalise on it, in order to provide an exciting and inspirational national research and technology development programme.

## **5.11 *Summary***

One of the main science drivers for the UK to be part of the Global Exploration Strategy is to understand the origins of life, and to search for life beyond Earth. Although we have made great progress towards answering these questions over the last decade, it is only by playing a full part in a global exploration programme that we will be able to continue our advances in understanding. Moreover, we have also identified other scientific areas that can take advantage of UK participation in a global exploration programme – both human and robotic. For example, the construction of a lunar base would enable exploration of the surface to elucidate the history of the Moon and of the solar system, while at the same time opening up the unique opportunities for astronomical observations and gaining operational experience that will one day be required for the human exploration of Mars. Our understanding of the universe, and our place in it, will be increased immeasurably as a result of these activities.

The science goals outlined above would provide an ambitious framework to stimulate technological and engineering advances, and also inspire the young to take greater interest in science and technology. It is clear that the science research goals of an exploration programme inform technology, commercial, education and outreach activities.

***Recommendation:*** **We recommend that the UK should maintain its leading involvement in planetary science within ESA Programmes and, where appropriate, in collaboration with other international partners. This must include continued involvement in the robotic exploration of Mars, especially through ESA's Aurora programme.**

***Recommendation:*** **Noting the Government's response to the Microgravity Review in 2004,<sup>17</sup> we recommend that the UK should investigate the current opportunities offered by a modest focused subscription to ESA's microgravity programme which could facilitate UK access to ESA's microgravity facilities. This would build up the UK life and physical sciences microgravity community in preparation for the longer term opportunities that will arise from participation in the GES.**

## 6 Technology and knowledge exchange

### 6.1 Vision

Our vision for technology and knowledge exchange through engagement in space exploration is the maximisation of benefit to the UK economy through the development of a generation of skilled engineers, the business opportunities afforded by space, and wider terrestrial applications of the technologies generated in support of UK participation in a programme of space exploration. This UK contribution centres around thirteen identified technology areas in which the UK should invest to demonstrate end-to-end instrument, platform and operations competences.

It is evident we are at a turning point in the formation of strategic engagement in space exploration. If the UK does not participate in this endeavour, we shall save money in the short term, but lose potential for our knowledge-based economy in forming technology collaborations with other nations, leadership in selected technologies and opportunities for wider economic benefit. We accept that the picking of winners presents a substantial investment risk in its own right, but note the failure to invest guarantees we lose the opportunity of gain.

The background and development of these ideas form the substance of this chapter.

### 6.2 Introduction

Technology plays a vital role in consideration of UK participation in a space exploration programme. Through its support of ESA and its industrial and academic base, the UK has a variety of current and potential technology strengths that it could offer any wider space exploration programme. The proactive development of these technologies will benefit the UK academic and industrial engineering base and provide opportunities for greater exploitation and transfer to other terrestrial markets. Enhancement of technology capabilities in support of space exploration brings several benefits:

- Participation of UK industry in supplying to the programme.
- Direct enhancement of industry and academic capability and the related engineering and technical skills base.
- Technology spin-out to substantial terrestrial markets.
- Enabling down-stream applications of space technology using the platforms, data and knowledge generated in the programme.



The possession of technology capability is a prerequisite for deriving the benefits of wider exploitation. We expect that strength in delivering end-to-end instrument, platform and/or mission capabilities will be required if the UK is to be an effective partner in international missions and if it is to secure leadership in selected areas. Our task has been to examine areas of technology in which the UK has, or could develop, distinctive capabilities in support of a space exploration programme and to map these against likely substantial wider markets. We have assessed these technologies against likely mission and collaboration scenarios in order to provide a recommended course of action.

**Figure 9 A Mars Sample Return mission will require extremely demanding technologies in robotics, sample handling and planetary protection, all areas of UK technological expertise (Artist's impression ESA)**

## **6.3 Technologies for UK participation in a space exploration programme**

### **6.3.1 Distinctive UK contributions to a space exploration programme**

Four technology categories relevant to space exploration were recognised. These are areas in which the UK has, or could enhance:

1. leadership or strongly participative positions based on the current space industry, e.g. small satellites, scientific instrumentation, mission operations;
2. leadership or strongly participative positions where our current capability resides in ‘parallel sector’ companies whose main markets are aerospace, defence, transportation, energy or mineral exploration, e.g. novel materials, energy sources;
3. niche leadership positions, e.g. planetary protection; and
4. contributions to projects led by other countries, e.g. large space optics.

The following assessment focuses on technologies that are relevant to the first three categories, since these offer the best opportunities for the UK.

### **6.3.2 Technology categories with space sector leadership potential**

Low cost missions	The UK has demonstrated world-class capability in developing low-cost platforms, building instrumentation and supporting their end-to-end operations. This leadership spans a distributed industrial and academic base that affords a number of possibilities for targeted (often service-driven) solutions, including telecommunications, navigation/localisation, <i>in situ</i> sensing and miniaturised devices.
Scientific instruments	The UK shows leadership in many areas, with a strong and distributed academic and industrial base. It has shown the ability to partner with other countries to achieve its science objectives through selected leadership and technology supply in scientific instruments. Particular competence has been shown in ruggedness, miniaturisation, instrument engineering and component technologies.
Software systems	The UK is a European leader in the development of robotic space exploration software systems – for both on-board satellites and ground based command and control systems. These currently underpin increasingly automated systems and smarter user interaction. UK experts are developing the software standards for cis-lunar and Mars space communications networks.
Entry descent and landing	The UK has distinctive capability in the design, development and implementation of entry, descent and landing elements for atmospheric targets such as Mars or Earth re-entry. UK industry and academia are particularly strong in modelling both atmospheric conditions and design processes.
Communications and navigation	We are well-positioned in European collaboration with a demonstrated expertise in small satellites and particular strengths in communications payloads and navigation technologies.

### 6.3.3 Technology categories with parallel sector leadership potential

Autonomous systems and robotics	<p>The UK is a European leader in autonomous systems and associated platform and instrumentation technology including robotics. Capability is held within the space, defence and aerospace sectors. Space applications to date have focused on cooperative orbiters, rovers, smart sensors and intelligent tasking. More recent developments address management across distributed systems. The UK could reach advanced status with further investment.</p> <p>The thriving UK robotics community can offer technology benefits into space exploration (for example manipulation of non-cooperative objects, multi-networked crew-aids, arm developments and visualisation and validation centres).</p> <p>The UK has world-class academic strengths in non-space autonomous systems for air, land and sea applications and industrial capability distributed across a number of companies. We can build rover platforms, heading towards automated vehicles and unpressurised vehicles, and could reach advanced status including pressurised vehicles with sufficient investment. Nobody in Europe is on a par with the USA so 'grand challenges' are required to advance our capability.</p>
Materials and structures	<p>The UK has selective leadership in intelligent structures, lightweight materials and distributed sensor/instrumentation networks. Enhancement of capabilities driven by space exploration will have a high likelihood of impact in terrestrial applications.</p>
Energy generation and storage, environmental resource management	<p>We have existing world class capability in space power generation and storage, significant government and industrial investment in new and renewable energy sources and means of conserving energy and resources such as water, waste and hazardous gases.</p> <p>This technology area can offer exciting potential synergy with terrestrial environmental and energy resource requirements. It is important to explore the distinct roles of low power (few watts) and high power (100-1000 watts) energy sources for space exploration and terrestrial exploitation.</p> <p>The UK has capability in nuclear energy fuel sources which could be used in space exploration although policy considerations have prevented their deployment in the past. This policy should be re-examined in the context of a new space exploration strategy.</p>
Aeronautics	<p>The UK has capability in transport aeronautics that may be applied to space exploration, e.g. cockpit developments and support aids, training systems and wing design.</p>
Geophysical exploration	<p>The UK has geophysical capabilities (academic, small and large industry) in exploring for minerals and other resources under the surface of the Earth which may be adapted to exploration under the lunar surface.</p>

### 6.3.4 Technology categories with niche leadership potential

Planetary protection	Planetary protection is a vital area in which the UK should retain its world-leading expertise.
Propulsion	The UK has capability in niche propulsion technologies that are considered valuable for space exploration.
Human physiology and biotechnology	There is strong aerospace/defence interest in human reaction and adaptation to extreme conditions, and UK strength in medical research that would be major beneficiaries of UK engagement in a human space exploration programme. There are potential benefits to terrestrial medicine resulting from advances in diagnostic and therapeutic technology as well as expertise in radiation dosimetry and protection required in support of human space exploration.

### 6.3.5 Which technologies really need space exploration as a catalyst?

A key objection to the argument for public investment in space technology research and development is that the innovation required may be achieved with less expense on Earth. We have not found evidence to support or contradict this assertion. Nevertheless, space as a scientific, technical and industrial challenge provides a strong catalyst for innovation, technology exchange and industrial leadership in a number of key areas that gain crucial advantage from demonstration in the space environment.

The technologies described above should all find terrestrial application. The following would benefit most from the extreme challenge of the space environment as a test bed:

- Autonomous systems.
- Miniaturisation, reliability and robustness of sensors and instruments including radiation performance and protection.
- Energy generation, storage and resource conservation / utilisation.

### 6.3.6 Terrestrial applications of technology developed for space exploration

There is evidence of substantial ‘spill-over’ economic impact of investment by the UK and other countries in space, although it is hard to predict exactly which technologies will yield the greatest impact

Markets	Space	Parallel Sectors				Other Market Sectors								
		Other Space	Defence, Security	Aerospace	Transport	Oil & Mineral exploration	Power	Materials	Manufacturing	ICT	Healthcare & Life Sci	Financial Services	Food Production	Entertainment
Technologies		H	H	H	H	H	H	H	H	H	H	H	L	
Structures & Materials		H												
Protection		H	M	M		M			L					
Propulsion		H	H	H	H		M							
Power		H	H	H	H		H		H	H	L		L	
Thermal Controls		H	H	H	H	H	H	H	H	H	M			
Avionics and Software		H	H	H	H	M	M			M	M	L	L	
Environmental Control & Life Support			L	L	L				H	H				
Crew Support and Accommodation			M	M	L					M		L		
Mechanisms		H	H	H	H									
In-Situ Resource Utilisation		L	H	L	M	H	L	L	L					
Analysis & Integration		L	L	L	L									
In Situ and Surface Operations		M	H	H	H	H								

H = High Potential

M = Medium Potential

L = Low Potential

Blank = No potential / unknown

**Figure 10 Impact of exploration technologies to other industry sectors**

through future investment. Nevertheless, an initial mapping of the likelihood of impact of the selected technologies in various industry sectors is presented. This highlights key opportunities in defence,

security, aerospace, transport, power/environment, oil and minerals and advanced manufacturing.

Support by the relevant funding agencies through Knowledge Exchange Services and Knowledge Transfer Networks should be provided at an early stage in mission scenario selection and implementation. This will enable understanding and initial quantification of the wider benefits, and then to realise them through active embedding of knowledge exchange in the space exploration programme. We have not considered ‘downstream’ applications of technology, data and know-how generated in the programme.

### **6.3.7 Engaging with other sectors**

Engagement with a variety of industry sectors during our enquiry led to the following conclusions:

- Engagement with the existing space sector is routine, as the companies are well networked and see future business in space
- Several of the technologies listed above must be sourced from companies in ‘parallel’ sectors, e.g. defence, aerospace, transport, oil and mineral exploration, energy, environment, etc. Engaging these companies requires space to be seen by them as a viable market. This requires clearly targeted preparatory technology development in the areas identified for UK contribution
- Plans to maximise the benefits of ‘spillover’ knowledge transfer must be built into the space exploration technology programme
- Wider applications with substantial economic impact will flow from this technology capability. Although exact prediction is difficult, areas of likely transfer have been identified. Support through knowledge exchange activity in the funding agencies is vital to realise this potential.

## **6.4 Critical technology areas**

### **6.4.1 Current UK technology focus**

The UK has a strong heritage in funding and exploiting robotic space systems over many years. The UK has particular strengths in autonomous systems’ technologies, which could support global space exploration missions. Based on discussions with experts in this field we consider these strengths to be well matched to the science data gathering requirements planned for the robotic lunar and Mars missions currently being considered. Furthermore we are confident that autonomous systems, given time and support, can offer a cost effective route to many future aspects of space exploration. Importantly this technology also has terrestrial potential and in our opinion justifies additional investment to ensure this becomes a cornerstone of the UK contribution to international space exploration.

However, over the next twenty to forty years, many requirements posed by mission scenarios will exceed the capability of autonomous systems. Here scientists and engineers operating *in situ* are the only solution. Fortunately the UK can build on its strengths in robotic space exploration and related technologies in support of these human missions. However to substantively exploit new and emerging technologies associated with direct human space exploration, the UK will need to invest additional effort over the next 5-10 years (if not sooner).

### **6.4.2 Energy generation and storage, and environmental resource management**

Government, industry and academic research groups are all responding to the challenges of efficient power generation, storage, distribution and conservation of energy in systems to prolong utility. The demand for utility management extends to other resources such as water, air and to waste products. Studies have already been undertaken for a number of space exploration mission scenarios and the UK has strength in certain technologies, but many uncertainties and trades-off remain.

The challenges of resource management in space exploration offer extreme versions of the issues faced on Earth. We regard this as a significant area with strong existing niche academic and industrial capability. Further investigation of this area is warranted as it is prime for spin-in and spinout, according well with parallel interests elsewhere in the UK technology strategy.

### **6.4.3 Radiation aspects**

We have concluded that within the parameters of cis-lunar, lunar and Martian exploration, the radiation issues for robotic exploration appear to be tractable over the next twenty years. Further research into the

biological effects of radiation is required to gain confidence in human surface operations on the moon or for travel to Mars. It is important to sustain existing systems that warn of solar radiation storms and to increase the warning times available from such systems. Nevertheless, these concerns are not regarded as insuperable.

## **6.5 Level of engagement with the Global Exploration Strategy**

We considered the following groups of engagement scenarios:

- Status quo.
- Enhanced participation in robotic missions (e.g. lunar, Mars).
- Full GDP participation in a human spaceflight programme.

### **6.5.1 Status quo**

Status quo is continuation of the UK's current policy, which is participation in the robotic elements of ESA's Aurora programme only. In this event, the UK should continue its tactics of limited national technology funding, as established for ExoMars, to secure targeted leadership in specific areas.

### **6.5.2 Enhanced participation in robotic missions**

This group of scenarios covers several mission possibilities driven by exploration, commerce and science. These have investment scenarios from incremental increases towards a much stronger participation in robotic space exploration missions that need and build our capabilities providing strong industrial return.

The best approach for the UK is to use our robotic space expertise in missions in and beyond Aurora. This means being 'on the surface' as well as remote sensing. If the increment in investment is substantial, the UK could offer its capability in the variety of technologies listed in section 6.3.1 to other agencies in order to advance its objectives. If these capabilities have been developed to become world-class instrument, support and platform capabilities the UK would be in a strong position to secure a substantial place in these missions. The UK could offer certain end-to-end mission capabilities based upon small satellites and this would be attractive to other agencies.

This scenario is not incompatible with limited participation in human space missions although it does not include the development of technologies in contribution to such missions. Indeed a strong approach to the development of the technologies described earlier in support of robotic space exploration will provide the UK with the potential to participate in human space exploration, albeit in support of those agencies who are leading missions.

### **6.5.3 Full GDP participation in human spaceflight**

In this scenario, we considered the potential for full commitment by the UK to human space missions. The key constraints on such scenarios are that the UK will invariably be a contributor of component technologies, instruments, platforms and support services to an international collaboration. There will be limited scope for UK leadership.

## **6.6 Current and potential strengths**

After examining the three scenarios (previous section), it is clear that:

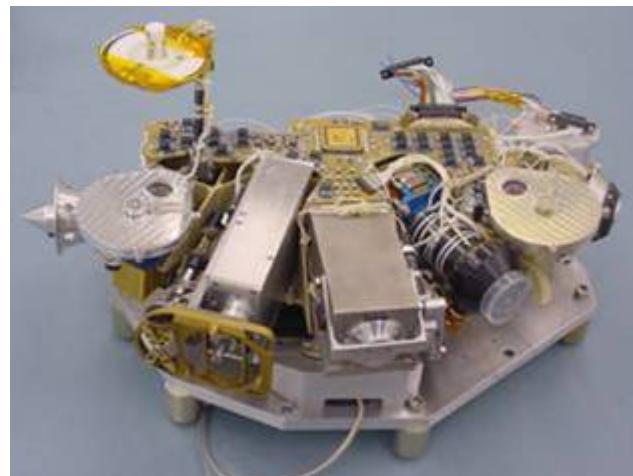
- continuing as we are (i.e. the Aurora robotic elements) will permit the UK to secure a positive position for space exploration technology and knowledge exchange but this position will be eroded as other countries progress similar and more ambitious programmes;
- there is opportunity for substantial benefits in pursuing a more proactive participation in robotic spaceflight technologies; and
- if we participate in a human spaceflight programme, we should seek out niche leadership roles.

Based on UK strengths, return on investment is thus most likely to be maximised by ambitious but selective development of robotic spaceflight technologies. The UK leadership should be developed at the system rather than sub-system level, embracing instruments, platforms and operations. For example the development of precision landing techniques, surface landers, rovers and their sensor suites, surface operations, sample return solutions and local communications and navigation services.

This approach is not surprising – the UK has championed many robotic space technologies over the past twenty years since its industry and scientists have not taken part in human space activities and so this is now largely the technological domain of others.

Any decision to participate in human spaceflight will be driven by factors in addition to maximisation of technology and knowledge exchange – for example, political, scientific, societal and commercial. In this event, the UK can offer its capabilities in support of such missions and:

- use these strengths to secure scientific participation, and also astronaut places;
- develop additional technology elements in support of human missions whilst recognising this may offer a lower financial return on investment (e.g. from robotic to pressurised rovers);
- obtain additional spin-out benefits, particularly in the field of medicine.



**Figure 11 The Beagle 2 PAW exemplifies the UK expertise in miniaturised instrumentation (Image Beagle 2)**

## 6.7 Collaboration scenarios

To exploit our position to best effect, the UK should partner with agencies offering complementary elements to ours. This will allow us to play to our strengths, form closer industrial links with the recently industrialised nations and leave us with freedom to use the resultant technology and know-how. We considered a range of scenarios including participation through ESA, NASA and other space agencies as well as missions that could be wholly or substantially led by the UK. We conclude that:

- There are political, economic and knowledge exchange benefits in partnering with other nations and we should look in particular to the emerging ‘super-economies’ for opportunities.
- The ESA collaboration path is well established although we must seek UK leadership and industrial benefit.
- Our interaction with NASA showed a great deal of openness and willingness to adopt UK technologies within US missions.
- The establishment of international collaborations will be influenced by downstream use and access to market (e.g. ITAR in US, respect for IP in China). Limitations on access to market for supply and freedom to use technologies should be key considerations in formation of alliances.
- Strength in UK technology capabilities will enhance our position in deriving the benefits we desire from space exploration.

## 6.8 Mission scenarios

We propose the following sequence of missions in support of the scenarios proposed for lunar exploration. It is important to note that scenario selection and sequence is merely representative and should not be taken as definitive. In practice they will be led by scientific, commercial and societal goals and limited by technology capability. These scenarios are thus intended to support the goals proposed by others and reflect the critical technology developments that could be offered by the UK. Technologies are presented in the same categories as in section 6.3.

Comsat	A mission to validate a low cost communications satellite platform and its operational performance. It may conduct some remote sensing science. Such a mission could be controlled and operated from the UK.
Lander	A mission to validate precision entry, descent and landing which may operate in conjunction with a lunar communications satellite. The lander may deploy a science network (seismology etc.) and could feature Earth oriented payload for operation and control by UK scientists and schools. Resource management strategies will be trialled.

UK Space Exploration Working Group

Rover	A mission to validate a low cost rover network. It may operate in conjunction with a lunar communications satellite and lander/delivery device. The focus would be to autonomously deploy a telescope/sensing network/probes over a sizeable surface area and/or to demonstrate the retrieval of a lunar sample back to a central lander. An alternative topic could be autonomous drilling/mining.
Sample return	A mission to validate a low cost micro-sample return strategy comprising small sample canister, its ascent propulsion and RVD with an in-situ sample collection and return platform. Such a mission would contain a small rover for sample determination and return. It may operate in conjunction with a lander, comsat and robotic network.
Pressurised rover	A mission to transport geologist astronauts across the lunar surface. The rover would be delivered remotely using other nations' delivery systems. It would house the astronauts in a pressurised vessel and would utilise imaging sensors on the rover to select and plan sampling strategies for efficient astronaut EVA. Both high data rate and high power energy management systems will be trialled.
Facility	A lunar equivalent of the British Antarctic Survey stations. It will be a working facility of science payloads, test beds and transport devices that initially operate autonomously under earth supervision but which later incorporate human tended activity (for example with the geologist astronaut). The technology developments are many and varied but would exploit the automated delivery and mobility systems developed earlier as well as in orbit data communications

See chart on next page for an overview of associated technology requirements.

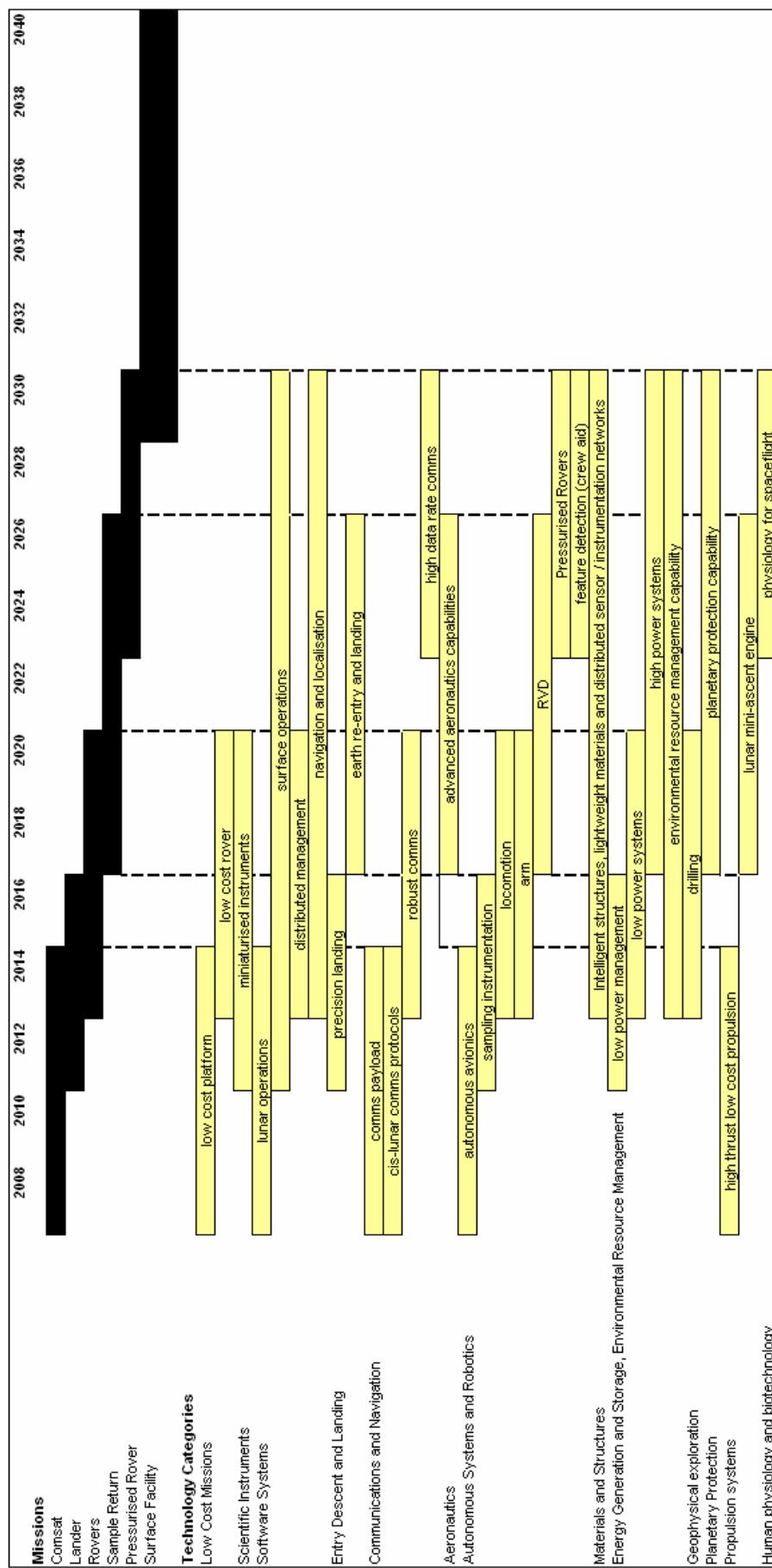


Figure 12 Timeline of technology requirements for lunar missions

## 6.9 Summary and recommendations

As far as technology and knowledge exchange are concerned, the best return on investment would be achieved by substantially increased investment in the robotic elements of space exploration, securing end-to-end capability at instrument, platform and/or mission level. This approach would build on current UK strengths that are already recognised by other space agencies and prime contractors, leading to the greatest potential for UK industrial and academic leadership. The degree of leadership will depend on the level of investment and mission selection.

It is important to note that the benefits accruing are dependent on mission scenarios that will probably be driven by exploration, commercial and scientific goals. Missions incorporating surface exploration and remote sensing appear to be the best matches for UK strengths.



**Figure 13 UK robotic rover technology demonstrator under test in Tenerife (Image EADS Astrium)**

The benefits of participation in the human elements of space missions could be gained through participation in bi/multi-lateral projects by contributing technology development in support of component and related robotic/platform technologies. This might mean, for example, supplying platforms such as rovers (human or robotic), communications and control infrastructure, and key component technologies in return for human spaceflight opportunities and activities.

The potential value of contracts, jobs created, increase in the engineering skills base, advancement in technology domains and knowledge exchange potential should be studied alongside any selected mission scenario, using the technology domains

discussed in this document as a basis.

The relevant funding agencies should provide support through their Knowledge Exchange services and Knowledge Transfer Networks at an early stage in mission scenario selection and implementation. This will enable understanding and initial quantification of the wider benefits, and their realisation through active embedding of knowledge exchange in the space exploration programme.

We propose that the UK should:

- Fund a programme of technology capability enhancements, grand challenges and technology demonstrators. It should:
  - Set technology ‘grand challenges’ to stimulate innovation and competition.
  - Ensure sustainability of the programme for the long-term development of exploration related technologies and the associated engineering skills base.
  - Embed knowledge exchange potential into the project selection, monitoring and output of each project to secure the greatest possible wider economic impact.
- Select and fund a sustainable programme of robotic missions at a level determined by the exploration, science and industrial goals of the space exploration programmes.
- Target areas for investment in which the space sector already has competences and thus form natural foci: autonomous systems and robotics, cost effective platforms, scientific instruments, software systems, entry descent and landing, communications and navigation.
- Conduct further detailed investigation into the potential for applying technologies from other sectors in the space exploration programme. The following areas could be of considerable potential: energy generation and storage, including nuclear power, environmental resource management, materials and structures (including intelligent structures, lightweight materials

and distributed sensor / instrumentation networks), aeronautics, and geophysical exploration. We believe power generation, storage and environmental resource management could offer exciting potential synergy with terrestrial environmental and energy resource requirements.

- Maintain niche areas that provide distinctive UK competence: planetary protection and propulsion systems.
- If the programme includes UK participation in human spaceflight, other technologies should be addressed, such as: crewed rovers and logistics vehicles and niche areas of human physiology and biotechnology.
- Develop strength in delivering end-to-end platform and/or mission capabilities to secure UK leadership in selected areas (we want to build the rover, not the wheel).
- Seek partnerships with other space agencies who offer opportunities for advancing UK capability, e.g. by supporting UK-led missions or carrying UK platforms on their exploration vehicles.

Mechanisms for delivery could include: specific national programmes, such as that set up by PPARC/STFC in preparation for UK involvement in Aurora ('CREST'); the proposed BNSC National Space Technology Programme; and subscription to future phases of the ESA Aurora Core Programme.

***Recommendation:*** In summary, we recommend that the UK should initiate a substantial and sustained national technology R&D and demonstrator programme focused on those areas of technology which underpin the UK's goals within the GES and strengthen the UK position in related ESA programmes. Knowledge exchange opportunities should be embedded in the programme from the start.

## 7 Commerce

“We must be creative in finding alternative means of harnessing other [i.e. non-government] funding for space”

- Malcolm Wicks, Parliamentary Under-Secretary for Science and Innovation, addressing the Parliamentary Space Committee, June 2007

### **7.1 *Introduction: Why are commercial considerations important?***

Space exploration has been science-driven so far, and the pursuit of knowledge will continue to be a good reason to explore beyond Earth orbit. However it is possible to identify historical examples where exploration capability (and the various economic and societal benefits that are enjoyed as a result) has jumped ahead dramatically when business drivers and their associated commercial returns are also identified, and used to drive the formulation of the exploration concept.

In addition, it is widely acknowledged that governments favour, where appropriate, the carefully managed injection of private sector funds to improve public sector value for money. 21<sup>st</sup> Century space exploration has now matured to be positioned at a critical ‘tipping point’: business possibilities are being routinely identified in a huge variety of civil and commercial sectors. Public-private partnerships (among other ‘flavours’ of funding mechanism) demand serious examination as candidates that will allow the exploration ‘business’ to mature as it evolves towards a scenario whereby full commercial exploitation of space is a reality.

Our objectives in this chapter are firstly to identify and discuss commercial exploration opportunities which are likely in the near term (approximately the next 7 years) and the longer term (beyond 7 years). Whilst we acknowledge that as yet there is little or no case for the latter, it is important to identify the markets of the future now. Government investment today in support of future markets, both robotic and those involving a human presence, could allow a UK benefit in the long term; any UK benefit from exploration opportunities would be reduced or eliminated if inactivity were chosen now. Secondly, we discuss mechanisms for funding, and where these involve government support, we have attempted to justify this support, based on risk and other indirect benefits to the government.

In particular, this section examines the sources of value in exploration that could be exploited by commercial companies, ranging from retrieval of scientific knowledge, accessing mineral resources and delivery of relevant downstream applications and services such as media provision via satellite communications, for entertainment, and education. The role of technology as a spin-off and its impact on commercial exploitation routes through the technology life cycle is addressed. The potential and suggestions for commercial financing are covered, as well as the pivotal role of the government as the primary risk-taker. A legal basis for commercialisation of exploration activities will be required, and some specific issues are summarised. The strategic benefit to the UK industrial and academic supply base of addressing this developing market is highlighted, and a statement is made on the commercial perspective for human space exploration. The chapter concludes with a summary on the best applications for UK commerce and industry to focus on together with suggestions for next steps to enable the commercialisation of space exploration.

## 7.2 Sources of value

Where can value be extracted from space and, in particular, exploration activities? What aspects of exploration can commercial companies exploit, in both manufacturing and services? Exploitation to create value and hence revenue can be direct from exploration activities, or indirect, the latter being a by-product of exploration.

Direct results can stem from the earliest exploration efforts, in keeping with our near term view described above. Direct commercial benefits from exploration hence need consideration within initial planning cycles, i.e. now. Prime examples that we analyse are:

- Exploration results (data and information).
- Service provision.

Exploration, whether successful or not, may generate a number of indirect results, although these only become apparent later in the exploration cycle (or mission life cycle). Longer term opportunities as described in section 7.1 include, but are not limited to:

- Unlocking of planetary resources (minerals, energy).
- Downstream applications and services (e.g. entertainment).
- Technology spin-offs e.g. high performance autonomous computing, advanced sensors and highly efficient power generation materials.

Below, we look at the product groups listed above and examine how they might offer value to private and public investors.

### 7.2.1 Direct value results

The results of exploration manifest themselves as either scientific knowledge, which is often seen as the principal objective, or technology and engineering knowledge. Although knowledge is a near term valuable commodity, it is still hard to describe this in specific and quantifiable terms which industrial investors seek. Hence this section is focused mainly on the commercial benefits to Government.

Scientific, engineering and technology knowledge tend to spin off from the process of preparing for and carrying out exploration. Areas of scientific knowledge relevant to exploration are described in detail in chapter 5. Scientific results have inherent value in advancing knowledge and understanding, and may have commercial value when delivered reliably in a timely, accessible form to selected industries (a terrestrial example being genomic information made available to commercial pharmaceutical manufacturers targeting hereditary diseases). Accessibility can be enhanced through international agreements. In addition, many potential commercial roles exist in supporting scientific analysis – for example through provision and maintenance of instrumentation, offering assured data storage, streamlining access and data distribution.

Investment to gain scientific knowledge can, in a broad sense, be justified by the perceived value of the knowledge. Although this is difficult to justify from a commercial investment basis, with specific, controllable and quantifiable risks and returns within a clear and limited timetable (typically 5-10 years), Government investment is based on different metrics. Our analysis is primarily targeted at Government investment, as purely commercial cases for space exploration do not yet exist. To governments, particularly in Western Europe where the ‘knowledge based economy’ is fundamental,\* the value of knowledge is intrinsic to societal well-being, fundamental understanding of our origins and future in the universe. Knowledge furthermore leads to potential for commercialisation, i.e. it delivers additional value. The value of knowledge can be gauged further by how much it costs to acquire it by other means. An example would be a country deciding to buy its remote sensing (or space derived intelligence) data from either the free market, or negotiating access to it through strategic international

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\* [Europe aims] "to become the most competitive and dynamic knowledge-based economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion." (strategic goal for 2010 set for Europe at the Lisbon European Council - March 2000). See [http://ec.europa.eu/employment\\_social/knowledge\\_society/index\\_en.htm](http://ec.europa.eu/employment_social/knowledge_society/index_en.htm)

alliances, instead of setting up its own system to acquire the information. The latter approach may offer short term cost savings but negate future commercial opportunities to sell data or services from its own system, as well as subjecting itself to a price floating according to the free market or the vagaries of politics.

We can therefore see a clear link between UK policy requirements stated in the UK Space Strategy 2003-2006<sup>18</sup> and knowledge and service related value derived from space exploration, since the first UK policy objective ‘Enhancing the UK’s standing in astronomy, planetary and environmental sciences’ can directly lead to the second and third ‘Stimulating increased productivity by promoting the use of space in government, science and commerce’ and ‘Developing innovative space technologies and systems, to deliver sustainable improvement in the quality of life.’

Technology / engineering knowledge, described in chapter 6, can be summarised as:

- the knowledge resulting from participation in development and operation of instruments, platforms and missions.
- technology capability that enables a robust exploration programme. This can be broken down into categories, of which those germane to the UK are:
  - Low cost missions
  - Scientific instruments
  - Adaptable, robust software systems
  - Entry, descent and landing
  - Communications and navigation
  - Autonomous systems and robotics
  - Materials and structures
  - Power generation and storage
  - Environmental control and life support
  - Aeronautics (for planets with an atmosphere)
  - Geophysical exploration
  - Planetary protection
  - Propulsion
  - Biotechnology in support of human physiology

Low costs from participating suppliers may be considered as commercial investment in their R&D (and a private subsidy to public funds) if there is an interest to develop one or more capabilities listed above. But R&D, even for companies whose strategy includes research, is a small component of business activity, and industry will not make large and speculative investments in technology development in the above or any other area on the basis that customers may arrive (the ‘build it and they will come’ approach). Industry will, on the other hand, build systems in return for cash or a guarantee of business from government, Skynet 5 being an example, and may take small risks at the margin if they see a line of business growing in a quantifiable manner or if they gain long term rights to resources or exclusive franchises that have clearly predictable returns. The latter also applies to Skynet 5. We make it clear that the former, at least, is not commercial investment to access a market, but state procurement.

Industry insight and involvement can steer a government-directed technology development programme to more rapid commercialisation, although this is not a hard commercial justification for exploration in its own right.

Knowledge and capability can be exploited indirectly: mechanisms for so doing include direct sales, joint ventures, and intellectual property sharing or transfer. The resulting indirect value then enables downstream applications and services as well as technology spin-offs (see below).

A third area of knowledge can be termed ‘human knowledge’, where value can be generated from engaging the public’s personal feelings through cultural, media and entertainment industries. Significant commercial opportunities probably lie only in the distant future, but where the general public is spending money (e.g. on entertainment, which Apollo showed most assuredly results from space exploration), then market opportunities should be researched. Human knowledge and its importance is addressed further in other sections.

### 7.2.2 Direct value service provision

The United Kingdom is a highly developed service provider. Our preferred role as a leader in robotic spaceflight programmes, and a niche provider to human spaceflight suggests that we can offer substantial benefit (hence value) to human spaceflight through developing robotics. Market opportunities we have identified are:

- **Basic and advanced communications relay services:** ranging from high data rate, value-added (but not mission-critical) information embodied as streamed video and high bandwidth payload data, to mission-critical data such as spacecraft telemetry and telecommand and astronaut voice communications.
- **Navigation positioning services,** augmenting inertial reference data and range / range-rate data supplied from Earth. Specific services, paralleling some aspects of Galileo could range from safety of life (for precision landing, in-space, or surface-to-surface transits) and search and rescue.
- **Robotic surveying services:** of the Moon and Mars, providing detailed imagery of the Moon's surface for use in planning and for lander navigation. Geo-referencing survey data would benefit from the navigation service detailed above.
- **Cargo transport services:** transport of materials for remote manufacture or consumables e.g. for fuels, propellants, life support. Precision delivery of instruments or consumables could be a further value-adding service. Further into the future, a sample return service (e.g. from the lunar surface to lunar orbit, to Earth orbit or to the Earth) could support terrestrial industries and future interplanetary activities.
- **Crew transport services:** transport of people to orbiting assets or surface bases. These services would require an assured or authenticated communication and navigation service, similar to what has been mooted for Galileo.
- **Robotic-assisted drilling for exploration,** leading in the further future to robotic or robotic-assisted mining, extracting resources for habitation, fuel or life support. Note that following consultation with terrestrial (resource) exploration industry, we do not consider fully robotic and autonomous extra-terrestrial drilling and mining to be practical within the horizon of this report.

The services above will need to target specific mission elements of whatever final architecture is put in place by the international community. We suggest communications satellites, landers, rovers, sample return vehicles, fixed and mobile human habitation and logistics elements such as pressurised rovers and propellant storage depots. The case for commercial benefit becomes significantly stronger if economies of scale can be realised, for example through single source servicing of multiple clients or missions. Single source servicing is most accessible to the first to market, particularly if the supplier helps to define standards and processes. For example, defining a lunar or planetary communications standard (utilising recent UK contributions to the developing Consultative Committee on Space Data Standards protocols) and launching a spacecraft to demonstrate this, test payload technologies and secure appropriate frequencies for future use would give the incumbent the potential for a major role.

We believe that a significant long-term market opportunity exists for exploration-based services. At present the UK can position itself to address this opportunity and gain some 'first mover' advantages. If the UK does not act in the coming year or so then others will step into the most obvious near-term market, and the opportunity to command this and other exploration markets in the long term could be lost. A working example is suggested below:

**Working example: lunar data relay service.** Given the number of missions targeting the Moon in the next two decades, we predict there will be a strong demand for communications and navigation services. However the example detailed below is not based on firm customer commitments, so will need to be validated by further analysis. Subject to this caveat, we have identified at least a dozen missions visiting the moon in the next ten years, more than half of which will land or impact its surface.

A simple, first order revenue model might assume a communications transponder on each mission

capable of transferring data to a communications relay spacecraft built by UK industry. An access fee to the relay service, and a suitable charging structure for initial access and then per unit of data transferred, could provide a revenue stream for the mission provider, ultimately feeding back to UK Government as taxes and industrial employment.

The table below illustrates some of these candidate missions.

**Table 1 Planned lunar missions**

	Nation	Mission	Approx. Date	Lander / orbiter	Navigation requirement
1	US	LRO (RLEP1)	2008	Orbiter	N
2	US	LCROSS	2008	Lander (impactor)	N
3	Japan	Selene	2007	Orbiter	N
4	India	Chandrayaan-1	2008	Orbiter	N
5	Russia	LunaGlob	2012-2013	Landers	Y
6	China	Chang'e-1	2007	Orbiter	N
7	Germany	German national mission	2012	Orbiter	N
8	UK	MoonLITE	2012	Orbiter + penetrators	Y
9	China	Chang'e-2	2013	Lander + Rover	Y
10	Japan	Selene-2	2013	Lander + Rover + Impactor	Y
11	ESA	Aurora MSR precursor	2013+	Lander, possibly orbiter	Y
12	US	Manned landings (several)	2019+	Landers	Y
13	China	Chang'e-3	2018	Sample return	Y

The following straw-man approach **assumes** a typical medium rate transmitter, antenna and pointing mechanism:

- Each Transmit/Receive unit on an independent mission requires 20-60 kg mass (including propellant) to reach lunar orbit.
- At current launch rates of >\$25,000/kg (based on India's PSLV, the lowest cost launcher with Earth escape heritage) to lunar injection, delivering the mass only of a 'bare bones' relay transceiver to lunar orbit would cost \$0.5-1.5M.
- The cost saving of deleting such a transceiver system from each planned mission in the table, assuming each has a redundant backup transceiver is estimated at \$1.5M from current industry suppliers.

**Further assuming** ten missions paid to use this system as backup or primary data and telemetry and telecommand relay (hence saving mass), the potential revenue could be \$20-30M, an attractive offset to the public outlay required to develop such a mission, and potentially of interest to private finance backers.

Charging per unit of data transmitted and providing data relay for more challenging surface landing missions would further increase the value of a shared telecommunications relay. A related argument is that the provision of a data relay service would encourage more missions by less affluent countries with space exploration ambitions, by reducing their costs and launch mass. This is known as a virtuous circle of business growth. A further argument favouring this approach is that low cost, frequently launched missions (at which UK industry excels) could transport, at cost, scientific instruments and test technologies for other nations, augmenting the return beyond the revenue calculated above.

Further elaboration of lunar data relay architectures, potential customer requirements and mechanisms to establish the best revenue stream is needed. Considerable work has been done by NASA, for example in developing network architectures for sustained human and robotic exploration,<sup>19</sup> although

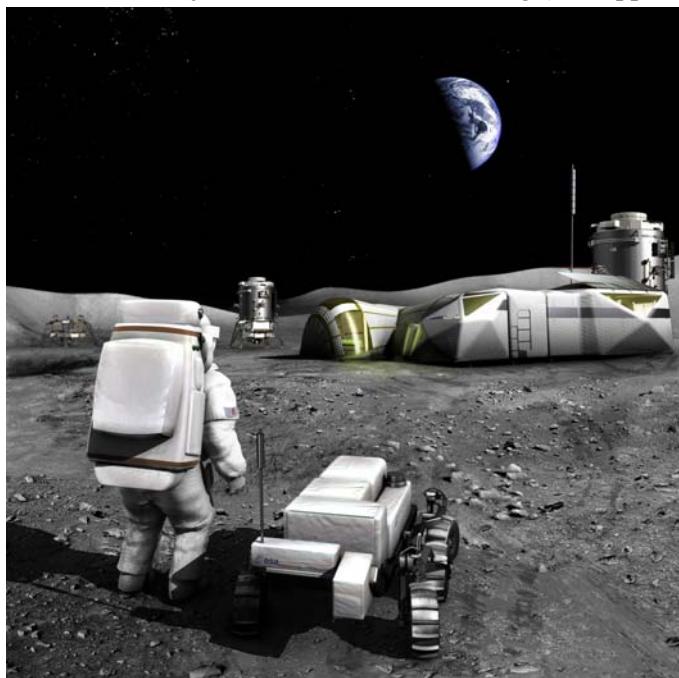
requirements developed by one agency need to be set in the international context.

We therefore recommend a detailed assessment to identify the structure, volume and certainty of customer commitments for communications relay and ancillary services which could be offered in parallel, and which could support a model as proposed. Identifying and quantifying services which could offer UK (government and industry) a return on investment in the near term is a key activity that should follow publication of this report.

### 7.2.3 Indirect value: Planetary resources

It is highly probable that the Moon, Mars and its moons, and Near Earth Objects contain natural resources of potential economic value to human civilisation. Such resources could be of value to the terrestrial world economy, or to future space operations, or both. Exploitation of Lunar/Mars resources following exploration to identify and quantify them is a logical step beyond creating the initial robotic and human infrastructure beyond Earth orbit.

An oft cited, but misleading, example of planetary resources is He-3, a rare isotope of helium, emitted by the sun and known to be present in small quantities in the near-surface lunar regolith. He-3 combined with deuterium (an isotope of hydrogen) has been claimed by some to be the holy grail of nuclear fusion, as an alternative to the conventionally studied deuterium-deuterium and deuterium-tritium reactions, as the deuterium-He-3 reaction emits no neutrons and superficially would appear to allow more cost effective fusion reactors. However, for a number of reasons, fusion involving He-3 has no practical advantages even were He-3 readily available on Earth. In our judgment it should be discounted as a justification for lunar mining (see Appendix H for further details).



**Figure 14 Permanent Moon bases will both require and enable the processing of *in situ* resources (Artist's impression ESA)**

to exist in various convenient locations including lunar cold traps, the moons of Mars, comets that cross the Earth's orbit, and Near Earth Objects, so are attractive targets for early exploration missions seeking to develop the business of 'Mining the Sky'.<sup>20</sup> Numerous other useful elements exist within lunar and Martian regolith, such as titanium and aluminium (see Appendix H). We recommend that further work on the value potential of planetary resources first considers the value chain in detail, from how a mineral rights exploitation regime might work, to identifying customers for the resulting products, and mechanisms for payment. The application of space resources to terrestrial needs should not be discounted, for example space based solar power which can only be enabled by exploitation of extra-terrestrial resources to build the infrastructure.

More practical and considerably less exotic examples of planetary resources that have potential as commercial commodities in-space in 10-20 years are water (ice), oxygen, hydrogen and methane. Water is useful as both a life support consumable and can be split by solar electrolysis into hydrogen and oxygen, which are useable as high performance rocket propellants. Improving access to targets elsewhere in the solar system, and greatly reducing the mass that must be launched from Earth are two obvious benefits of accessible water resources. Methane can act as the basic building block for a wide range of useful polymer products, again reducing mass which must be launched from Earth. Methane and oxygen are known as 'soft' cryogens, i.e. they can be stored in liquid, or condensed forms with a much lower energy cost than hydrogen, enabling both in-space and planetary surface propulsion (e.g. hydrocarbon combustion engines for rovers). Methane and water (ice) are thought

Services to future mineral exploiters are also noteworthy. These include extraction, purification and storage technologies. Examples where the UK has a world lead are the British Titanium low energy process for extracting titanium from rutile (titanium oxide ore) purely by electrolysis, producing useful oxygen in the process, and the cryogenic fluid handling capabilities of the British Oxygen Company (BOC). Early low cost robotic-assisted drilling to explore the planetary resource potential will enable an early determination of real commercial potential.

#### **7.2.4 Indirect: Other downstream applications and services**

Commercial application (terrestrial and elsewhere) of scientific results are generally impossible to predict although technology spin-offs have been analysed in detail by NASA and ESA. An example of how services can be developed from government investment in technology (exploration technology being a subset of general space technology) can be found in the recent ‘Case for Space’ report produced by UKSpace.<sup>21</sup> The Case for Space showed how relatively small government investments can stimulate new markets to prove the commercial case for new products, before the arguments for a full commercial operation were clear. In particular, BNSC’s MOSAIC (microsatellite applications) programme grew into over £100M of contracts to UK industry (a return to investment ratio exceeding 9:1), while also generating value added data sales service companies such as DMCii. Through MOSAIC, the UK government bought one DMC microsatellite, which in turn enabled SSTL to sell six further spacecraft to date.

Programmes such as Aurora, where the UK is the second largest contributor, are ideal targets to seek a demonstrated return to the UK to justify the government’s investment. There is further potential for development and expansion of services initially provided to exploration missions, into services for subsequent long term lunar/Mars exploitation. The following examples are suggested for consideration; the first may be realisable within 10 years, the second probably has a 20 year-plus gestation period.

- Tourism – transport of space tourists around the Moon, in lunar orbit or to the surface of the Moon. Although the nascent space tourism industry is firmly focused on suborbital access to the edge of space, it is only a matter of time before orbital and beyond Earth orbit tourism takes place, and many of the most notable space tourism companies have not denied such aspirations. The US based company ‘SpaceAdventures’ is currently claiming it has at least two passengers for a circumlunar flight using Soyuz hardware, at a price of £50M each. Daughter industries may spring up on Earth, for example virtual or flight simulator tours of the Moon and Mars.
- Virgin Galactic in the UK has adapted the current commercial space activity funding model, adding substantial direct investment from the would-be tourists themselves as a deposit against future flights. Initial flights focus on those who can afford the high cost, around £100k for the experience. Similarly to air travel in its early days, it is expected that flights will become more affordable and conceivably open to the masses in the same way that budget air travel now exists. However it is notable that this capability is being created outside the UK, and while the market at present appears to be mostly outside the UK, UK capital is funding much of the development. In part this is because of access restrictions to UK technology, but further, regulatory reforms are needed in the UK to enable further activity. Such activity could comprise more paying UK passengers, but also transport of scientists and their experiments, and with surprisingly modest technology changes, adaptation to deliver small payloads at relatively low cost to orbit. The latter would potentially offer an attractive but at present unavailable low cost, frequent reflight, and reliable means of launching small satellites and robotic space systems, thus building on existing strong UK capabilities. In section 7.5 we recommend that regulatory reform to encourage tourism and other exploration focused enterprises takes place in the UK.
- Tourism is a subset of entertainment – a range of activities that are likely to be spawned through indirect engagement with the space exploration industry. Although the argument that entertainment could be a commercial justification for exploration is weak, the public’s appetite for space exploration related entertainment is clear, for example through virtual environments of lunar or Martian surfaces on Earth; incorporation of these environments into games or even remote control of assets (the latter was proposed by LunaCorp in the USA, using a lunar rover:

although the business case was unsuccessful, it could be revisited if exploration of the Moon becomes more frequent in the coming decades). We recommend that commercial links between the entertainment of the future, which is essentially providing media to the public, and space exploration, which generates considerable public interest, are investigated further.

### **7.2.5 Indirect value: Technology spin-offs**

It is generally hard to predict the development of existing and new terrestrial markets stemming from technology developed for exploratory missions. Often incorrectly cited examples from Apollo are Teflon (non-stick), powdered long life fruit drinks (Tang) and Velcro. Real spin-offs from space exploration have included high performance autonomous computing, advanced sensors e.g. for thermal imaging, highly efficient power generation devices (triple junction photovoltaic cells) and ventricular assist devices for patients with weak hearts. Further examples are provided by NASA<sup>22</sup> and ESA<sup>23</sup>.

Numerous other sectors including defence and security, aerospace, transport, oil and gas, power, materials, manufacturing, ICT, healthcare, financial services, food production, and entertainment may gain the benefit of spin-off technology. Spin-offs may be combined with exploitation of the scientific results of exploration and should be noted as they occur to continually demonstrate the value of space exploration and exploitation to enhancing the quality of life through new technology.

## **7.3 Commercial exploitation routes**

Routes to industrial exploitation of new capabilities are usually based on a technology life cycle. Exploration, knowledge and research / development can all lead to market development, but this requires consideration of parallel and interactive development of:

- products / services;
- customer use and demand; and
- supply chain and value chain (raw supply, business-to-business, consumers).

It is incumbent on UK industry, government and academic partnerships in space exploration to have the ‘long view’ of commercial exploitation routes for new initiatives. One model approach can be drawn from the Collaborative R&D element of DTI’s Technology Programme, specifically where a condition for funding is that an exploitation route is identified. Lessons learnt from this and any similar UK government programmes could be applied as ‘best practise’ for space exploration.

## **7.4 Commercial financing and the role of Government**

The potential for private investment depends firmly on risk versus reward. While there is limited supply of finance from industrial companies and Government, a practically unlimited supply exists from financial investment markets (\$55 trillion of funds under management worldwide in 2006), for investing *at the right price for the risk*.

The commercial opportunities that exist in space exploration from primary risk-taking are potentially vast, but in the main they are not well enough defined to sustain a rational business case that would be credible enough to attract capital markets finance. It seems probable that commerce will eventually see the opportunities to exploit mineral and other resources in space, and will likely see the benefits of investment of advanced scientific exploration. Yet this will not happen until an exploration programme is underway with early results providing evidence to support business cases. However, it also seems clear that the governmental resources available to the endeavour are insufficient to propel mankind towards its destiny in space at a satisfactory rate of progress. Thus, the firepower of private industry needs to be harnessed and used as a tool to achieve long run objectives.

By bringing commerce into the strategy from the outset, companies can build credibility, expertise and a track record of success that will enable them to generate a faster and more rapidly escalating level of investment into space exploration in the future. Capital markets do not like surprises or sudden big bang plans, they like smooth growth based on evidence of expertise. Critically, they prefer business plans in the provision of services which are protectable and sustainable to the lumpy cash flows that result from simple hardware sales.

Consortia of companies should be encouraged to develop, in order to provide as much of the work as possible of an exploration strategy in a service provider model. Thus, if government resources over a period of 15 years or more can be committed to the purchase of services (rather than ‘hardware’ or ‘missions’), the capital markets will take the risks that the consortia can deliver against their promises. These promises can include the delivery of scientific instrumentation and associated research as well as, e.g. telecommunications, power, construction and transportation. Crucially, in a service provider model, consortia may be willing to provide services on a less than 100% cost recovery basis if in return, upside rights (the rights to future market growth) over future exploitation are available.

But in establishing a service provider model, a second order of efficiency is created. When the USA, and also China, India and possibly other nations have indicated a desire to send human missions to the Moon and perhaps to Mars, an opportunity exists for the service provider to generate significant economies of scale and scope by selling its basic services to all of these nations. The market will also be extended, in time by commercial missions stimulated by a new generation of ‘space tourists’. Thus the primary risk takers can focus their resources on funding their basic targets, leaving tertiary services plus the financing of long term experimentation to the capital markets and consortia they support.

The UK is a global leader in project and Public/Private Partnership financing. Combining this with the expertise in space insurance (see next section) and low cost space science technology, coupled to a political drive to persuade other nations to outsource work to British consortia could produce incredible leverage. There is every possibility that the UK government could harness private resources to produce the most comprehensive and powerful space exploration capability in the world.

Governments are also instrumental in commerce where international politics and relations (e.g. space agency to space agency) play a strong role. Government-to-government deals (barter) can also support exploration programmes, such as the ongoing NASA-BNSC agreement to cooperate on exploration. The role of government in regulation is addressed below.

## **7.5 Regulatory and legal issues**

There is a need for an agreed legal basis and jurisdiction for exploitation of exploration, to reduce or eliminate impediments to commercial investments.

Provisions for rights to the ownership and exchange of physical and intellectual property, and for both contractual and non-contractual commercial liability, must be defined and backed up by implementing agreements, authorities and regulations. Relevant extant international agreements include:

- The UN Outer Space Treaty (1967),
- Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (1968)
- The Convention on International Liability for Damage Caused by Space Objects (1972).
- Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (1979).  
*Note that no major spacefaring nation has ratified this treaty.*

The UN Office for Outer Space Affairs maintains the Register of Objects launched into Outer Space and provides the Secretariat for the Committee on the Peaceful Uses of Outer space (COPUOS). COPUOS and its Scientific and Technical and Legal Subcommittees drafted the space Treaties and Principles and monitor compliance.

The regulatory and legal framework must be conducive to commercial ventures and at the outset of any commercial activity there must be a stable situation where the investors in the system are able to fully exploit it. Agreements must be made at international level and the Government will need to take on-board the commercial requirements in the relevant fora. We endorse the recommendations of the UK parliamentary select committee in their recent report<sup>24</sup> which states, ‘*We are concerned that the current licensing regime impedes enterprise. We welcome the review of the implementation of the licensing regime and look forward to the public consultation on BNSC’s proposals. We recommend that the BNSC pay particular attention to the needs of SMEs in this area.*’

We recommend that the current UK licensing regime should be reviewed and updated in line with the recommendations of the Science and Technology Select Committee. Current issues include insurance

requirements for contingent liabilities. We welcome the public consultation that BNSC is initiating on this subject later in 2007. We believe that such reform will encourage high value added activities such as space tourism and related activities such as inexpensive, regular and reliable launch of scientific payloads and small spacecraft that build on existing UK strengths.

## **7.6 The UK supplier base and its relevance to sources of value**

We believe that participation in exploration offers strategic value to the UK supply base, through:

- knowledge and skills of engineers;
- capital equipment and industrial processes;
- commercial and management experience; and
- industrial supply chain relationships.

We refer to the technology categories from chapter 6 (Technology and knowledge exchange), *viz* low cost missions, scientific instruments, adaptable and robust software systems, entry, descent and landing, communications and navigation, autonomous systems and robotics, materials and structures, power generation and storage, environmental control and life support, aeronautics, geophysical exploration, planetary protection, propulsion and biotechnology in support of human physiology.

The UK has a strong competitive position. We feel that retention of our competitive position on the international playing field is critical to maintenance and stimulation of increased productivity (by promoting the use of space in government, science and commerce) and assuring sustainable improvement in the quality of life.

By way of an example, UK (space) insurance capability may be enabling for many future space exploration ventures, for the following reasons:

- Firstly, insurance costs are typically the third largest cost of a satellite project, following on from the cost of the satellite and the cost of the launch service.
- Secondly, insurance allows entrepreneurs to take risk. Entrepreneurs drive market developments, and the availability of insurance has been a fundamental factor in the development of the commercial space market to date — and will continue to be so in the future. Hence, space insurance could be seen as directly stimulating the thriving commercial space sector.
- Finally, while risk assessment for exploration will be difficult because of the complex and numerous factors involved, UK capability is experienced with large, complex projects carried out over long periods of time. UK experts and financiers may have an integral role to play in allowing the growth of global exploration capability and services developed specifically in the UK to serve international exploration efforts.

A related issue is the importance of early (or rapid) and inexpensive in-space technology testing and simulation for both robotic and human spaceflight missions. Risk mitigation using world-leading UK competencies in small satellites, automatic and autonomous systems and simulation will be crucial to maintaining the cost effectiveness of robotic exploration and ensuring the affordability of human space exploration.

## **7.7 Commerce and human spaceflight**

Human space exploration has not *historically* been a focus of UK efforts, principally because it has been difficult to see the benefits in terms of science, stimulating the economy and in improving quality of life on Earth. From an exclusively commercial perspective, it could be said that human space exploration is not *currently* an effective use of money for the UK in the context of other national spending priorities in general and specifically in the context of short term returns from other areas of space. However, this report has highlighted the growing case for an involvement of humans in space exploration, and has suggested (Appendix D) a 5-year, relatively inexpensive, experiment to judge the potential returns which astronauts could make to the UK and our aspirations for exploration.

Our view is that human space exploration merits the experimentation suggested in Appendix D since there will be an almost inevitable increase in public interest, investment in the sector as a whole, and

potential leveraged benefits from being involved with other countries' human space exploration programmes. However the focus of this chapter remains on robotic exploration because the benefits at present are quantifiable, and our opinion is that commercial returns from robotic missions are likely to considerably outweigh those from human exploration within the horizon of this report.

## **7.8 Summary: Commercial benefits of exploration**

Although space exploration has been science driven to date, and compelling science will continue to be a good reason to explore beyond Earth orbit; exploration capability has historically jumped ahead when business drivers and commercial returns are identified. Governments also favour injection of private sector funds to improve public sector value for money. We have identified a number of possible business possibilities and opportunities relevant to space exploration, which merit more detailed study to assess their opportunity potential for commercial exploitation.

In particular we have summarised the sources of value in exploration. Some are direct, such as scientific and engineering knowledge (both exploitable as future commercial offerings), and service provision to space explorers. Some are indirect, or longer term, such as planetary resource exploitation for both terrestrial and in-space benefit, and delivery of downstream applications and services such as media (high bandwidth imagery, video and information) to public, industry and government stakeholders. A working example of value generation through a direct service provision has been presented. We have proposed communications relay and backup for all international exploration missions, delivered through a low cost spacecraft and ground station service. Some possible revenue figures for consideration accompany the proposal. A key point to note is that despite the lack of definition in commercial markets accessed through space exploration, offsetting public expenditure from near term commercial return (within 10 years), and eventually capital market financing appear possible.

We recommend a detailed assessment to identify the structure, volume and certainty of customer commitments for communications relay to justify and elaborate the model proposed. We further recommend a longer term study to understand the value chain for exploiting planetary resources, including examining mechanisms for a (mineral) rights exploitation regime, mechanisms for payment and identifying customers for the resulting products. Understanding the value chain in each case would strongly support cases made for UK investment in exploration capabilities.

**Recommendation:** **We recommend that a survey is carried out to identify customer commitments and quantify value added business for the exploration-related services identified in this report - from near term (e.g. lunar communications relay) to long term (e.g. exploitation of planetary mineral rights).**

We also recommend that the records are made each time a successful technology spin-off takes place to continually demonstrate the value of space exploration and exploitation to enhancing the quality of life through new technology. It is important to ensure that commercial exploitation is borne in mind, through the technology life cycle wherever investment is made, and we have suggested best practice drawn from current UK collaborative research and development programmes. Specific suggestions for future commercial financing were covered, including the pivotal role of the government as the primary risk taker. A legal basis for commercialisation of exploration activities will be required, and we have highlighted some specific issues. We also note the strategic benefit to the UK industrial and academic supply base of addressing this developing market, in particular through capabilities such as low cost small satellites and robotic/autonomous systems, as well as further areas identified in section 6.3.2. We conclude by stating that several promising applications for UK commerce, industry and academia partnerships, supported by government exist. On the topic of human space exploration, we recommend the approach described in Appendix D to quantify the benefits through a 5-year exploratory programme, but note that commercial returns from robotic missions are likely to considerably outweigh those from human exploration within the horizon of this report.

<b>Recommendation:</b>	<b>We recommend that the current UK licensing regime should be reviewed and updated to encourage high value added activities such as space tourism and related activities such as inexpensive, regular and reliable launch of scientific payloads and small spacecraft which build on existing UK strengths and support proposed UK efforts in exploration.</b>
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Early terrestrial explorers faced many challenges, including an unknown environment, supply chain difficulties, uncertain funding and poor maps and charts. Entrepreneurs however sought to provide critical services, euphemistically termed ‘roads and commodes’ to the explorers, and generally profited handsomely. Space exploration in many ways is no different. The UK, through its strengths in small, cost-effective satellites and autonomous robotics, is well-placed to provide significant robotic infrastructure and make a business out of providing routine communications navigation and other services to the space explorers of the 21<sup>st</sup> Century. Affordable prospecting tools (landers, rovers – the modern version of ‘picks and shovels’) and a wide range of specific technologies, enabling cost effective ‘roads and commodes’ to provide wider access to sites of potential interest are a further possibility. Services including delivery of media for entertainment and spin-outs are harder to predict, but on the basis of historical precedent may lead to even greater revenues than the early services we have discussed and attempted to quantify.

## 8 Society

### 8.1 *Introduction*

While science lies at the core of space exploration programmes there are substantial, wider benefits that span the boundaries between science, education, commerce, culture and society.

The benefits to the UK of an increased involvement in space exploration are wide-ranging. In addition to the potential for scientific discovery and technological innovation we have identified substantial and positive consequences for:

- science education in schools;
- the uptake of science, technology and engineering subjects in British universities;
- the public understanding and appreciation of science and the perception of scientists;
- the international standing of the UK; and
- the public view of the UK as a world leader.

We find a key factor in achieving a high impact for society in the UK from an enhanced investment in space exploration to be the in situ involvement of human explorers. This is not to overlook the remarkable interest in the NASA Mars Rovers and indeed the public interest shown in the UK Beagle 2. However humans are much the most effective explorers and there is substantial evidence that, in addition to scientific advantages, their presence greatly increases public interest and support.

### 8.2 *Space and education*

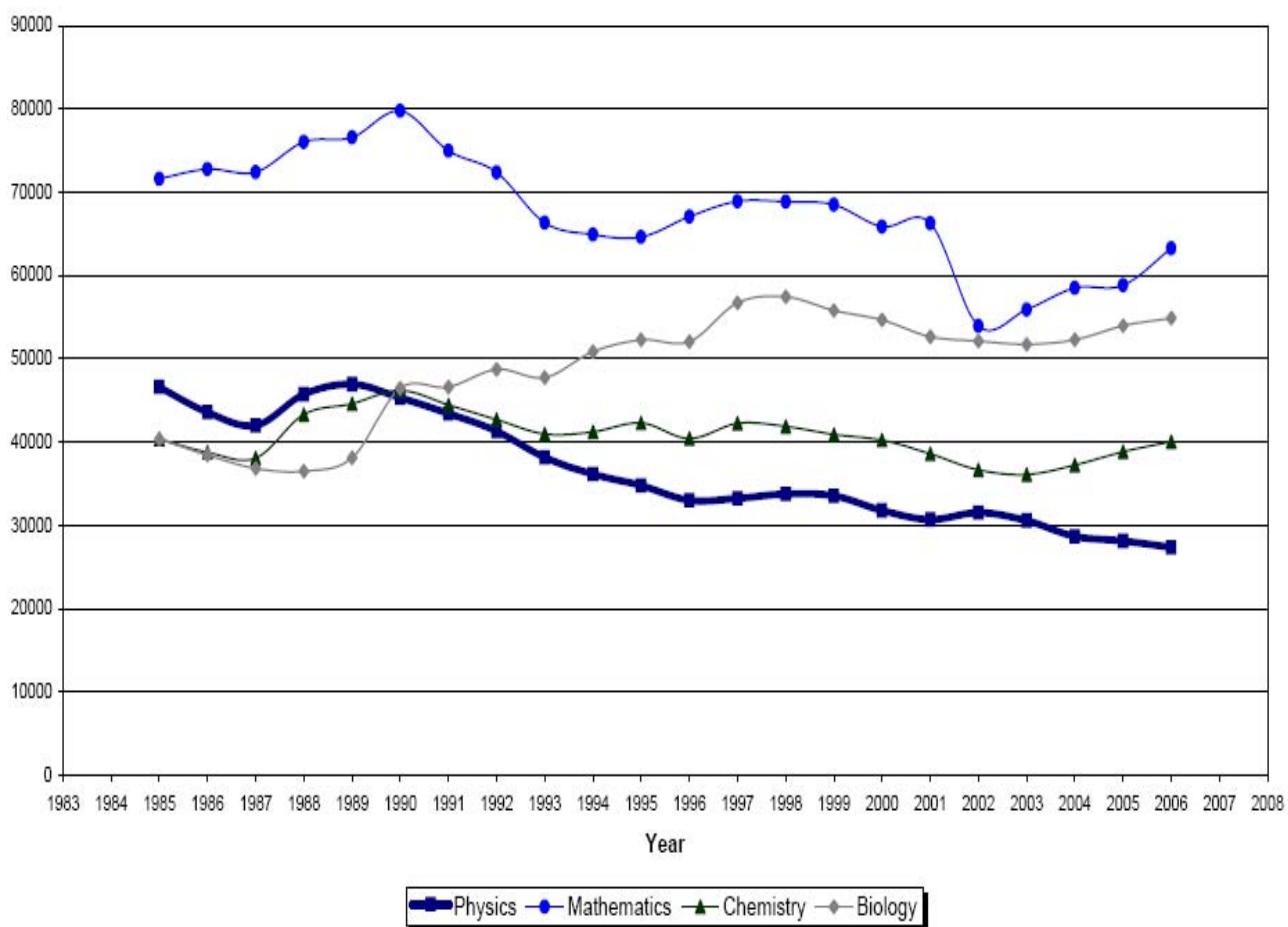
#### 8.2.1 **The education crisis in science and technology**

It is now widely recognised that there is a crisis in student recruitment for courses in science, engineering and technology, or SET,<sup>25,26</sup> which threatens the UK's ability to maintain its role as an international economic and technological power.

In searching for solutions, there is evidence<sup>27,28</sup> of a broad student interest in Space and Astronomy, interests that – unusually in SET – are shared by girls. We agree that such interests endow an enhanced space exploration programme with a particularly important opportunity to reverse this decline, and endorse Barstow's recommendation that Space be adopted as a flagship topic in the national curriculum.

Following the 2006 Budget, a key Treasury paper<sup>29</sup> spelled out ambitions to achieve year on year increases in the number of young people taking A-levels in physics, chemistry and mathematics. The basis of concern is very real, with physics entries for A-level having fallen from 48,000 in 1989 to 28,000 by 2006. In 1997 it was 33,000; thus the fall has slowed during New Labour's tenure but the underlying trend persists and its reversal is clearly a matter of urgency.

While in his speech to the Royal Society, reported in Science and Public Affairs in March 2007, the then Prime Minister Tony Blair stated that the number of science undergraduates had increased by a quarter since 1997. However, closer examination of these data reveals that increased enrolment in non-traditional courses such as Information Technology, Communications and Forensic Science masks the serious long term and ongoing fall in the core subjects of physics, chemistry and engineering.



**Figure 15 Number of entries to A-level examinations in science and mathematics 1985-2006 (source AQA)**

Figures for the closure of university physics departments bear this out. The number of universities offering physics degrees fell from 79 in 1994 to 51 in 2004 (source IoP), since when Reading University has been a further well-publicised planned closure. The result is that communities and industry across swathes of the UK are now without a university physics department. Interestingly astrophysics- and space science-based degrees, now common in many UK physics departments, have been among the few areas to show growth in student numbers and new staff over the past decade (HESA and RAE statistics).

### 8.2.2 Evidence for positive benefits to science education

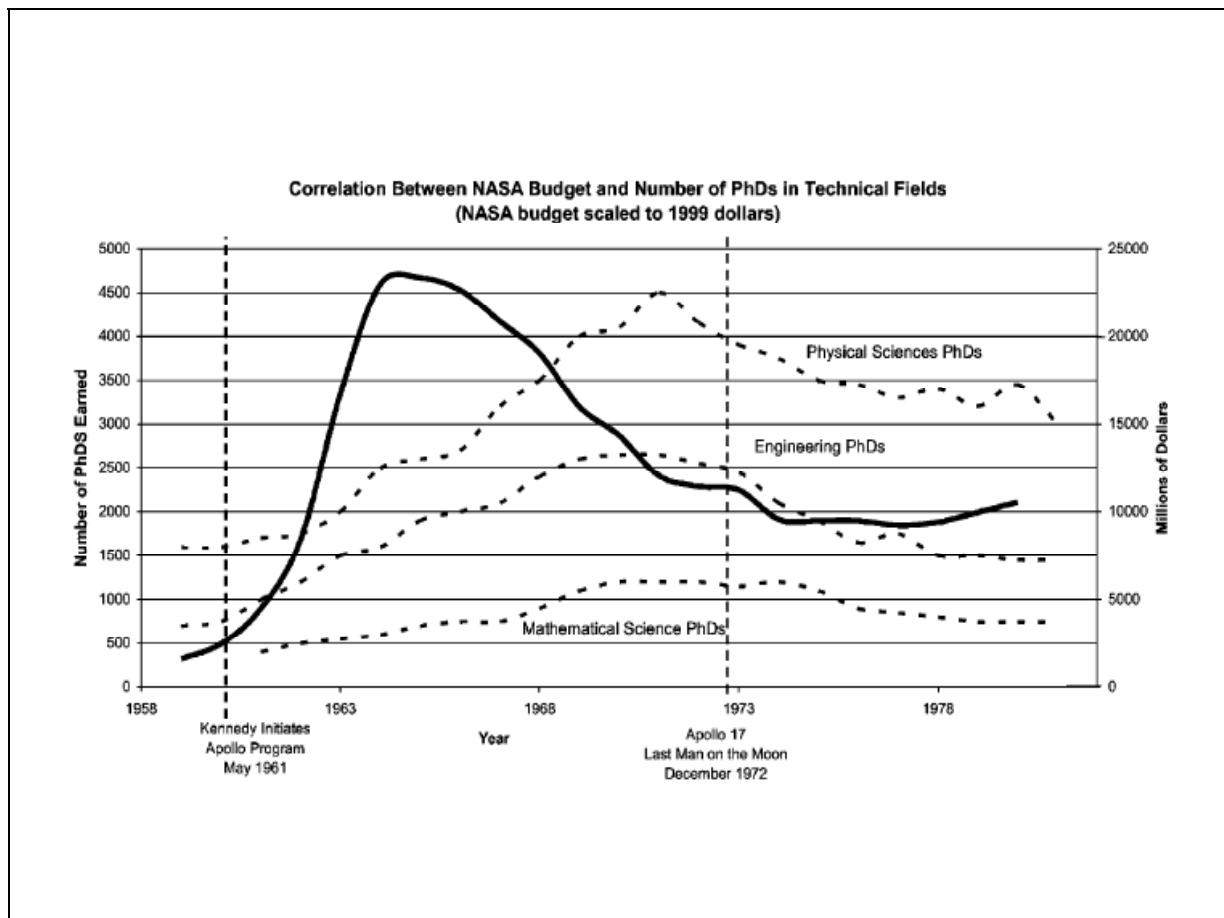
Substantial evidence exists to suggest that space exploration, and human spaceflight in particular, are of value in inspiring school children to study science and in attracting undergraduates into science careers. We have attempted to summarise the existing objective data alongside subjective and anecdotal evidence. Taken as a whole it is our view that these comprise a compelling argument for further UK engagement in the field of space exploration. There is growing quantitative evidence that space research is one area of SET that does capture student interest, with the involvement of astronauts being especially effective.

### 8.2.3 Space exploration and the education crisis

#### The Apollo Programme and the uptake of technical doctorates in the United States.

The Apollo Effect represents the earliest example of the relationship between space exploration and attitudes to science in higher education. The numbers of graduates in technical sciences in the USA

grew significantly some 5-10 years after the start of the Apollo Project, and this increase was maintained throughout, the falling numbers then occurring only after the termination of the programme. This is consistent with a picture where high school students become enthused, leading to increased graduation numbers with a 5-10 year time lag before the corresponding increase in uptake of technical degrees amongst this cohort at postgraduate level.



**Figure 16 The Apollo Effect** (figure reproduced with permission of author)<sup>30</sup>

### The Education and Skills Case for Space report

Further evidence for the positive impact of space exploration on science education derives from *The Education and Skills Case for Space* report,<sup>27</sup> published in 2006. This suggested that linking space activity with young people improves educational standards and skills and can affect choice of a science or technology subject post-16 or on entering university. It concluded (paragraphs 1.47 and 1.48):

*"Space has an overall positive and direct effect on educational and career decisions, and a generally beneficial impact on motivation, behaviour and achievement. In the context of a general decline in interest and uptake of the physical sciences, an emphasis on space-related areas appears to oppose the trend at GCSE, A-level and in Higher Education"*

The bulk of the data was derived from questionnaire responses and is hence largely anecdotal in nature. However, objective evidence was presented for the significant positive effect of Scottish Space School, Space Camp Alabama and the Challenger Learning Experience at National Space Centre, Leicester. It is worth noting that all three of these facilities employ human space exploration as the principal hook for their educational activities. Indeed the Scottish Space School and the National Space Centre (NSC) are emerging as the best sources of hard evidence of the benefits across a broad student age range within the UK and the evidence derived from their activities is listed in further detail below.

## Scottish Space School

The scale and initial feedback from the Scottish Space School is impressive. In 2005/6 over 22,000 students, in the age range 5-18, were involved at some level in the *Blast off to Science* programme<sup>31</sup>. Extended visits by a team of NASA astronauts and engineers directly engaged several thousand students and their teachers. Feedback was generally highly positive, with accounts of a career-changing experience being common.

To quote a former student:

*"The Space School has completely transformed my outlook on life and my future, and I now feel a career in science and technology is within my grasp"*

A teacher commented:

*"Space School may turn out to be the defining moment in the careers of many of our young people; it has certainly inspired me to motivate my pupils towards science"*

At the end of each academic year 120 SSS students attend a week-long summer school at Strathclyde and Glasgow Universities, with a further 50 students being selected for the Space Camp at Johnson Space Center in Houston - NASA's astronaut training ground. On-line tracking of students from the 2004-2006 Schools have shown 82% going on to study science or engineering courses at university.

It seems very probable that by reaching such a wide audience, albeit only briefly, the Scottish Space School and NSC are having a measurable and positive benefit for very significant numbers of children.

Experience in Scottish Space School has demonstrated that personal contact with a NASA astronaut can be highly significant for the young and is the sort of singular event that can stimulate the required sea change in attitudes to 'hard' science and to career choices. The additional impact of a British astronaut can at present only be imagined.

Human adventure captures the imagination in ways that robots in practice do not:

*"The attendees at Scottish Space School are inspired by the astronauts: individuals who explore. Out of thousands of students who have experienced Space School, none say they want robots and not humans"*

(Alex Blackwood, Director Careers Scotland Space School)

## National Space Centre, Leicester

The NSC was opened in summer 2001, since when the number of visiting schoolchildren has been maintained at ~50000 a year, typically in groups of ~30-100 plus teachers. The target group of 8 to 14-year-olds is being extended this year to the 14-18 age group — coinciding with the opening of new educational programmes.

Two academic studies have been published on the effect of NSC visits on children's attitudes to science. Jarvis and Pell<sup>32</sup> studied 655 10- and 11-year-old boys and girls, before as well as two and five months after taking part in the Challenger Centre 'Rendezvous with a Comet' experience. They found, post-visit:

- 24% of the children had an increased aspiration to become scientists
- there was an overall increased appreciation of the use of science to protect the planet
- teachers reported an improvement in team working
- beneficial effects were more marked among girls (perhaps because of their lower aspirations)

They concluded:

*'it is remarkable that a 2-3 hour experience should have such a lasting positive benefit for almost a quarter of the children with regard to their career aspirations to become scientists'.*

Jarvis and Pell<sup>33</sup> also carried out a further study on 295 children (again 10-11 years old) having spent a half day touring the NSC Visitor Centre, in addition to taking part in the 'Comet Rendezvous' or a 'Voyage to Mars' Challenger Mission.

The positive impact of the Challenger experience, where students work as either astronaut flight crew or mission controllers, was confirmed. For this second group Jarvis and Pell (2005) found:

- 20% of the pupils showed an increased desire to become scientists in the future
- those children also showed a positive advantage over the other children with regard to science enthusiasm\*



**Figure 17 Secondary school students at Beijing Space School in 2003 inspired by China's first human spaceflight one month earlier (K Fong)**

To put the evidence from NSC and the Scottish Space School into the context of the 'crisis in SET', we should consider the effect of a national effort building on their experiences, and the recommendations of the Barstow Report: changing the career intentions of only 2% of talented children towards SET would represent an increase of 10,000 for the present A-level cohort.

The important role that space plays in stimulating a scientific and technologically literate society seems to be recognised throughout the world. Countries such as India and China with fast growing economies that may overtake the UK by 2025 also have a larger number of science and technology graduates and recognise space as a strategic part of this stimulus.

### **8.3 Public support for human space exploration: the taxpayers.**

Space is an area of science and technology that particularly appeals to the general public. The Air and Space Museum in Washington is the most popular visitor centre in the USA, while in the UK, the National Space Centre in Leicester has been one of the most successful Millennium-funded science centres, with over one million visitors to date. In the context of the present report it is interesting to note that NSC visitor numbers increased by 20% following the introduction of a human spaceflight facility in 2005.

Several other independent review bodies have made reference to the potential value of human spaceflight programmes in terms of public engagement. The 2003 Microgravity Review panel was tasked with reviewing microgravity research and applications and the case for participation in the European Space Agency's related life and physical sciences (ELIPS) programme. The terms of reference this group were formally confined to science, technology and commerce. While they cautiously recommended minimum level involvement in the ELIPS programme, the panel also alluded to wider benefits stating:

*"We have ... found considerable public interest in activities in space, particularly those that have human involvement. This has been exploited by several space agencies to enhance the interest of the community in science and its applications, and the UK could do the same."*

Recommendations of the Microgravity Review Panel 2003

In 2004 the Report of the Aurora Cross-Council Meeting also highlighted the value of the human elements of that programme:

*"There was ... significant support from some parts of the community for the human component of the Aurora programme for the purposes of planetary geological exploration, medical research and for public outreach. It was recognised that these arguments for participation in the human*

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\* defined by Jarvis and Pell as the willingness to engage in science at school or at home

*spaceflight aspects reinforce each other.”*

Report on the Aurora Cross-Council Meeting, May 2004<sup>34</sup>

During the course of the Royal Astronomical Society's commission on the scientific case for human spaceflight, the public view on a possible UK astronaut programme costing £150M a year was tested via the BBC web site. The public response was strongly positive with 62% in favour and only 26% against. In making the case for an expanded UK effort in space exploration, including humans, we might let the public speak for themselves. Views sent to the BBC web site and reflecting the majority opinion included the following (for further examples, see Appendix F):

*“With all the arguments, nit picking and irritations about EU budgets, Iraq, road/rail congestion, NHS etc etc Britain really, really needs a big idea to challenge and inspire us. It's like a family, it can spend all the money on bills and housework but without the holiday, life gets very tedious. Lets just look over the horizon for a change.”*

*“Recent BBC report of UK pupil saying science is ‘dull and hard’ clearly suggests that children neither have any role models in science nor their imagination is fired up to pursue science. Even more than 35 years on, some of the Apollo astronauts are still motivating and inspiring US school children to become future astronauts. A robot can never achieve what a geologist can do once on a planetary body.”*

*“Will it solve world hunger? Probably not, as that is a matter of political will as there is already enough food in the world for no one to starve. But spending money on these sort of projects may bring about ideas and technologies that may help, and increase the co-operation between nations that is needed to solve these sorts of problems.”*

*“I'd spend lots more on space to help British industry retake the lead in newer technology areas.”*

*“Humankind are natural explorers, we need to keep expanding our frontiers or continue in our stagnation.”*

Following the release of that report, the RAS polled its membership which approved by 442 to 18 votes a statement which included: “The RAS recognises that there may be some scientific goals that can only be achieved within a human spaceflight programme (see the Report of the RAS Commission on The Scientific Case for Human Spaceflight). However these goals are likely to be feasible only within a greatly expanded scientific space programme.” (The full text is included in Appendix G.)

### 8.3.1 The importance of public engagement

The current perception of UK Space is that it is ‘worthy but dull’ (numbers in parentheses refer to paragraphs in *The Education and Skills Case for Space*):

(1.12) [UK Space] fails to be open and accessible: [it is] dominated by two groups – industry experts and amateur enthusiasts – whose average profile is white, male and middle-aged.

(3.2) UK approach to Space hinges on the economic and technological benefits, and its principal focus is on satellite and communication applications. “The unintended effect of this cumulative message was to portray space as ‘worthy but dull’ “

(3.3) The UK does not have an official ‘vision for space’. The Demos think-tank report summarises this failed vision thus: “The UK will be the most developed user of space-based systems in Europe for science, enterprise and environment. UK citizens will provide and exploit the advanced space-based systems and services which will stimulate innovation in the knowledge-driven society.” It comments that “none of this is wrong; it all makes perfect sense. But the danger is of it being so sensible that it fails to ignite any new public or political enthusiasm for space”

(3.25) The UK's association with the utilitarian end of space (satellites and communication) make it an industry invisible to the majority. NASA is the first port of call for most [in the UK].

It is noticeable that while NASA is a globally recognised brand, the public in the UK is largely unaware of ESA, of the UK contribution to space research and almost no-one recognises BNSC or the research councils.

When it comes to encouraging and inspiring future generations of scientists it is no longer enough to rely upon serendipity. Activities of science communication must be promoted well beyond their current status. If we are to capitalise on the motivational role of exploration in encouraging young people to study science, then any future programme needs to be accompanied by a well-planned and properly funded strategy for communication and public engagement.

This is a complex task part of which involves creating a sense of ownership and involvement amongst the British public. Space exploration is a story of human endeavour and scientific discovery - and it is a story worth telling. If we were to embark upon a new programme of space exploration the UK would have the opportunity to create its own identity in space giving British people a sense of engagement in a programme of national undertaking.

## **8.4 Political - the UK's standing in the world**

The present review is particularly timely given the renewed and global interest in space exploration, with several international agencies already having announced their interest in establishing crewed lunar bases.

In the 18 months since the Royal Astronomical Society's independent report, which supported the scientific case for human space exploration, the plans and ambitions of other leading nations for Human Spaceflight have advanced. NASA continues to develop a detailed strategy for returning to the Moon and sustaining a human presence there, China has flown 2 successful astronaut missions in Earth orbit, is planning a third as well as targeting a lunar landing by 2020, while India has announced plans for a lunar base in the same decade. The possibility of the UK becoming isolated is clearly increasing.

It could be seen as a challenge – and a threat – that all members of the G8, apart from the UK, (France, Germany, Italy, Canada, Russia, USA, Japan) are active in human space exploration programmes. Other nations, with fast growing economies that could overtake the UK by 2025 and aspire to becoming major powers in coming decades, countries such as China, India and Brazil, are either already actively involved or plan to become involved in human space exploration.

ESA planning for lunar missions is underway. Japan already has an active astronaut corps; its longer-term ambitions, towards the Moon in particular, are set to be decided by 2015. Ten ESA member states are already signed up to its human spaceflight programme; these include the major industrial nations, Germany, France and Italy, but not the UK. Of the European countries not signed up (Austria, Greece, Luxembourg, Ireland, Portugal and the UK), only the UK remains a major global industrial power.

## **8.5 Scenarios and consequences**

In assessing the implications of future options for the UK it is important to contrast the status quo, with an expanded programme where the UK participates in a global endeavour involving humans and robots at a level consistent with our scientific, industrial and economic status.

The evidence suggests radically different outcomes for public interest and support: if we continue as we are UK space will continue to be perceived as ‘worthy but dull’ and will remain largely invisible to the wider public. We will become isolated from the other G8 nations and our space exploration capabilities will be overtaken by lesser economic powers.

Adherence to a policy of purely robotic exploration, under the status quo or in the context of an enhanced robotic programme, will deprive us of the ability to leverage human space exploration as a tool for education and public engagement. This in turn would do nothing to redress the crisis in science education and leave us with a limited ability to generate greater public support for space activities. It is perhaps unrealistic to believe that a sustained, significant increment in public funding for UK space activities could be secured in the absence of an increase in public interest and support. Evidence suggests that a space programme involving humans is likely to have – and retain – a higher public profile.

But whatever level is decided for future UK involvement in space exploration, it is important in a democracy that public impact and benefit are maximised. Space has great inspirational value for the young, our future scientists and engineers, and the UK involvement needs to be ‘branded’. If we are not a significant partner in a future global space exploration collaboration, including humans as well as

robots, UK space activities will continue to be poorly visible and an important opportunity to re-enthuse the public about science generally will be lost.

Several organisations in the UK currently administer programmes that make use of human space exploration as a vehicle for science education and as a tool for research. In addition to NSC's Challenger Learning Centre and the Scottish Space School these include undergraduate programmes in space medicine at University College London, Kings College London and Glasgow University as well as several bilateral research agreements with NASA and ESA laboratories. However, these programmes and the high impact of their associated benefits are facilitated, in whole or in part, by external space agencies. It is not realistic to expect that this support will continue should it become clear that the UK has no interest in engaging in human spaceflight activities; indeed ESA, have already formally withdrawn their support for all research activities relating to human space exploration in this country. Put simply when it comes to space exploration the UK cannot expect to have its cake and eat it – we cannot hope to enjoy the benefits that derive from human spaceflight, be they scientific, educational, cultural or societal, if we are not prepared to invest and play an active role in human space exploration.

## **8.6 A new era in space exploration**

The circumstances that led to the UK's historical decision not to be involved in human space exploration have changed. More nations than ever are committed to space exploration and there is a growing recognition that humans are essential to the science goals of future space programmes. The time is right for a reassessment of the UK's role in human space exploration, on scientific and technical grounds, and taking account of geopolitical, economic and cultural factors.

Chapter 5 of this report has suggested that important scientific questions about the nature of life, and the origins and history of the solar system, will be most effectively addressed by a blend of human and robotic exploration. The UK has a high international standing in planetary studies and to maintain and build on this expertise will require the freedom to take part in future international programmes on their scientific merit.

A global, collaborative endeavour in space exploration, in which humans are to play a central role, seems certain to materialise from current negotiations between international space agencies. The UK needs a clear vision and early commitment so that we can play an influential role and take full advantage of this new challenge. It is important to recognise that the Global Exploration Strategy and the recently signed NASA-BNSC Joint Statement of Intent create narrow windows of opportunity during which agreements of high value might be secured in the opening phases of these activities. Procrastination in this field has the potential to damage our future prospects significantly.

## **8.7 Summary and recommendations**

We find that the wider benefits of space exploration to education, commerce, society and culture are substantial but currently undervalued and inadequately exploited by existing UK space policy. UK space activities are currently all but invisible to the wider public and, because of this, fail to achieve their potential as a powerful vehicle for science education and as a tool for inspiration.

This is, in great part, a result of the UK's lack of involvement in human spaceflight. As the world enters a new era of space exploration it is no longer useful or wise to maintain the distinction between human and robotic spaceflight – and to do so would leave the UK increasingly isolated from the main thrust of international space efforts.

We do not advocate the pursuit of programmes of exploration solely because they are inspirational in nature. Rather we suggest that, in order to reap maximum benefit from UK space activities, we must better appreciate the complex interaction between science and society and the impact that this has on the popularity of science in schools and universities. The raft of benefits associated with space exploration, from science and technology to education and culture, should not be considered separately. For any space programme to be judged truly successful the whole should be far greater than the sum of these individual parts.

We therefore recommend that the UK should begin to engage in programmes of human spaceflight activity in order to prepare for an influential role in the Global Exploration Strategy and to enable it to

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reap the full spectrum of benefits associated with space exploration. In parallel with this the UK should develop a strategy for exploiting these benefits; one that should include co-ordinated and properly funded, sustained programmes of public engagement and education.

This is a new era in space exploration, in many respects a second space age. If the UK hopes to play an influential role in this endeavour, if it hopes to shape the way that space is explored and exploited by the world in this new century, then it must play a role in the full range of human and robotic space exploration activities from the start.

## 9 Implementation and scenarios

In order to achieve the goals described in this document consideration has been given to specific mission scenarios, international collaborations that might be sought and how such a programme might be implemented in the UK.

### 9.1 Programme scenarios

We considered the following four scenarios in order of increasing commitment:

- Status quo.
- Enhanced participation in robotic missions (e.g. Moon, Mars).
- Preparatory/limited programmes of human spaceflight.
- Full GDP participation in international human space exploration programmes.

#### 9.1.1 Status quo

This refers to the continuation of existing UK policy. It comprises a GDP-based contribution to the ESA Space Science Programme and a substantial contribution to the robotic and preparatory elements of the ESA Aurora space exploration programme. The Space Science Programme undertakes some planetary science missions selected in competition with missions in other area of space science (e.g. astrophysics). The Aurora programme, in contrast, is initially focused on the robotic exploration of Mars and in preparing Europe for a wider participation in space exploration. At present the majority of funding of Aurora is focused on the first mission, ExoMars, scheduled for launch in 2013. A later step is expected to be an international Mars sample return robotic mission (circa 2020 launch).

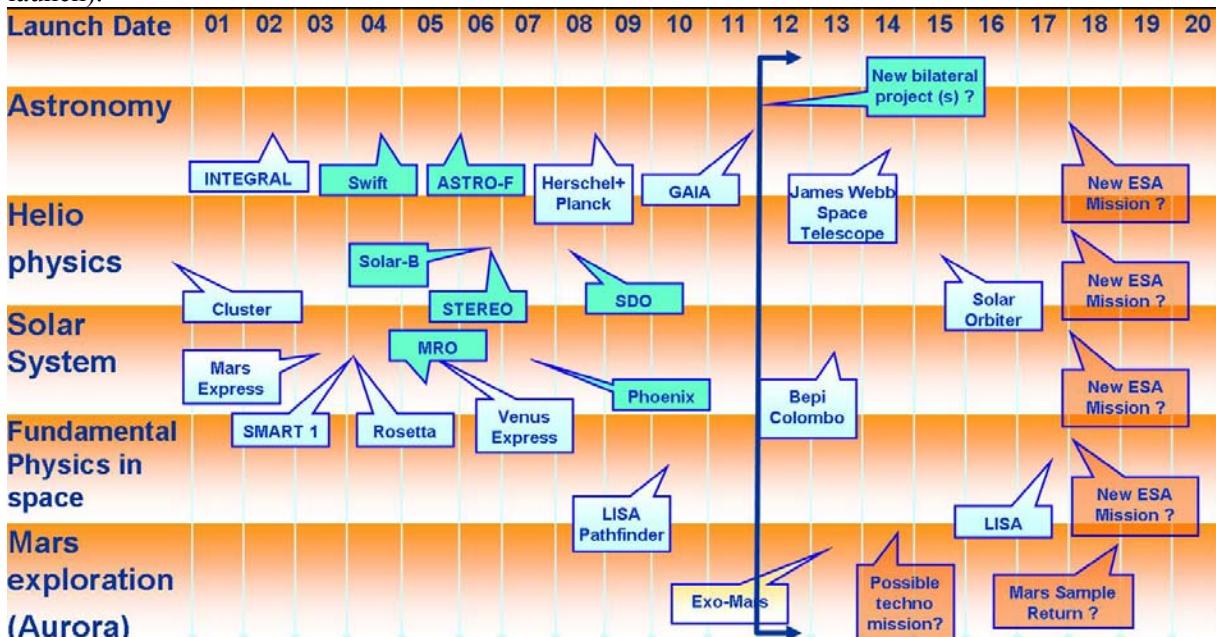


Figure 18 The UK's current robotic space science and exploration programme. Missions in blue boxes are through ESA; those in green are bilateral contributions to international missions; orange boxes represent future possibilities (Credit STFC)

The UK should prepare for involvement in the next round of activities to be included in the Aurora programme that are to be agreed at the ESA Ministerial Meeting in 2008. This would enable the UK to maintain (or if it chose, expand) its role in space exploration through ESA.

Maintaining the status quo, the UK would continue its tactics of limited national technology funding to secure targeted leadership in a few discrete areas. While involvement in the robotic aspects of Aurora is sufficient to maintain existing strengths it provides no mechanism for developing new capabilities or

expanding the UK portfolio of space activities. This threatens the UK's future competitiveness in the field of space exploration and impairs our ability to influence the future direction of global space exploration strategy. It would also inevitably remove the opportunity for the UK to choose to participate in scientific activities enabled by human space exploration.

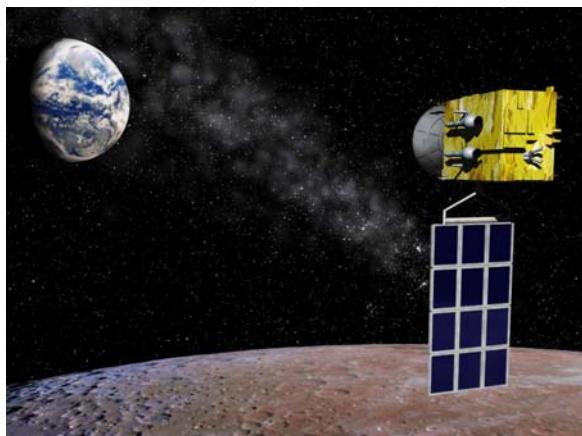
Pros	Cons
Maintains existing expertise in automated platforms. Good risk/return on financial investment in technology. UK models for financial exploitation of automated platforms/satellite technology already exist. Lowest cost.	Does not deliver lunar science aims. Does not provide access to International Space Station microgravity life and medical science data. Does not maximise opportunities for international collaboration offered by Global Exploration Strategy and limits UK ability to influence future international space science programmes. Bars UK scientists from many future opportunities in solar system research. Excludes benefits from human spaceflight activities (such as biomedical technologies, spin-outs and life and medical science data). Very limited possibilities for commercial developments. Limits ability to further public interest and understanding of science. Limited further value as a tool for education.

Whichever of the four scenarios described in this section is chosen, it is clear that the UK must, at the very least, continue its involvement in the programmes to which it is already subscribed. (See Recommendation 3 on page 74.)

### 9.1.2 Enhanced participation in robotic missions

This option refers to mission possibilities driven by exploration, commerce and science but excludes participation in human space exploration programmes. It builds on existing UK strengths in robotic activities through a stronger participation in robotic space exploration missions, using and building on our capabilities to provide a strong return for industry.

This extends the status quo option described above by including robotic exploration of the Moon and perhaps other destinations (the Near Earth Asteroids).



**Figure 19 MoonLITE is a UK concept for a science-driven lunar mission which would exploit UK expertise in small satellites (Artist's impression UCL)**

From the perspective of the benefits to technology and knowledge exchange this scenario offers good return on investment. It makes use of UK expertise in robotic space missions in and beyond Aurora. If the increment in investment were substantial, the UK could offer these capabilities to other agencies in order to advance other objectives. This would leave the UK in a strong position to secure a substantial place in the robotic elements of the Global Exploration Strategy.

However, exclusion from participation in human spaceflight activities impacts the UK's ability to prosecute the full programme of science described in the Global Exploration Strategy and deprives us of the ability to address a number of fundamental questions directly. From the public perspective it would be almost indistinguishable from the 'Status

Quo' scenario and hence of limited added value to education and programmes of outreach and to society in general.

Pros	Cons
<p>Maintains and develops existing expertise in automated platforms and robotics, extending and capitalising on involvement in Aurora.</p> <p>Secure method for extending proven capability to participate in all mission stages.</p> <p>Selected leadership in more areas.</p> <p>Strengthens opportunities for knowledge exchange.</p> <p>Optimal solution from perspective of technology and knowledge exchange.</p> <p>Some opportunities for commercial development such as communications services.</p> <p>Less costly than participation in HSE programmes.</p> <p>Valuable science return from lunar robotic exploration.</p>	<p>No participation in comprehensive human exploration of Moon and Mars.</p> <p>Bars UK scientists from many future opportunities in solar system research; limits UK ability to influence future international space science programmes, and lack of HSE component isolates the UK from all other G8 nations in space policy.</p> <p>Leaves the UK unable to address several fundamental scientific questions.</p> <p>Excludes benefits from human spaceflight activities (such as biomedical technologies, spin-outs and life and medical science data).</p> <p>Indistinguishable from Status Quo to the general public. Therefore limits ability to further public interest and understanding of science.</p>

To carry out this option, we propose in addition to the Aurora activities a sequence of missions in support of the scenarios proposed for lunar exploration. Example projects could include:

- A mission to validate a low cost communications satellite platform and its operational performance.
- A mission to validate precision entry, descent and landing, possibly in conjunction with a lunar communications satellite and some science capability.
- A mission to validate a low cost rover network, possibly in conjunction with a lunar communications satellite and lander/delivery device.
- A mission to validate a low cost micro-sample return strategy comprising small sample canister, its ascent propulsion and RVD with an in-situ sample collection and return platform. It may operate in conjunction with a lander, comsat and robotic network.
- A mission to transport a geologist astronaut across the lunar surface. The rover would be delivered remotely using other nations' delivery systems.
- A lunar facility of science payloads, test beds and transport devices that initially operate autonomously under Earth supervision but which later incorporate human tended activity.

Scenario selection and sequence will be led by scientific, commercial and societal goals and reflect the critical technology developments that could be offered by the UK.

<b>Recommendation:</b>	<b>In summary, we believe that the UK should initiate a targeted robotic lunar programme based on the use of low cost satellites, rovers and resulting operational services, ideally in collaboration with other partners while keeping control of some key technologies.</b>
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Further details of the science that could be supported were given in section 5.2.1 and the technical details were described in section 6.8.

### 9.1.3 Enhanced robotic and preparatory human spaceflight programme

This scenario includes the enhanced robotic elements described above as well as a limited early effort in

human spaceflight.

This has the principal disadvantage of being more costly than either of the previously described scenarios and would be a significant departure from existing policy. However a scenario including a limited effort in the field of human spaceflight would be useful in helping the UK to prepare for a more substantial and influential role in the Global Exploration Strategy and would allow the UK to access the full range of benefits associated with international space exploration programmes. This would have significant positive benefits in the fields of science, education and commerce.

It would also allow the UK to assess the benefits to be gained from a more substantial involvement, while avoiding the associated costs. It would thus provide a useful exit strategy should the expected benefits fail to be realised.

These additional human-related elements could form a coherent programme running from 2010 to 2015, at which point the decision on whether to take a full role in space exploration could be made.

Pros	Cons
<p>Maintains and develops existing expertise in automated platforms and robotics, extending and capitalising on involvement in Aurora.</p> <p>Prepares for participation in comprehensive human survey of Moon and Mars.</p> <p>Provides access to microgravity data including life and medical science research.</p> <p>Improved ability to influence future global space exploration strategy.</p> <p>Possibility of return from biotechnology associated with HSE missions.</p> <p>Potential for selected leadership in areas relevant to HSE as well as in robotic/automated platform technology.</p> <p>Provides all the advantages of enhanced robotic scenario with added benefit of spin out from HSE technologies.</p> <p>Some opportunities for commercial development, such as services and infrastructure.</p> <p>Opportunity to attract new funding partners.</p> <p>Best platform for programmes of public engagement and education.</p> <p>Less costly than full participation in HSE programmes.</p> <p>Takes advantage of many current opportunities for international collaboration offered by Global Exploration Strategy.</p> <p>Valuable science return from lunar robotic exploration.</p>	<p>More costly than scenarios focussing on robotic technology alone.</p> <p>Will require new funds and may require new administrative mechanism.</p> <p>Requires novel bilateral agreements with international space agencies.</p> <p>Increased risk; accidents involving humans could lose public support for space exploration in general.</p> <p>Cost-effectiveness of scientific return is unproven.</p> <p>Danger of mission-creep: poor management could lead to funding demands on existing science budgets.</p>

Based on the review of the plans of other nations (see chapter 4), coupled with our assessment of the scientific benefits (chapter 5) we have concluded that from around 2020 a growing part of the international effort to explore the solar system will be carried out through human space missions. In order to secure the benefits of playing a role in this endeavour, it will be necessary for the UK to begin to develop relevant skills. If this is started in parallel with the robotic activities mentioned above it would also allow the early delivery of some of the benefits of human spaceflight listed in chapter 8 ('Society') while also enhancing the UK's ability to influence international plans for exploration and the direction of global strategy.

There are various ways in which the UK might re-engage in human spaceflight activities: for example

through ESA; as a bilateral arrangement with Russia or NASA; or through some combination of these. A key goal of a preparatory human spaceflight programme would be to evaluate the perceived benefits before making a longer-term commitment to human spaceflight.

**Recommendation:** **We recommend that the UK should take appropriate early steps to prepare for a future role in human space exploration efforts by securing flight opportunities for British astronauts within the next decade to conduct science research and advance science education.**

Further details are given in Appendix D.

We note that ESA will be inviting applications to join its corps of astronauts during 2008. While UK citizens will in principle be able to apply, their chances of flight will be effectively zero unless the UK makes a commitment to participate in the relevant programmes. A commitment from the UK to participate in these programmes might provide an alternative route for such a preparatory programme.

#### 9.1.4 Full GDP participation in human space exploration

This refers to a full commitment by the UK to human space exploration programmes at a level commensurate with the size of the UK's economy.

If the UK were to begin a preparatory programme including human space activities now (as described in the previous section), it would then be in a position to decide whether to take a full role in the wider global exploration efforts by 2015 – around which time Europe is likely to move its spending on the ISS to wider space exploration activities. This approach would still allow the UK to play a significant role, while allowing time to review the early benefits of such a programme before it is necessary to commit the larger funds that would be required for a GDP-level involvement.

The UK is likely to continue to be a contributor of component technologies, instruments, platforms and support services in international collaborations of this type. There are however areas of science and commerce where the UK could play a leading role if it were to commit to the wider goals of human space exploration.

This scenario would represent a significant deviation from existing UK space policy and would require the largest increase in overall funding of all the scenarios. However, it has the advantage of fully realigning the UK with the space exploration activities of the other G8 nations and would greatly simplify interactions with the European Space Agency. Full participation in programmes of human and robotic space exploration would be accompanied by access to the full spectrum of benefits associated with space exploration programmes. This scenario provides the UK with the best ability to influence the future direction of international space strategy and would allow future generations of scientists to choose which missions to participate in, rather than being limited to those with no human involvement.

Pros	Cons
<p>Maintains and develops existing expertise in automated platforms and robotics, extending and capitalising on involvement in Aurora.</p> <p>Prepares for and commits to participation in comprehensive human survey of Moon and Mars.</p> <p>Provides access to microgravity data including life and medical science research.</p> <p>Provides best ability to influence future global space exploration strategy.</p> <p>Provides full access for UK scientists to future opportunities in research of the solar system.</p> <p>Possibility of return from biotechnology</p>	<p>HSE effort requires new funds to avoid top-slicing of science budget.</p> <p>Most costly scenario, requiring significant increment to existing budget from new sources. Requires largest commitment of public funds.</p> <p>May require novel bilateral agreements with international space agencies.</p> <p>Requires new administrative mechanism.</p> <p>Potential contamination of samples in searching for evidence of life.</p> <p>Most risky; accidents involving humans could lose public support for space</p>

<p>associated with HSE missions.</p> <p>Potential for selected leadership in areas relevant to HSE as well as in robotic/automated platform technology.</p> <p>Provides all the advantages of enhanced robotic scenario with added benefit of spin out from HSE technologies.</p> <p>UK contracts would be fully assisted by ESA ‘juste retour’ rules.</p> <p>Industrially attractive contracts: larger and of longer duration (though harder to win).</p> <p>Robotics still a key component for UK success.</p> <p>More technology opportunity: UK very good tier 1 supplier in space parallel industries.</p> <p>Good opportunities for UK commercial activities across wide range of fields from services and infrastructure to new media and tourism.</p> <p>Best platform for programmes of public engagement.</p> <p>Best return on investment for education programmes.</p> <p>Takes full advantage of current opportunities for international collaboration offered by Global Exploration Strategy.</p>	<p>exploration in general.</p> <p>If major discoveries do not emerge, initial public excitement may wane, e.g. Apollo programme.</p> <p>Opportunities for leadership limited by lack of experience in HSE.</p> <p>Danger of mission-creep: poor management could lead to funding demands on existing science budgets and other national and international priorities.</p>
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This would be the most obvious route to involvement in human space exploration, but it would require a step-change in funding equivalent to increasing the UK civil space budget by about a third. This would enable us to take part in all of ESA’s human programmes, but the UK would not have the capability to become involved at this level in the short term and thus would not be able to derive enough benefit from the investment required. We do not therefore recommend this option at this stage, but propose instead that it be regarded as a long-term goal to aim for while building involvement in incremental steps.

## **9.2 International collaboration**

We have outlined above four possible programme scenarios, any of which could be achieved through different routes. These include participation through subscription to ESA programmes, collaboration with NASA and other space agencies and those which could be wholly or substantially led by the UK. We conclude that:

- There are political, economic and knowledge exchange benefits in partnering with other nations in these exciting frontier challenges and we should look in particular to the emerging ‘super-economies’ for opportunities
- The ESA collaboration path is well established although we must seek UK leadership and industrial benefit
- Our interaction with NASA showed a great deal of openness and willingness to adopt UK technologies within US missions
- The establishment of international collaborations will be influenced by our downstream use and access to market (e.g. ITAR in US, respect for IP in China). Limitations on access to market for supply and freedom to use technologies should be a key consideration in formation of such alliances.

- Strength in UK technology capabilities will enhance our position in deriving the benefits we desire from space exploration

The Canadian model for participation in human space programmes is one the UK could successfully adopt. In this example, specific national technology (the Canadian robotic arm for use on the Shuttle and the ISS) is provided to other partners in exchange for both commercial contracts and flight opportunities for astronauts.

**Recommendation:** **Based on the foregoing, we recommend that the UK should identify and exploit opportunities for mutually beneficial, bilateral activities with NASA and other prospective partners. The Global Exploration Strategy and the recently signed NASA-BNSC Joint Statement of Intent create narrow windows of opportunity during which agreements of high value might be secured.**

### 9.3 Implementation actions

Irrespective of which scenario beyond the status quo is implemented, there are cross-cutting actions needed to secure the maximum benefits to the UK from any enhanced participation in space exploration.

Firstly in order for the UK to fully exploit the scientific return, a strategic approach to building an effective user community is needed. An approach that is being followed in the UK's national preparation for ExoMars is to have an annual call for fellowships in astrobiology. These are targeted at building the experience of scientists who will lead their field in the future. This approach could be extended to cover the full range of life and physical sciences relevant to the exploration programme.

**Recommendation:** **We recommend that the UK should build capacity in relevant UK scientific and technological communities by funding and establishing academic chairs, fellowships, post-doctoral and doctoral positions at UK centres of excellence. These positions should cover the full range of life and physical sciences relevant to the exploration programme, and would expand upon the success of the existing Aurora Fellowship scheme.**

**Recommendation:** **Furthermore we recommend engagement with research and industrial communities across a broad range of sciences and technology to assess the opportunities that may be raised in the new era of space exploration. This should extend beyond the existing BNSC core partners (DIUS, STFC, NERC) to include MRC and EPSRC and industrial sectors such as mining, prospecting, media and entertainment.**

Chapter 8 has identified the wider benefits of space exploration to science education, commerce and culture.

**Recommendation:** **We recommend that the UK should develop a strategy for exploiting the substantial, wider benefits of space exploration to science, education, commerce and culture. This should include co-ordinated, properly funded and sustained programmes of public engagement and education**

### 9.4 Costs

A detailed costing of the various possibilities is not provided here as it would require a fuller assessment by industry, academia and BNSC officials based on specific mission options, assumptions on the nature of international partnerships and detailed analysis of the roles that could be played by non-governmental finance. However, it is possible to give the rough order of magnitude of costs associated with each of the four scenarios we have listed in section 9.1 (all at 2007 economic levels):

- The current cost of participating in Aurora (i.e. the 'status quo') is around £20-25M p.a.
- An underpinning technology development programme would cost around £20M p.a. This could be built up gradually using various mechanisms, such as a dedicated

national programme, the proposed National Space Technology Programme, or participation in ESA programmes such as the Aurora Core Programme.

- A series of small lunar missions with strong UK involvement would cost a similar amount initially - though it would make sense to share the work and the cost with international partners (this would correspond to the ‘enhanced robotic’ scenario).
- A very rough estimate of the cost of a precursor human exploration programme would cost in the region of £10-15M p.a. over five years starting in 2010 (see Appendix D).
- Full participation in human spaceflight activities at a level proportionate to our GDP through ESA would cost around £60M p.a. starting in 2015. This is derived as follows. The annual budget of the ESA human spaceflight programme (focused on space station infrastructure including the Columbus laboratory and the ATV) was €365M in 2006; and the cost of the related microgravity science programme was €100M/yr. We assume that by 2015, the corresponding expenditure has been entirely re-focused on space exploration with no real terms growth or decline. This equates to €465M (or about £310M/yr) at 2006 economic conditions. At present, the UK NNI (net national income) represents about 18% of the total of ESA member states. This means that a ‘GDP UK share’ is 18% of any particular programme. For example, the UK contributes about 18% of the mandatory ESA Science Programme. An 18% share of a putative ESA human exploration programme is thus £56M/year at 2006 economic conditions.

We believe that it is unrealistic to seek full participation in human space exploration at a level commensurate with our GDP at this stage since this would involve a huge step-change which would not deliver sufficient benefits in the short term. We also believe that to continue with the status quo is equally unacceptable, since we would be limiting the UK to participation in only those activities in which it is currently engaged with no prospect of catching up later in order to take on new activities. In these circumstances, there would be no opportunity for UK scientists to choose to participate in international science missions that included humans and no prospect of UK citizens being selected as astronauts in the future.

We firmly believe that a significant new investment in robotic exploration activities is needed in order to deliver a range of benefits to science, to knowledge exchange and to industry and that a further investment in a preparatory human spaceflight programme is needed to deliver benefits to these areas as well as to stimulate the development of skills through inspirational space exploration and allow future access to a range of future science missions. This will also allow the building of capacity for future work and will allow the UK to judge the merits of future participation in a wider range of human space activities before a decision is needed on such investment at GDP levels.

We have emphasised in this report that the importance and benefits of space exploration to the UK extends beyond the value in pure science return. The range of benefits preclude a single ‘user’ in government being identified. Therefore a more strategic approach is needed. This is an organisational issue which it is inappropriate for this group to address other than to observe that the funding approach should recognise these wider benefits in education, technology and inspiration.

## 10 Synthesis of findings

There are scientific questions of great interest that can only be answered through the continued exploration of space. To date much of this science has been achieved through the use of unmanned spacecraft and robotics – in the UK exclusively so. However it is clear that in the coming epoch of space exploration there will be many questions that can only be answered if humans are present. This is especially true for the exploration of the Moon and Mars. Human lunar exploration will re-start around 2020, while a human Mars mission is not expected until the 2030s. A permanently crewed lunar outpost will enable areas of science well beyond the study of the Moon itself.

The debate as to whether or not humans or robots are best suited to space exploration is now redundant. Just as there are scientific questions of profound importance to space science that for the foreseeable future can only be addressed by using automated platforms, so there are those that can best be addressed through human presence.<sup>2,3,43</sup> (See Appendix E for details.)

Future UK space exploration strategy should acknowledge this and, while building upon our tradition of excellence in the field of remote sensing and satellite technology, we should prepare for a future role in programmes of human space exploration.

### 10.1 Exploration of the Moon

The primary scientific importance of the Moon arises from the fact that it has an extremely ancient surface, mostly older than 3 billion years, with some areas extending almost all the way back to the origin of the Earth-Moon system 4.5 billion years ago. It therefore preserves a record of the early geological evolution of a terrestrial planet, which more complicated bodies such as Earth, Venus and Mars have long lost, and a record of the inner solar system environment from billions of years ago. The Moon is thus a museum of the history of the solar system, and contrary to public perception, its surface, with its varied geology, remains largely unexplored. The surface can be surveyed by orbiters, but access to subsurface will require a programme of field geology and geophysics (including drilling to c. 100 m to km depths) that will require a mix of robotic and human presence. In addition to its scientific value, a thorough geological survey of the Moon will enable its long-term commercial and economic potential to be assessed and protected.

The Moon is also a vantage point from which to undertake new and challenging observations. A lunar observatory will revolutionise many areas of astronomy. These will include searches for evidence of life elsewhere in the universe, our understanding of the origins of life on Earth, and of climate change with its implications for the future of life on our planet:

- (i) We are now starting to discover large planets in other star systems. But to study Earth-like planets we may need a stable observatory on the airless Moon, since the accuracy we require may well be beyond the expected ability of free-flying telescopes of missions such as Darwin. Moreover, spectroscopic observations of Earth from the Moon will provide knowledge that we will require in order to interpret the spectra of extra-solar Earth-like planets when and if these are discovered.
- (ii) Understanding the dynamics of the connection between the Sun and the Earth is vital for predicting climate change. This is one of the most urgent challenges facing humanity and a stable lunar observatory could prove invaluable. It would also provide us with essential knowledge about space weather, which we are going to need if we are to protect astronauts on future missions beyond Earth.

### 10.2 Exploration of Mars

Mars is also an important target for exploration, especially in the context of our search for life elsewhere in the solar system. Mars' surface has been mapped by orbiters at 10-100 m scale but the absolute chronology of its surface features is unknown. Existing knowledge from Mars hints that geological changes affect the habitability of a planet. The history and nature of its lost atmosphere are unknown and may have important lessons for our own planet. Mars is a laboratory where we can learn about the habitability of planets and the prospects for life elsewhere.

Before humans can visit Mars to complete the above, we need to understand the environmental hazards,

be able to predict dust storms and measure the UV and cosmic radiation at the surface and to identify the most attractive locations. These require explorations with robotic sensors and the ability to return rocks from the surface, a venture which requires technical advances.

Human exploration of Mars will also require that we gain operational experience on hostile planetary surfaces, and a better understanding of the physiological and psychological consequences of long-term human exposure to the space environment. This knowledge and experience will be gained through precursor activities on the Moon and the International Space Station.

### **10.3 Humans and robots**

Exploration on the Moon offers unique information on the history of the solar system (including the early Earth's atmosphere and dynamo) and the evolution of our Sun. Recovering that evidence left on and beneath the lunar surface by the solar wind, and bombardment by comets and cosmic rays will require collection of material at depths of 100 metres or more in a variety of different geological settings on the surface of the Moon. We agree with the RAS Commission, which concluded that a robotics approach alone could not deliver this now or in the foreseeable future.

### **10.4 Technology and knowledge exchange**

Space exploration of the Moon, Mars and beyond offers unique opportunities for the UK economy through development of a generation of skilled engineers, products and services. Today the UK has secured a positive position in such exploration technology and knowledge exchange through its involvement in robotic exploration of the planets. It is sensible to build upon this by seeking wider opportunities for such partnerships since these would have the greatest potential for UK industrial leadership.

In the short-term we can therefore expect technology to focus on lunar and Mars initiatives that address communications, precision landing, smart roving, sample collection and surface operations. There are in addition new opportunities; from novel sources of energy and their management to drilling and construction. These bring together needs that can exploit already established UK terrestrial expertise in transport, aeronautics, materials, energy conservation and biomedicine.

### **10.5 Commerce**

Human society is now at a 'tipping point' where real business cases are being identified for space-based services beyond the relay of information around the Earth. We feel that commercial markets could complete, through mechanisms such as public-private partnerships, the government funding necessary to launch such new space ventures. Exploitation and enhancement of an initially government-stimulated infrastructure could enable highly profitable commercial applications in the same way that data-relay, GPS and reconnaissance have developed around the Earth. We have explored an example of data relay from a likely growing number of robotic and human lunar explorers and concluded that value can be extracted, although risk and customer commitments do need further study.

The UK is fortunately a leader in numerous areas of technology and science which lend themselves to innovative services linked to exploration. Government commitment to supporting the academic and industrial base in the UK should continue, coupled with revision of the UK space regulatory framework to maximise opportunities for entrepreneurs. High profile opportunities involving launch vehicles and low cost space missions are noteworthy, and will also serve to increase public interest with benefits to the future UK workforce. Commerce, along with education and society also stand to gain strong positive benefits from a UK presence in human space exploration and we endorse the recommendation to introduce a new programme to quantify these benefits.

Finally, if the UK does not act to secure these clear opportunities in space exploration, others will fill the void. Significant economic gains as well as benefits to the quality of life in the UK will not occur.

### **10.6 Society**

The benefits associated with increased UK involvement in the exploration of space are truly wide-ranging - from the international standing of the UK, through education and training in subjects vital to

future wealth creation, to the public view of the UK as a world leader.

It is widely accepted that there is a crisis in education in the UK, with the numbers of youngsters enrolling in science and technology subjects dropping at all levels. Space exploration can help, offering an outstanding opportunity to motivate a whole new generation of young people to study science.

There is no doubt that space is awe inspiring for the public and especially the young, who are the seed-corn for our future technology. Motivational factors are stronger where human astronauts are involved.

Planning for a renewed and enlarged programme of human space exploration is well advanced in several space-faring nations. Europe, through ESA, is actively involved and expects to begin recruiting a new astronaut corps next year.

## **10.7 Implementation and scenarios**

Reviewing the current involvement of the UK in robotic planetary science, we have concluded that this has yielded good scientific return and has helped build a capable technology base in universities, national laboratories and industry. It has also contributed to the UK's 'innovation engine' through the training of skilled individuals and by creating technology which has terrestrial application. The UK's present involvement in the ESA science programme and also in the robotic exploration of Mars (primarily through the ESA Aurora programme) is to be commended.

We have concluded that there is immediate scope to yield increased benefit to the UK through a targeted, near term involvement in exploration of the Moon, emphasising UK science interests and expertise in small satellites and robotics and likely to be undertaken through international cooperation on a bilateral/trilateral basis. A first mission could be launched as soon as 2012. Such involvement would make the UK an early contributor to the Global Exploration Strategy.

There does not presently exist a compelling rationale for the UK to immediately join the current ESA human spaceflight programme at a GDP level, as this is focused on completion and exploitation of the International Space Station. In particular, there would be little or no technological return and, *a priori*, the UK cannot be certain of securing astronaut places given the expectations of other member states.

However, we have concluded that there will be excellent scientific opportunities in a range of disciplines in the period beyond 2020 when the US intends to establish a permanently crewed lunar outpost, and also there exist significant wider societal benefits in participation in human spaceflight. This means that aiming to participate in the human exploration of the Moon (and later, of Mars) is a valid and important objective for the UK. Such involvement would build on the existing UK capabilities strengthened through early involvement in robotic lunar exploration.

In order to bridge the gap between the UK's present activities and capabilities and this mid-term goal of human exploration, it is necessary to develop a detailed plan for a preparatory phase of UK involvement in human spaceflight. This plan should be implemented in the decade beginning 2010 and involve a well-structured mix of scientific, technological and educational goals using the International Space Station as the destination as foreseen in Appendix D, a range of approaches seem feasible and a first astronaut flight in 2012 is quite conceivable.

In summary, we advocate a targeted and step-wise UK space exploration strategy based on both robotic and human activities. This national strategy should be implemented through negotiation with international partners in the context of the Global Exploration Strategy. Using this approach, it will be possible to demonstrate the scientific, technological, commercial and societal benefits as each milestone is implemented.

## 11 Recommendations and next steps

In order to make the most of emerging opportunities in the field of space exploration, maintain existing standards of excellence and develop new capabilities that ensure a prominent role in future international space activities the UK should:

1. Pursue a programme of space exploration in which an active role is played in both the robotic and human elements of the Global Exploration Strategy. (See p8)
2. Develop a strategy for exploiting the substantial, wider benefits of space exploration to science, education, commerce and culture. This should include co-ordinated, properly funded and sustained programmes of public engagement and education. (See p69)
3. Maintain leading UK involvement in planetary science within ESA Programmes and, where appropriate, in collaboration with other international partners. This must include continued involvement in the robotic exploration of Mars, especially through ESA's Aurora programme. (See p30)
4. Initiate a targeted UK robotic lunar programme based on the use of low cost satellites, rovers and resulting operational services, ideally in collaboration with other partners while keeping control of some key technologies. (See p65)
5. Identify and exploit opportunities for mutually beneficial, bilateral activities with NASA and other prospective partners. The Global Exploration Strategy and the recently signed NASA-BNSC Joint Statement of Intent create narrow windows of opportunity during which agreements of high value might be secured. (See p69)
6. Take appropriate early steps to prepare for a future role in human space exploration efforts by securing flight opportunities for British astronauts within the next decade to conduct science research and advance science education. (See p67)
7. Build capacity in relevant UK scientific and technological communities by funding and establishing academic chairs, fellowships, post-doctoral and doctoral positions at UK centres of excellence. These positions should cover the full range of life and physical sciences relevant to the exploration programme, and would expand upon the success of the existing Aurora Fellowship scheme. (See p69)
8. Engage with research and industrial communities across a broad range of sciences and technology to assess the opportunities that may be raised in the new era of space exploration. This should extend beyond the existing BNSC core partners (DIUS, STFC, NERC) to include MRC and EPSRC and industrial sectors such as mining, prospecting, media and entertainment. (See p69)
9. Investigate the current opportunities offered by a modest focused subscription to ESA's life and physical sciences programme (ELIPS) which could facilitate UK access to ESA's microgravity facilities in order to build up the UK life and physical sciences microgravity community in preparation for the longer term opportunities that will arise from participation in the GES. (See p30)
10. Initiate a substantial and sustained national technology R&D and demonstrator programme focused on those areas of technology which underpin the UK's goals. Knowledge exchange opportunities should be embedded in the programme from the start. (See p41)
11. Survey and identify customer commitments, and quantify value added business for the exploration-related services identified in this report – from near term (e.g. lunar communications relay) to long term (e.g. exploitation of planetary mineral rights). (See p52)
12. Review and update the UK licensing regime to encourage high value added activities such as space tourism and related activities such as inexpensive, regular and reliable launch of scientific payloads and small spacecraft which build on existing UK strengths and support proposed UK efforts in exploration. (See p53)

These strategic recommendations would allow maximum benefit to the UK by focused incremental funding in national, ESA and other international bilateral initiatives. The proposed programme

represents a broader ambition than the current science-driven exploration of space and so additional funds will be needed to promote the necessary activities in education, science, technology and knowledge exchange.

We believe this will generate new scientific knowledge, increase excitement for science and technology in the young to help build the workforce of the future, and provide a grand challenge to invigorate the UK economy.

## Appendix A Abbreviations

ALMA	Atacama Large Millimetre Array
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
ATV	Automated Transfer Vehicle
AU	Astronomical Unit (the distance from the Earth to the Sun)
AurAC	Aurora Advisory Committee (UK)
BNSC	British National Space Centre
CCLRC	Council for the Central Laboratory of the Research Councils (subsumed into STFC in April 2007)
CNES	Centre National d'Études Spatiales (French Space Agency)
CNSA	China National Space Agency
CREST	Collaborative Research in Exploration Systems and Technology (STFC programme)
CSA	Canadian Space Agency
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australian government body responsible for space)
DIUS	Department for Innovation, Universities and Skills
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Space Agency)
DMC	Disaster Monitoring Constellation
DTI	Department of Trade and Industry (now superseded by Department for Innovation, Universities and Skills and Department for Business, Enterprise and Regulatory Reform)
ELIPS	European Programme for Life and Physical Sciences and Applications utilising the International Space Station (ESA's microgravity programme)
EO	Earth observation
EPSRC	Engineering and Physical Sciences Research Council
ESA	European Space Agency
ESF	European Science Foundation
EUV	extreme ultraviolet
EVA	extra-vehicular activity
GDP	Gross Domestic Product
GES	Global Exploration Strategy
GPS	Global Positioning System
HESA	Higher Education Statistics Agency
HME	Human Spaceflight, Microgravity and Exploration (an ESA Directorate)
HSE	human space exploration
ICT	Information and Communications Technology
IoP	Institute of Physics
IP	Intellectual Property
ISRO	Indian Space Research Organisation (Indian Space Agency)
ISS	International Space Station
ITAR	International Traffic in Arms Regulations (US)
JAXA	Japan Aerospace Exploration Agency
JSC	Johnson Space Center (NASA)
KARI	Korea Aerospace Research Institute

KT	knowledge transfer
LEO	Low Earth Orbit
LOFAR	Low Frequency Array
LRO	Lunar Reconnaissance Orbiter
MBH	massive black hole
MRC	Medical Research Council
MSS	Mobile Servicing System (on ISS)
MSSL	Mullard Space Science Laboratory (UCL)
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NERC	Natural Environment Research Council
NESTA	National Endowment for Science, Technology and the Arts
NEXT	Next Exploration Science and Technology mission (ESA)
NRC	National Research Council (US)
NSAU	National Space Agency of Ukraine
NSC	National Space Centre (Leicester)
pc	parsec (about $30 \times 10^{12}$ km)
PPARC	Particle Physics and Astronomy Research Council (subsumed into STFC in April 2007)
PSLV	Polar Satellite Launch Vehicle (India)
RAE	Research Assessment Exercise
RAL	Rutherford Appleton Laboratory (STFC)
RAS	Royal Astronomical Society
Roscosmos	Russian Space Agency
RVD	rendezvous and docking
SET	science, engineering and technology
SOFIA	Stratospheric Observatory for Infrared Astronomy
SSS	Scottish Space School
SSTL	Surrey Satellite Technology Ltd
STAB	Space Technology Advisory Board (BNSC)
STFC	Science and Technology Facilities Council (created April 2007 from CCLRC and PPARC)
UCL	University College London
UHE	ultra high energy
UHECR	ultra high energy cosmic rays
UKSBA	UK Space Biomedicine Association
UN	United Nations
UV	ultraviolet
VSE	Vision for Space Exploration (US)

## Appendix B    Terms of Reference of the UK Space Exploration Working Group

### B1.    **Background**

The Group shall be an *ad hoc* committee that shall undertake tasks to:

- review current global plans for space exploration;
- assess what opportunities and benefits exist for UK participation, and;
- provide advice to BNSC and partners as to which areas the UK should focus on if it wishes to engage in space exploration.

This analysis is to be undertaken on behalf of BNSC partners for input to UK Space Board; BNSC Space Advisory Council; PPARC Science Committee (or its successor); STAB; and other relevant advisory committees.

These Terms of Reference have been reviewed by the Chair of UK Space Board and the DG of BNSC and agreed by UK Space Board.

Day to day, the Working Group shall report to the BNSC Director of Space Science and Exploration.

### B2.    **Objectives**

UK Space Board wishes to understand these developments further and to understand the specific opportunities and benefits that may exist for the UK. To this end, the following tasks shall be carried out:

1. Review existing documentation addressing international plans and programmes (actual or projected) for space exploration (robotic and human) and synthesise into a consistent format.
2. Attend key international meetings especially NASA/AIAA exploration conference in Dec 2006; ESA/BNSC Exploration Workshop in Jan 2007, and JAXA workshop in March 2007.
3. Review the **scientific rationale\*** for space exploration (robotic and human), focused on key destinations (Moon, Mars, asteroids) and synthesise into a consistent format.
4. Review the **technological and knowledge transfer** goals for space exploration (robotic and human) and synthesise into a consistent format.
5. Review the short and long term **commercial opportunities** (manufacturing and services) arising from global space exploration and synthesise into a consistent format.
6. Review the wider **societal benefits** from space exploration (including at least educational, outreach, political) and synthesise into a consistent format.
7. Assess the outputs of Tasks 1-5 and - using a 1-2 day workshop mechanism - propose three-four different **scenarios for UK participation** (e.g. 'classical' through ESA; bilateral with NASA; through partnering with developing countries; purely commercial...) and describe the pros and cons including (to a first order) the likely cost implications to Government. One scenario shall be a minimum/zero participation, in order to assess the implications of non-engagement.
8. Prepare and agree a set of **conclusions** and **recommendations** to UK Space Board and DG of BNSC based on the findings of the Working Group.

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\* science shall encompass all relevant disciplines: planetary; solar; astronomy; medicine; microgravity etc.

### B3. Membership

Responsibility	Lead responsible	Additional Support
Working Group Coordinator	Jeremy Curtis, CCLRC Rutherford Appleton Laboratory*	Laura Bocarro (secretariat)
Science Rationale sub-Group	Prof Monica Grady (PPARC Science Committee* and member of ESF Space Science Committee)	Dr Ian Crawford (Birkbeck College; member of PPARC lunar mission options science steering group) Prof Jenny Thomas (Chair PPARC Science Committee) Prof Peter Wilkinson (Associate Director, Jodrell Bank Observatory, University of Manchester) Prof John Zarnecki (PPARC Council*, ESA exploration working group lead for science-driven scenario)
Technological/KT Rationale sub-Group	Nathan Hill (PPARC Industry coordinator;* author of ABOTTS report on KT potential of Aurora)	Dr Ian Gibson (BNSC Director of Technology and Industrial Policy) Dr Mike Hapgood (Head of Space Plasma Group at RAL; Chair of ESA Space Weather Working Team; representing CCLRC*) Chris Lee (UKSpace rep. on AurAC, Chair of Space Science and Exploration sub-committee of UKSpace) Dr Steve Welch (UCL MSSL Technology Management Group; lead of Photonics Knowledge Transfer Network)
Commercial Rationale sub-Group	Prof Sir Martin Sweeting (CEO SSTL; Member of Advisory Committee to ESA HME programme)	John Auburn (Chair of UKSpace – space industry trade association) Dr Andy Hide (LogicaCMG) Chris McLaughlin (VP Corporate and Investor Communications, INMARSAT Ltd. - leading UK-based space telecoms company) Richard Tremayne-Smith (Head of International Relations, Manned Space and Microgravity, Small Satellites, and Space Environment at BNSC, representing DTI) David Williams (CEO Avanti Communications – commercial space and media company)
Societal Rationale sub-Group	Prof Frank Close (Particle Physicist; writer and broadcaster; Chair of RAS Commission on the Scientific Case for Human Space Exploration)	Alex Blackwood (Careers Scotland; organiser of Scottish Space School) Dr Kevin Fong (Co-Director, Centre for Altitude Space and Extreme Environment Medicine; holder of NESTA Fellowship to work at NASA JSC; Chair of UKSBA; Hon. Senior Lecturer in Physiology, UCL) Katy Haswell (TV presenter; communications and new-media) Prof Steve Miller (Professor of Science Communications and Planetary Science, UCL) Prof Ken Pounds (ex CEO PPARC; ex President of RAS)

\* The above list reflects the affiliation of members of the Group when it was set up in January 2007. However, PPARC and CCLRC were merged to form the Science and Technology Facilities Council (STFC) in April 2007. The current affiliations are shown on the list on p2.

## Appendix C Acknowledgements

The members of the Space Exploration Working Group are indebted to the following individuals for their help either in preparing this report or commenting on previous drafts:

Martin Agnew (BAE Systems Advance Technology Centre)  
Walt Aldred (Schlumberger Cambridge Research)  
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Dr Adam Baker (SSTL)  
Laura Bocarro (STFC)  
Dr Philippa Browning (Univ. Manchester)  
Dr Bill Colglazier (Executive Officer, US National Academy of Sciences and CEO, National Research Council)  
Professor Len Culhane (Chairman, Space Academic Network)  
Phil Davies (SSTL)  
Professor Mike Edmunds (STFC Council)  
Dr Lindsay Fletcher (Univ. Glasgow)  
James Hamilton (British Titanium/Green Metals Ltd)  
Dr Tim Horbury (Imperial College)  
David Iron (LogicaCMG)  
Rich Leshner (NASA HQ)  
Professor Alan O'Neill (Director, National Centre for Earth Observation)  
Dr David Parker (STFC/BNSC)  
Professor John Peacock (Univ. Edinburgh)  
Dr Chris Pickering (QinetiQ)  
Professor Lord Rees of Ludlow (President, Royal Society and Astronomer Royal)  
Professor Michael Rowan-Robinson (President, Royal Astronomical Society)  
Marcia Smith (Director, NRC Space Studies Board)  
Jeff Volosin (NASA HQ)  
David Wade (Atrium Space Insurance Consortium)  
Dr Tim Yeoman (Univ. Leicester)

## **Appendix D A scenario for preparatory human spaceflight activities in the UK**

### **D1. Introduction**

One of the tasks of the Working Group was to assess scenarios for UK involvement in a space exploration programme. In this Appendix, for illustrative purposes only, we give an outline for a potential UK human spaceflight programme, with very approximate estimates of cost.

If the UK should choose to be an influential partner, when the human exploration of the Moon begins in 2020 and later when the first human exploratory efforts on Mars take place, preparatory human spaceflight activities will be required in the short-term. The purpose of these programmes would be:

1. To enable the UK to evaluate the relative costs of participation at full GDP level.
2. To identify and define areas of scientific research related directly to human space exploration upon which the UK might focus.
3. To identify and define areas of science and technology related directly to human space exploration in which the UK might develop niche leadership.
4. To determine more comprehensively the impact of larger scale programmes upon science education in schools and universities.

These preparatory activities could include astronaut training opportunities, exposure to terrestrial extreme environment analogues and human spaceflight opportunities secured through bilateral arrangements. It is essential that any such programme be accompanied by a corresponding programme of science, public engagement and education. By way of illustration a scenario under which British astronauts might secure flight opportunities within the next five to ten years is outlined below. The timelines and mission details are illustrative but this scenario is feasible logically, economically and politically within existing frameworks.

### **D2. Programme illustration for UK pathfinder astronauts**

A five-year programme is proposed, for purposes of illustration, to run between 2010 and 2015, under which two British astronauts could be flown aboard the International Space Station before 2014. The total cost for this programme would be £50-75 million. This would allow the UK to judge the return to science, industry and to society in general (principally through education) before any commitment is made to longer-term human space exploration with international partners.

The astronauts would carry out research in life and medical science, astrobiology, lunar geology and aerospace engineering in partnership with UK universities. They would be supported by two backup astronauts. The programme would include four research Chairs together with eight postdoctoral posts and 16 PhD students in order to build capacity in the research community. This would be supplemented by a team of four education specialists to provide an outreach programme to schools and the public.

Astronaut training and flight opportunities will be traded for technology and expertise while science and launch costs will be funded directly through public funds or via a public private partnership. It is possible that a limited, well circumscribed British project with a sufficiently high public profile would attract sponsors from the private sector, from the space industry and from areas outside of the existing UK network.

### **D3. Mission structure and timelines**

- |       |                                 |
|-------|---------------------------------|
| 2010: | Astronaut Selection             |
| 2011: | Astronaut training begins       |
| 2013: | First British Astronaut flight  |
| 2014: | Second British Astronaut flight |

#### **Notes:**

1. Four astronaut candidates would be selected in 2010. Of these two would eventually fly and two would serve as mission backup.
2. Flight opportunities after 2010 rely upon Soyuz as the delivery system.

3. Raw flight costs are approximately \$20 million per flight.
4. Flight costs include basic training, flight, and a small payload mass.
5. This price does not include comprehensive, operational training required for more in depth operations. (These include extravehicular activity and formal Mission Specialist activities).
6. The price does not include payload mass for more substantial flight experiments and payload development costs.

#### **D4. Science programme and suggested timelines**

The flown science will rely largely upon bilateral agreements between UK laboratories and international space agency laboratories. Medical science could, for example, be coordinated through the US National Space Biomedical Research Institute. Potential research areas include: space life and medical science; astrobiology; lunar geology and aerospace engineering.

Date	Flight Programme:	Ground Programme:
2009	Announcement of opportunity	Announcement of opportunity
2010	Science payload selection	Ground Project selection
2011	Science payload development	Ground Project development
2012	Manifest payloads for flight	Project Execution
2014	Flight of first group of science payloads	
2015	Flight of second group of science payloads	Data reduction, processing and publication
2015	Data reduction, processing and publication	

**Notes:**

1. The science programme requires partnership with UK university departments to provide an infrastructure within which research can be properly executed.
2. As part of this scenario, research Chairs would be endowed at 4 universities. Accompanying each Chair would be 2 postdoctoral posts and 4 new PhD programmes. The university partnership should therefore yield 4 chairs, 8 postdoctoral posts and 16 PhD graduates during the five year programme.
3. Each Chair could be endowed at an estimated cost of £5 million. The total cost of the university partnership therefore is £20 million.
4. The flight programme should include a small number of high quality research projects. While these represent the programme highlights, in terms of visibility and media attention, they by no means represent the bulk of the science programme.
5. The role of the flight programme is to provide a focus for science education and outreach. The flight component is the unique selling point of this endeavour.
6. The ground programme will be broader in scope and more extensive. It will be prosecuted by a larger science team than the flight programme and the effort will be spread across four universities.
7. Although related to human space exploration goals, it will not be dependent upon data derived from the flight programme. This serves to protect the overall programme against slippage of launch schedules, flight losses, failures and cancellation.
8. The role of the ground programme is to build capacity and expertise in the UK in preparation for lunar exploration operations.
9. The overall programme should be designed such that launch failures, losses and cancellations do not represent single point vulnerabilities. Even in the absence of flight opportunities the programme should still be able to deliver a programme of high quality

#### **D5. Outreach**

The success of this effort depends upon an integrated and well co-ordinated programme of education and outreach. It is anticipated that this will account for a significant fraction of the overall costs.

1. The outreach programme requires a dedicated, full time team.
2. This team would be responsible for educational outreach as well as public outreach.
3. The outreach team comprises four individuals with specific outreach remit:
  - 1 full time team leader (£45k per annum)
  - 2 supporting outreach staff members (£35k per annum)
  - 1 PA/administrator (£30k per annum)
4. The outreach team will cost £0.6 million over 5 years in salary alone.
5. Outreach programme costs and materials are not factored into this sum.
6. Self-funded media partnerships should be formed in parallel with the outreach programme.

## Appendix E    The relative efficiencies of human and robotic exploration of planetary surfaces<sup>35</sup>

Although humans will face many dangers and obstacles operating on other planets, mostly because of their physiological limitations when compared to robots, under certain circumstances potential scientific returns are sufficient to justify employing astronauts as field scientists.<sup>36,43</sup>

We illustrate the value of astronauts as field geologists with a single example from the Apollo missions. Apollo 17 landed in the Taurus-Littrow Valley on the south-east shore of Mare Serenitatis. The valley lies between two large mountain blocks (the North and South Massifs), and is approximately 8 km wide. The Apollo 17 Lunar Module landed close to the centre valley, near a prominent cluster of small craters. During their three days on the lunar surface, the two astronauts conducted three traverses with the lunar roving vehicle. Each sortie was just over 7 hours long, resulting in a total time spent outside the Lunar Module of 22.1 hours. The total distance traversed was 35 km, and a total of 110 kg of rock and soil samples were collected and returned to Earth.

The Taurus-Littrow valley turned out to be a geologically diverse locality. The valley floor consists of a basaltic fill, which flooded the Serenitatis Basin approximately 3.75 billion years ago. The North and South Massifs are highland blocks that were uplifted by the Serenitatis impact, approximately 3.9 billion years ago. Samples were obtained from both these units. In addition, a number of interesting serendipitous geological discoveries were made. Firstly, there is the ‘orange soil’, discovered close to the base of the South Massif, and which turned out to be a deposit of 3.6 billion year old volcanic glass. The second example is the coarse-grained sample found close to the base of the North Massif, which represents material from a very ancient (*c.* 4.3 billion year old) igneous intrusion. All these samples, together with those obtained at the other Apollo landing sites, have added greatly to our knowledge of the origin, and subsequent geological evolution, of the Moon.<sup>37,38,39</sup>

It is instructive to compare the speed, and relative thoroughness, of the Apollo 17 exploration of the Taurus-Littrow valley with what could have been achieved using small-scale robotic rovers of the *Spirit* and *Opportunity* type. During its first 330 days of operation on Mars, *Spirit* traversed a total distance of just 3.9 km, which may be compared with the 35 km covered in three days by the Apollo 17 crew. A *Spirit*-type rover deposited in the middle of the Taurus-Littrow valley would not have moved off the basaltic valley floor in a whole year’s worth of operation, and would therefore not have approached the interesting geological localities around the Massifs. Moreover, while in one year *Spirit* remotely determined the approximate major element geochemistry of perhaps a dozen rocks, the Apollo crew was able to collect, and return to Earth for more detailed analysis, 471 discrete samples having a total mass of 110 kg. In addition, in their 22 hours on the surface, the Apollo 17 astronauts obtained a 3 m deep core sample of the regolith, measured the lunar heat flow by sinking thermocouples about 2 m below the surface, deployed 8 explosive packages around the Taurus-Littrow valley as part of an active seismic profiling experiment, measured the local gravity field using a traverse gravimeter, measured the mechanical and electrical properties of the lunar regolith, and performed a number of additional surface experiments<sup>37,38</sup> – all in just three days of field work.

Comparing the three days spent exploring the 8 km-wide Taurus-Littrow Valley with the 330 days spent by *Spirit* exploring just 3.9 km of the floor of Gusev crater, there can be no doubt that human exploration is not only orders of magnitude more efficient than robotic exploration, but that astronauts can accomplish exploration goals that are not possible using robots. Given the tremendous technical success of *Spirit* and *Opportunity* it seems harsh to point out their limitations, but the truth is that had human crews landed at those sites on Mars they could have accomplished all that rovers have done in a year in a single afternoon. Moreover, many of the scientifically most interesting localities on Mars (such as scarps at the edge of the polar ice deposits, and the floors and walls of outflow channels) are characterised by steep slopes and rugged terrain that are not readily accessible to robotic exploration. It is at just such locations where the versatility and experience of human explorers come into their own.

## Appendix F Public responses to BBC poll

During the course of the RAS study the public view on a possible UK astronaut programme costing £150M a year was tested via the BBC web site. The public response was strongly positive with 62% in favour and only 26% against. In making the case for an expanded UK effort in space exploration, including humans, we might let the public speak for themselves. Views sent to the BBC web site and reflecting the majority opinion included the following:

*I'd spend lots more on space to help British industry retake the lead in newer technology areas.*

*Humankind are natural explorers, we need to keep expanding our frontiers or continue in our stagnation. Travelling the solar system will help unite the planet and make politics insignificant, thus solving many of the worlds problems. Also, by only existing on one planet we are putting all our eggs into one basket!*

*Robot probes are ok, but they can never anticipate the unexpected. Maybe Beagle 2 wouldn't have failed if there'd been a man with a spanner aboard.*

*With all the arguments, nit picking and irritations about EU budgets, Iraq, road/rail congestion, NHS etc etc Britain really, really needs a big idea to challenge and inspire us. It's like a family, it can spend all the money on bills and housework but without the holiday, life gets very tedious. Lets just look over the horizon for a change.*

*There is a strong argument that cheaper unmanned space projects reap greater scientific rewards than manned missions, but I think the desire to explore is an intrinsic part of human nature and long may it continue. Our ultimate fate depends upon it.*

*Through government funded investment in this high tech arena we can build upon our highly skilled but very small workforce in this industry. Creating well paid, highly skilled jobs should be a priority for any government. Look at what France gets back from its significantly higher contribution to the ESA.*

*Recent BBC report of UK pupil saying science is 'dull and hard' clearly suggests that children neither have any role models in science nor their imagination is fired up to pursue science. Even more than 35 years on, some of the Apollo astronauts are still motivating and inspiring US school children to become future astronauts. A robot can never achieve what a geologist can do once on a planetary body.*

*Today people don't care about science and it is really starting to show. The world needs a new scientific challenge and a new goal to shoot for we need the kids to get excited about math and physics that way we have a new generation that wants to learn about everything around them. We need to provide curiosity for the young because that is what drives man to learn.*

*Unmanned missions are excellent pathfinders, scouts and adjuncts to human missions. However for detailed exploration and investigation humans have unparalleled dexterity, adaptability, and expertise that robots lack as well as understanding, imagination, and intuition. It is worth noting that a human astronaut on foot would have covered the ground in a single day that that current mars exploration Rovers took more than a year to cover. They would have also explored it more effectively. While the initial cost of human missions is higher the return on that investment is many times what would be achieved by a robotic mission.*

*I think the most notable thing about this question is its phrasing: in terms of money. Forget the potential for developing new spin-off technology, forget how useful it is to have British engineers and technicians working alongside people who can teach them new tricks, forget the direct access to important scientific data that we need. Only the money matters; everything else is secondary. This is so typical of the modern British way of looking at anything, that it is hardly surprising we've lost ground to other, more forward-thinking nations in almost every field of endeavour. The only field where we seem to reign supreme, in fact, is banking and financial services - money-counting, in other words.*

*I really don't understand why this isn't obvious. These benefits are staring us in the face. So what are we waiting for - let's get out there in the forefront of this brave new 'world' - while we still can.*

*It is important that the British Government get off its backside and invest in*

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*the countries future. Sitting on the sidelines and watching the likes of China, India and others overtake us is irresponsible. Space is the future.*

*It's funny how the day after opinions on funding human spaceflight are followed immediately by a report stating that most schoolkids find science difficult and/or dull. Surely there is a connection here.*

*Yes, my husband and I find scientific exploration in times of an increasing return to religious fundamentalism very important and would not have any problems supporting human space exploration. Science is extremely important for us humans to understand ourselves and what's going on around us.*

*Manned spaceflight involves probably the widest range of different disciplines possible. Psychology, physiology, and multiple engineering disciplines are all involved. When different specialists work together is when new ideas evolve and we in the UK are needing to move to being an 'ideas economy'. Specific examples from the space industry include fuel cells, smoke detectors (after the Apollo 1 fire), the Gaia Hypothesis, (from James Lovelocks planetary research) and some of the first ideas about global warming after planetary scientists asked why Venus was so different from Earth.*

*Will it solve world hunger? Probably not, as that is a matter of political will as there is already enough food in the world for no one to starve. But spending money on these sort of projects may bring about ideas and technologies that may help, and increase the co-operation between nations that is needed to solve these sorts of problems.*

## Appendix G    The RAS poll on UK involvement in human space exploration

The RAS conducted a poll of its Fellows in February 2007 on possible UK involvement in human space exploration. Over 450 members of the RAS voted on the statement (below) and overwhelmingly (by 442 to 18) endorsed it.

The text that was agreed is as follows:

*'The RAS strongly endorses the scientific benefits of space missions, which have transformed our knowledge of the Earth, the solar system and the universe over the past 50 years.'*

*'The RAS holds to the view that the prime driver in selection of scientific space missions, within an inevitably limited budget, should be the quality of the science.'*

*'The RAS recognizes that there may be some scientific goals that can only be achieved within a human spaceflight programme (see the Report of the RAS Commission on [The Scientific Case for Human Spaceflight](#)). However these goals are likely to be feasible only within a greatly expanded scientific space programme.'*

*'The RAS also recognizes that the space programme is a powerful attractor of schoolchildren and students towards STEM subjects, and that the space industry is an important sector of the UK economy. Educational, economic and technological arguments might support a UK involvement in human spaceflight. However this would require separate funding, additional to the science budget.'*

## Appendix H Notes on possible lunar resources

It is possible that the Moon contains natural resources of potential economic value to human civilisation. In principle, such resources could be of value to the terrestrial world economy, or to future space operations, or both.

### H1. Helium-3

Much previous work on lunar resource exploitation has centred on the possible use of  $^3\text{He}$  in the lunar regolith as a potential fuel for future nuclear fusion reactors.<sup>40</sup> The alleged advantage over the deuterium-tritium (D-T) fusion reactions currently under investigation is the lower neutron fluxes resulting from the use of the neutron-poor  $^3\text{He}$  isotope. However, this is flawed. D- $^3\text{He}$  fusion has a much lower reaction cross-section than D-D, and so any D in the reactor will dominantly fuse with D to make tritium. In turn this will lead to a dominant D-T reaction, which is the primary fusion process already employed at JET. Thus D- $^3\text{He}$  fusion has no obvious practical advantages, even were  $^3\text{He}$  copiously available and we discount this as a reason for lunar mining.

There have been suggestions that  $^3\text{He}$ - $^3\text{He}$  fusion could achieve such ends. However the rates for this are significantly suppressed relative to the conventional D-T reaction, which itself has yet to be demonstrated as a practical reactor, and there is no realistic expectation that such a  $^3\text{He}$ - $^3\text{He}$  fusion programme will be pursued within the next 30 years, if ever.

It is difficult to see that  $^3\text{He}$  can ever be the panacea it is sometimes claimed to be, or how it could ever be economic (passing over the fact that its technical feasibility has yet to be demonstrated anyway).

### H2. Polar volatiles

It is widely recognised that permanently shadowed polar craters may contain deposits of frozen water (and other volatiles) delivered to the Moon by Comet impacts. Observations from both the *Clementine* and *Lunar Prospector* orbiters provides some indirect evidence for such deposits, and instruments on *LRO* and *Chandrayaan-1* may be able to confirm or refute these observations. Detailed knowledge of the extent and composition of any such deposits will probably require *in situ* analysis and/or sample return. If present, such volatile deposits (especially water) would be of great value for future human operations on the lunar surface (as a potential source of water, hydrogen, and oxygen), in addition to being of wider scientific interest.

### H3. Other exploitable resources

The extent to which other economically exploitable mineral deposits may exist on the Moon is currently unknown. As the Moon is apparently wholly lacking in water (apart from the possible polar ice deposits mentioned above), the hydrothermal concentration of economically important minerals, which is important for ore formation on Earth, cannot have occurred. On the other hand, there has been a lot of molten rock on the Moon in the past (e.g. an original ‘magma ocean’, and several later episodes of partial melting) to produce a range of intrusive and extrusive igneous rocks. Gravitational settling of crystals within melts can in principle concentrate economically important minerals, and the very low viscosity of lunar basaltic melts is expected to enhance the efficiency of this process.<sup>41</sup> To quote from Papike *et al.*:<sup>42</sup>

*‘It is therefore possible that layered ore deposits similar to or even larger than those on Earth may occur on the Moon.’*

### H4. Conclusion

Like so much else in lunar science, we won’t have an answer to the extent of economically exploitable lunar resources (if any) until we have conducted much more thorough geological surveys of the Moon than anything attempted to date. Thus, while it is premature to predicate a return to the Moon on economic exploitation of lunar resources, there is a strong case for conducting in-depth scientific exploration so that, among other things, its long-term economic potential can be assessed.<sup>43</sup>

## Appendix I      References

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- <sup>1</sup> *The Global Exploration Strategy: The Framework for Coordination*, May 2007, agreed and published by ASI, BNSC, CNES, CNSA, CSA, CSIRO, DLR, ESA, ISRO, JAXA, KARI, NASA, NSAU, and Roscosmos, [http://esamultimedia.esa.int/docs/GES\\_Framework\\_final.pdf](http://esamultimedia.esa.int/docs/GES_Framework_final.pdf)
- <sup>2</sup> *The Scientific Context for Exploration of the Moon* – Final Report, National Research Council of the National Academies, 2007
- <sup>3</sup> Close, F., Dudeney, J., Pounds, K., *Report of the RAS Commission on the Scientific Case for Human Space Exploration*, Royal Astronomical Society, 2005 *Report of the RAS Commission on the Scientific Case for Human Space Exploration*, Royal Astronomical Society, 2005, [http://www.ras.org.uk/images/stories/ras\\_pdfs/Final%20Report%20October%202005.pdf](http://www.ras.org.uk/images/stories/ras_pdfs/Final%20Report%20October%202005.pdf)
- <sup>4</sup> ‘Spineto Declaration’, from Second Workshop on International Cooperation for Sustainable Space Exploration, Abbazia di Spineto, Sarzana, Italy, May 2006, [http://www.esa.int/SPECIALS/Global\\_Space\\_Exploration/SEM76YBE8YE\\_0.html](http://www.esa.int/SPECIALS/Global_Space_Exploration/SEM76YBE8YE_0.html)
- <sup>5</sup> *The Vision for Space Exploration*, NASA, February 2004, [http://history.nasa.gov/Vision\\_For\\_Space\\_Exploration.pdf](http://history.nasa.gov/Vision_For_Space_Exploration.pdf)
- <sup>6</sup> *Joint statement of intent for cooperation in the field of space exploration by the United States National Aeronautics and Space Administration and the United Kingdom British National Space Centre*, 19 April 2007
- <sup>7</sup> *Moon: the 8th Continent: Human Spaceflight 2025*, Report of the Human Spaceflight Vision Group, ESA, 2003
- <sup>8</sup> *Future of European Space Exploration: Towards a European Long term Strategy*, ESA, 2005
- <sup>9</sup> *China's Space Activities in 2006* ([http://news.xinhuanet.com/english/2006-10/12/content\\_5193446.htm](http://news.xinhuanet.com/english/2006-10/12/content_5193446.htm))
- 10 C.P. Sonett, *Some consequences of solar wind induction in the Moon*, Phil. Trans. R. Soc. Lond, A285, 537-547, 1977.
- <sup>11</sup> *Climate Change 2001*, Third Assessment Report of the Intergovernmental Panel on Climate Change, <http://www.ipcc.ch/pub/online.htm>
- <sup>12</sup> *Science for a sustainable future 2002-2007*, NERC, 2002, <http://www.nerc.ac.uk/publications/strategicplan/sustainablefuture.asp>
- <sup>13</sup> Zook, H.A. and McCoy, J.E.: *Large scale lunar horizon glow and a high altitude lunar dust exosphere*, Geophys. Res. Lett. 18, 2117-2120, 1991.
- <sup>14</sup> *Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report*, US National Research Council (available at <http://www.nap.edu/books/0309095301/html>).
- <sup>15</sup> ESA, *Darwin and Astronomy*, ESA SP-451, 2000
- <sup>16</sup> Quoted from RAS discussions with Daniel and Newman of Oxford University and McAree of University of Queensland (as cited in RAS Commission Report, 2005).
- <sup>17</sup> Wakeham, B., Sykes, R., Williams, P., Garwood, S., *Recommendations of the Microgravity Review Panel*, (2003), and Ministerial statement, <http://www.microgravity.org.uk/review.htm>
- <sup>18</sup> *UK Space Strategy 2003-2006 and beyond*, BNSC, 2003, <http://www.bnsc.gov.uk/content.aspx?nid=5550>
- <sup>19</sup> G. K. Noreen, R. J. Cesareo, L. J. Deutsch, C. D. Edwards, J. A. Soloff, T. Ely, B. M. Cook, D. D. Morabito, H. Hemmati, S. Piazzolla, R. Hastrup, D. S. Abraham, M. K. Sue, F. Manshadi, *Integrated Network Architecture for Sustained Human and Robotic Exploration*, IEEEAC paper #1378, Aerospace Conference 2005 IEEE, 5-12 March 2005. pp. 20.
- <sup>20</sup> Lewis J S, *Mining the Sky: Untold Riches from the Asteroids, Comets and Planets*, Perseus Books, 1998. pp 300.
- <sup>21</sup> *Case4Space summary report*, UK Space and EADS Space, October 2006. pp. 24.

<sup>22</sup> *The best of NASA's spin-offs*, <http://www1.jsc.nasa.gov/er/seh/spinoff.html>

<sup>23</sup> *ESA - Improving daily life – Spin-off technology*,  
[http://www.esa.int/esaCP/GGGIPLH3KCC\\_Improving\\_0.html](http://www.esa.int/esaCP/GGGIPLH3KCC_Improving_0.html)

<sup>24</sup> House of Commons Science and Technology Committee, Session 2006-07, Seventh Report, 2007: *A Space Policy*, <http://www.publications.parliament.uk/pa/cm200607/cmselect/cmsctech/66/6602.htm>

<sup>25</sup> Roberts, Sir G., *SET for Success*, 2002 - [http://www.hm-treasury.gov.uk/documents/enterprise\\_and\\_productivity/research\\_and\\_enterprise/ent\\_res\\_roberts.cfm](http://www.hm-treasury.gov.uk/documents/enterprise_and_productivity/research_and_enterprise/ent_res_roberts.cfm)

<sup>26</sup> Smithers, A., *Science in Schools and Universities*, Buckingham University, 2006

<sup>27</sup> Spencer, P., Hulbert, G., *The Education and Skills Case for Space*, survey for BNSC, EADS Astrium, PPARC and Yorkshire Forward, 2006

<sup>28</sup> Barstow, M., *Bringing Space into School Science*, report commissioned by BNSC, 2005 - <http://www.scitech.ac.uk/Resources/PDF/barstow.pdf>

<sup>29</sup> *Science and Innovation Investment Framework 2004-2104: Next Steps*, HMSO, March 2006 - [http://www.hm-treasury.gov.uk/media/7/8/bud06\\_science\\_332v1.pdf](http://www.hm-treasury.gov.uk/media/7/8/bud06_science_332v1.pdf)

<sup>30</sup> Ehmann, BL, et al., Humans to Mars: A Feasibility and Cost-Benefit Analysis. *Acta Astronautica* 56(9-12), p851-858, 2005. Data based on:

*Technical Degrees awarded in the United States* (<http://www.nsf.gov/statistics/nsf06319/appa.cfm#taba1>) and *NASA Budget figures* (<http://www.hq.nasa.gov/pao/History/presrep95/e1a.htm>)

<sup>31</sup> Blast off to Science programme: [www.careers-scotland.org.uk](http://www.careers-scotland.org.uk)

<sup>32</sup> Jarvis and Pell, *Journal of Research in Science Teaching*, vol 39, pp979-1000, 2002

<sup>33</sup> Jarvis and Pell, *Journal of Research in Science Teaching*, vol 42, pp53-83, 2005

<sup>34</sup> Holdaway, R., *Report on the Aurora Cross-Council Meeting*, 7 May 2004,  
<http://www.pparc.ac.uk/aurora/Documents/auDocuments.aspx>

<sup>35</sup> Crawford, I.A., 'Towards an Integrated Scientific and Social Case for Human Space Exploration,' *Earth, Moon & Planets*, **94**, 245-266, (2005), <http://www.springerlink.com/content/l8rh21128j3325ng/fulltext.pdf>

<sup>36</sup> Cockell, C.S., "The Value of Humans in the Biological Exploration of Space," *Earth, Moon & Planets*, **94**, 233-243, (2005), <http://www.springerlink.com/content/f7r176t36044u233/fulltext.pdf>

<sup>37</sup> Heiken, G.H., Vaniman, D.T., and French, B.M. (eds.): 1991, *The Lunar Sourcebook*, Cambridge University Press, Cambridge, 736 pp.

<sup>38</sup> Wilhelms, D.E.: 1993, *To a Rocky Moon: A Geologist's History of Lunar Exploration*, University of Arizona Press, Tucson, 477 pp

<sup>39</sup> Canup, R.M. and Righter, K.: 2000, *Origin of the Earth and Moon*, University of Arizon Press, Tucson, 670 pp.

<sup>40</sup> Schmitt, H.H. *Return to the Moon*, Copernicus Books, (2006).

<sup>41</sup> Haskin, L.A., Colson, R.O., Vaniman, D.T., Gillett, S.L. "A geochemical assessment of possible lunar ore formation", in *Resources of Near Earth Space*, eds. J. Lewis, M.S. Matthews, M.L. Guerrieri, Tucson University Press, 17-50, (1993).

<sup>42</sup> Papike, J., Taylor, L., Simon, S. "Lunar minerals", in *The Lunar Source Book*, eds., Heiken, G.H., et al., Cambridge University Press, Cambridge, 121-181, (1991).

<sup>43</sup> Crawford, I.A., "The Scientific Case for Renewed Human Activities on the Moon," *Space Policy*, **20**, 91-97, (2004).