Advancing
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Report of the Commission on the Scientific Case for Human Space Exploration

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(A) Executive Summary

1. **Scientific missions to the Moon and Mars will address questions of profound interest to the human race. These include: the origins and history of the solar system; whether life is unique to Earth; and how life on Earth began. If our close neighbour, Mars, is found to be devoid of life, important lessons may be learned regarding the future of our own planet.**

2. **While the exploration of the Moon and Mars can and is being addressed by unmanned missions we have concluded that the capabilities of robotic spacecraft will fall well short of those of human explorers for the foreseeable future.**

3. **Assuming a human presence, the Moon offers an excellent site for astronomy, with the far side and polar-regions of the Moon being shielded from the 'light pollution' from Earth. In addition, the absence of an atmosphere and the extended lunar night open up the prospect of deep sky observations across the electromagnetic spectrum and with diffraction-limited resolution.**

4. **There are also benefits for medical science to be gained from studying the human physiological response to low and zero gravity, to the effects of radiation and in the psychological challenge posed by a long-duration mission to Mars.**

5. **However, we believe the essential scientific case at present for Human Space Exploration (HSE) is based on investigations on the Moon and Mars. We have identified 3 key scientific challenges where direct human involvement will be necessary for a timely and successful outcome.**

   5.1. **Mapping the history of the solar system (including the atmosphere and dynamo of the young Earth) and the evolution of our Sun can be studied via the unique signatures left on and beneath the lunar surface. The possibility that bombardment by comets may have deposited organic molecules throughout the solar system can also be explored, with dramatic implications for the origins of life on Earth. Such investigations will require recovery and analysis of rock cores to depths of up to 100 metres in a variety of different geological settings across the surface of the Moon. We do not believe that a robotics approach alone can deliver this now or in the foreseeable future.**

   5.2. **Pursuing the question of life on Mars is likely to involve human exploration no matter what the outcome of current and planned robotic missions may be. An early positive signal, indicating that life is readily able to exist on Mars, would further motivate plans for humans to go there. Conversely a continuing negative outcome from robotic investigation would leave open the possibility that life may have retreated below the hostile surface layers. Investigating this will require deep drilling to penetrate the permafrost, with subsequent analysis of rock and ice cores to seek signs of extant or extinct life. Again, we are not**

persuaded that a robotics approach alone can deliver this now or in the foreseeable future

5.3. If Mars is found to be a dead planet what lessons can be learned about the long-term viability of our planet to support life? Such a broad-ranging question is likely to require detailed planetary-wide exploration. The expert advice we have received is that such exploration could not be successfully carried out by robotic means alone. Humans are considered far better explorers than robots now and are likely to remain so for decades to come.

6. **There appear to be no fundamental technological barriers to sending humans to the Moon or Mars. Such missions could be mounted using current launcher technology, though a higher thrust propulsion system would offer an important reduction in transfer time and cost for an interplanetary mission. Solar flares and cosmic rays provide significant health risks for humans in space, but we are persuaded that human physiology is not a fundamental limitation for missions to Mars, though the latter may require careful timing with regard to the 11 yr solar activity cycle.**

7. **It seems clear that a major international human space exploration programme involving a return to the Moon, with the longer term aim of sending humans to Mars will happen, probably led by the USA. However, a significant capability also exists in Europe and Russia, and we note growing ambitions in China, India and Japan. By present government policy the UK would not be involved. Since it appears to be a question of when, rather than if, humans return to the Moon, and then on to Mars, we consider that UK position would look increasingly isolated.**

8. **If the UK did decide to play a full role in an international HSE programme to explore the Moon and Mars the cost could be of order £150M per year and would need to be sustained over 20-25 years. We believe it would not be realistic for the bulk of this to be taken from the existing Government funded science budget. Rather, a decision to be involved should be taken on the basis of broader strategic reasoning that would include commercial, educational, social, and political arguments as well as the scientific returns that would follow**

9. **We find compelling evidence that the outreach potential for HSE can be a strong positive influence on the interests and educational choices of children towards science, engineering and technology. "Careers in Scotland" run a particularly impressive programme 'Blast Off to Science' which uses Space as its theme during a summer programme, which in 2005 reached 22500 schoolchildren across Scotland. The involvement of NASA astronauts is a key element in the programme's success. We have no doubt that the presence of British astronauts in such outreach activities would further enhance their potential for inspiring both young and old.**

10. **Involvement in technologically advanced exploration of the solar system will provide a high profile challenge for UK industry, with consequent benefits in recruitment of new engineers and scientists. Evidence from NASA and ESA**

surveys have shown a significant economic multiplier from investment in space projects, with an additional overall gain in competitiveness.

11. **In summary, we find that profound scientific questions relating to the history of the solar system and the existence of life beyond Earth can best – perhaps only - be achieved by human exploration on the Moon or Mars, supported by appropriate automated systems The wider commercial educational, social and political benefits help justify the substantial expenditure that full UK participation in a future international programme of HSE will require. A BBC recent web site poll of public opinion has suggested that there would be strong support for such involvement by the UK. It is hard to conceive that the UK, one of the world's leading economies, would stand aside from such a global scientific and technological endeavour. We therefore regard it as timely for HMG to re-evaluate its long-standing opposition to British involvement in human space exploration.**

(B) The Formation and Membership of the Commission

12. The decision of the Royal Astronomical Society (RAS) to commission an independent review of the scientific case, focusing on astronomy and geophysics, for human space exploration (HSE) should be seen in the context of the European Space Agency's (ESA) *Aurora/Inspiration* programme, and recent changes in US space policy. Important decisions will shortly have to be made as to whether, and to what extent, the UK should participate in the next phase of *Aurora* whose longer term objective is to send humans to Mars, and how ESA should respond to the United States of America Presidential *Vision for Space Exploration* initiative. Support for a manned component of *Aurora* does not currently match UK government plans for space. In inviting three eminent scientists, none of whom had previously adopted a position on HSE, to constitute a commission to review the scientific issues, the RAS hoped to put the debate on a more objective footing which, depending on the outcome of the review, could conclude by asking the government to review its position

13. The Chair of Commission is **Professor Frank Close OBE**, Professor of Physics and Fellow at Exeter College, Oxford, where his research interests are in the quark structure of matter. His theoretical studies are centred on elementary particle physics, and in particular on what glues quarks together inside nucleons. After gaining his first degree at St Andrews he moved to the University of Oxford to undertake his doctoral studies with Richard Dalitz. He then did postdoctoral research at Stanford, before moving to CERN. In 1975 he moved to the Rutherford Appleton Laboratory in Oxfordshire, where he worked for 25 years, latterly as the head of their Theoretical Physics Division. He came to his current position in Oxford University at the turn of the century.

14. **Dr John Dudeney OBE** is Deputy Director of the British Antarctic Survey (BAS). He joined the British Antarctic Survey after graduating in physics in 1966 and spent two consecutive winters at the Antarctic Peninsula as an ionospheric physicist and as Base Commander in 1968 of Faraday Station. He gained his PhD from University College London (UCL) in 1974 and then embarked on a career of ionospheric/space physics research with the BAS. He headed the British Antarctic Survey's Upper Atmospheric Services Division from 1990 until 1998 when he became Deputy Director of BAS. He has served on or been involved with a number of international committees and bodies, both scientific and non-scientific, and has made around 20 trips to Antarctica.

15. **Professor Ken Pounds CBE FRS** is Emeritus Professor of Space Physics at the University of Leicester. He moved directly from postgraduate research at UCL under Sir Harry Massey, to an Assistant Lectureship at Leicester in 1960, helping set up the new Space Research Group, which was active in the early UK national and European (ESRO) space science programmes. He became the first Director of X-ray Astronomy at Leicester in 1974 and was Head of Physics and Astronomy from 1986 until his retirement in 2002. He was a pioneer in the new discipline of X-ray astronomy and fronted the UK involvement in space missions with NASA, ESA and space agencies in Japan, Russia and Germany. From1994-8 he was seconded as Chief Executive of the Particle Physics and Astronomy Research Council (PPARC). Between 1990-1992 he was President of the RAS.

(C) The Terms of Reference

16. The Commission was asked to review the scientific case for HSE, focusing on astronomy and geophysics, so that its findings could be taken into account by the British Government before the Ministerial meeting in December 2005, which will decide the next stage of the *Aurora* programme.

17. In addressing the basic question, 'Will having people in space materially advance our knowledge, especially of astronomy and geophysics, in ways that are otherwise impossible or less certain?' the Commission was left free by the RAS to devise the parameters of the study and where appropriate to draw on the insights of other disciplines. However it was thought likely that some the following issues would be considered:

    17.1. An assessment of the role of astronauts in the conduct of geological and geophysical field work on planetary surfaces (e.g. an examination of the value of human versatility in the field, an assessment of the quantity and quality of sample collection in comparison to what can be achieved robotically, and an assessment of the range of geophysical and other equipment that astronauts may be able to deploy and maintain on planetary surfaces).

    17.2. In the particular case of Mars, an assessment of the relative merits and constraints of human versus robotic micro-palaeontological fieldwork, and the relative advantages and weaknesses of having preliminary sample analysis conducted 'in situ' rather than returning possibly very large quantities of material to Earth.

    17.3. An assessment of the value of a human infrastructure to support large-scale exploratory activities on planetary surfaces (e.g. drilling boreholes to 100m or km-depths, such as may be required for sampling buried palaeo-regoliths on the Moon, and searching for extant, sub-surface litho-autotrophic organisms on Mars).

    17.4. An assessment of the value of a human spaceflight infrastructure in maintaining and upgrading space-based astronomical and geophysical instruments including an assessment of the relative merits of the lunar surface for astronomical observatories, bearing in mind the possible value of a nearby human infrastructure.

18. The Commission, it was felt, additionally, may wish to consider the views of other learned bodies in respect of:

    18.1. the scientific value of microgravity research,

    18.2. the importance of human physiological research in micro- and reduced-gravity environments for fundamental biological knowledge, medical applications, and future human space activities.

19. Finally, the Commission was free to comment on the costs and value for money of HSE, taking into account the inspirational value of high-profile human space

activities as a means of encouraging young people to pursue careers in science and engineering, and in raising the profile, and the stature, of scientific activities and the scientific world-view among a wider public.

(D) Summary of the activities/meetings of the Commission

20. Formation of the Commission was formally announced at the Royal Astronomical Society on 10 December 2004 in association with an RAS Discussion Meeting entitled *The Scientific Case for Human Space Flight*. Meetings of the Commission were held in London, Oxford and Cambridge (where a public debate was staged during the annual meeting of the Division for Planetary Sciences of the American Astronomical Society) over a nine-month period between December 2004 and September 2005. Evidence was taken from a range of experts (see appendix 1) and the views of scientists and the general public were polled (see appendix 2 and 3). In addition a wide range of written sources were available for consultation including the manuscripts arising from the proceedings of the RAS Discussion Meeting mentioned above. A list of useful web sites is given in Appendix 4.

(E) The need for a wider context

21. The Commission accepted the terms of reference but early in our deliberations we concluded that it would be necessary to set our findings in a broader context. This is because of the very substantial costs that are necessary to support a human space exploration programme exceed a reasonable fraction of national science budgets and therefore are likely to require additional arguments to justify government investment in HSE.

22. Our analysis took into account the broader science context, public inspiration, outreach and education, the commercial /industrial dimension, and the overall political and international environment. These topics are covered in more detail below, but we opted not to investigate the general topic of microgravity research that has recently been reviewed by the Wakeham committee[1].

(E1) The Wider Science Context

23. There are two major scientific questions that were outside our specific remit, but which we saw as part of the wider scientific context and where we received both unsolicited and solicited input from a wide variety of sources (the RAS questionnaire and BBC poll, the Cambridge debate, and individual and group inputs). These are the questions of whether life is unique to our Planet and the implications of space travel on human health and well-being.

24. The question of whether life is unique to our planet or whether it can/does exist elsewhere in the cosmos transcends mere scientific curiosity and touches the fundamental issue of what it means to be a human. Even at the purely scientific

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[1] Wakeham B, Report of the Microgravity Review Panel (2003)

level determining whether life does exist elsewhere will reveal a great deal about its origins, nature and adaptability, all big questions in themselves.

25. The search for life elsewhere in our solar system has for many years focussed heavily on the planet Mars. This is because Mars has an atmosphere (albeit a tenuous one nowadays), a wide range of surface features, weather and seasons. Although Mars apparently now has no surface liquid water, no appreciable magnetic field and no obvious signs of life, there is growing evidence that it once had a very different climate with abundant liquid water and probably a magnetic field to protect the surface from cosmic rays. In such circumstances there is a good chance that the conditions necessary for life to appear were present, and if it did that fossil evidence will remain. It is also possible that simple life-forms continue to exist on the planet, possibly at or near the surface, but more likely deeper down at the boundary of the permafrost where liquid water will continue to exist. The case to explore Mars for evidence of life is therefore compelling. The issue is then to determine the best way to carry out that exploration: robotically, by sending humans, or with a combination of the two? We investigate and reach a view on the human versus robot question later in this report.

26. We received strong representations from the UK space biomedicine community about the importance of this area of scientific endeavour; they stressed that the UK community is in danger of being sidelined due to lack of funding and of opportunity to participate even as junior partners in international programmes. It can be argued that there is only value in having a space biomedicine research programme if there is an intention of sending people into space, and therefore it cannot of itself be a justification for spending money on human space flight. However, we received evidence from Dr Kevin Fong[2] that the improved basic understanding of human physiology arising from studies of behaviour as a function of gravitational force, will benefit human health and well-being here on Earth. This point was also made by the UK Space Biomedicine Group (UKSBG) in their unsolicited written submission[3]. The latter also point out the spin-off benefits in terms of improved diagnostics and biomedical sensors that have come from space biomedicine research. However, the UKSBG[2] are concerned at the current approach of the UK… "*to participate only in the robotic aspects of the ESA Aurora programme, and* [*to*] *assess its position on the human aspects* [*only*] *in the latter stages.*" They comment that: *"we consider this approach to be fundamentally flawed, as it will miss the window of opportunity that currently exists to become actively involved in these fields. There is at this time a nascent effort in UK space biomedical research, consisting of a network of life and medical science professionals in this country with a good understanding of this field, and links with international space life science laboratories. This effort has thus far been supported only by ad hoc funds, but it cannot be sustained indefinitely in the absence of formal, centralised funding.*" Finally, we note that the Microgravity Review Panel chaired by Professor Wakeham[4] recognised that "*access to ESA microgravity facilities would support the work of many high-quality UK researchers carrying out work of fundamental importance*."

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[2]Verbal evidence taken at the Commission meeting in London on 24 August 2005
[3] Letter dated 25 August 2005 signed by 21 members of the recently formed UK Space Biomedicine Group
[4] Wakeham B, Report of the Microgravity Review Panel (2003)

27. **We do not have the background or expertise to draw authoritative conclusions on the value of a thriving UK space biomedicine programme for human health and well-being, but we do find the arguments we have heard persuasive, and have not heard strong arguments to the contrary.**

(E2) Public inspiration, outreach and educational Context

28. Public interest in Space has traditionally been greatest where humans were directly involved. Our enquiries confirm that is still the case. Public support for UK involvement in a future programme of HSE was tested with the assistance of the BBC who covered the issue on their News/Science website in June. Over several days the site was visited over 35000 times and over 20000 votes were registered. More particularly 3370 detailed comments were submitted from across the UK. An analysis of a representative sample of 1800 of those responses showed a strong majority (61%) in favour of the UK playing a full part in a future, international, HSE programme, with reasons given ranging from the technological challenge to our engineers and scientists, inspiration of the young, to reviving a proud tradition of Britons as explorers. For those against (26%) the main objection was cost, and the wish to 'first sort out problems on Earth'. On the cost issue the supporters of HSE felt the required investment was modest for the world's 4th richest country, noting larger sums being proposed for contemporary, less popular, initiatives 'such as the introduction of ID cards'. For further information about this poll see Appendix (3).

29. Public support in the USA was also tested recently by Gallup. More than three-quarters (77%) of the American public said they supported a new plan for space exploration that would complete assembly of the International Space Station, build a replacement for the Shuttle, go back to the Moon and then on to Mars and beyond. With funding for such a program expected not to exceed 1 percent of the federal budget, 51% of adults surveyed say they support the program and 26% strongly support it. NASA's current share of the total federal budget is 0.7%, or about $58 per year for the average citizen. During the height of Project Apollo, NASA's share of the budget was about 4 percent. Among the Gallup survey's other findings:

    29.1. Seven in ten adults (71%) were somewhat interested (49%) or very interested (22%) in America's space programme.

    29.2. Of nine possible answers, most (26%) said the main reason for America to explore space is because it is human nature to do so. Almost one-quarter (24%) said it is to conduct science experiments.

    29.3. Eight in ten adults agreed (48%) or strongly agreed (32%) that America's space program helps give America the scientific and technological edge it needs to compete with other nations in the international marketplace.

29.4. More than three-quarters of adults agreed (48%) or strongly agreed (28%) that America's space program benefits the nation's economy by inspiring students to pursue careers in technical fields.

30. We note that the above motivations are shared by many of those who responded to the BBC poll in support of a UK initiative in human spaceflight.

31. Outreach activities based on the achievements in Space Science are popular, with the pleasing discovery for the general public that research in space is not just a US activity. The recent experience of the National Space Centre in Leicester confirms that Human Spaceflight has a particular interest for the general public. Since the opening of the *Human Spaceflight: Lunar Base 2025* in July, volume from the family market was 31% up versus the same period in 2004. The *Star Wars Day* at the start of the period drew a record 2,656 visitors.

32. The outreach potential of HSE, bringing scientific and technological programmes into the public domain has particular value in influencing the interests and educational choices of children. In the USA the coincidence of a strong growth in graduate schools in science and engineering with the Apollo programme is well documented[5].

33. Here in the UK there is anecdotal evidence of the attraction of Space Research as an influence in the career choice of undergraduates in subjects such as physics and engineering. "Space School UK", a summer school for 14-17 yr old science students held annually since 1989 regularly finds an ambition to become an astronaut high on the career ambitions. However students recognise that to achieve such a goal at present would require emigration, most likely to America.

34. Human Spaceflight has been chosen as the theme for a major initiative in Scotland addressing the current shortage of students studying science and engineering. '*Blast off to Science*' is a programme run by "Careers Scotland" each summer for the past 3 years. In 2005 some 22500 schoolchildren from across Scotland were involved, with the course aims being to provide inspiration, increase motivation and raise aspirations of young people in science, technology, engineering and maths. A key factor in the success of the programme is the strong support of NASA, who send a team of astronauts to visit schools across Scotland. At the end of each Summer School a selected group of teachers and students are chosen to attend a Space Camp in Houston. As one 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*." The Scottish experience inevitably raises the thought that having British astronauts at the School would further increase its impact.

35. **We find compelling evidence that the outreach potential for HSE may significantly influence the interests and educational choices of children towards science engineering and technology**.

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[5] Fong K, *Human spaceflight in the UK: the cost of non-participation, (2004), RAS meeting*

(E3) The Commercial/Industrial context

36. Several detailed studies, eg by NASA and ESA, have claimed that investment in the technically challenging field of space science/engineering yields economic benefits with a substantial multiplier. The proposed return to the Moon and subsequent human expedition to Mars will undoubtedly bring many new engineering and logistical challenges. Furthermore, given the timescales involved, it is clear that many of those challenges will be enthusiastically taken up by a generation still in school or college A recent report from the National Academy of Sciences Space Science Board drew attention to the fact that America's new *Vision for Space Exploration* will need to recruit 50-75000 scientists and engineers over a 30-year period.

37. The position in the UK is at present very different. National policy up to now has been to support activities in space only for scientific research or for applications of clear commercial benefit (eg communications). A lead role in development of a European launcher was abandoned in the 1970's and now the UK has only a minor role in the commercially successful Ariane. ESA's Human Spaceflight programme has remained 'off-limits'.

38. For UK industry the 'juste retour' principle adopted for such ESA programmes has meant no opportunity to bid for related R&D contracts, thereby losing the associated value added from the 'spin-off' of new technologies, and the benefits in recruitment and training of a new generation of engineers and scientists.

39. We do not claim to be experts in the issues of the commercial value of HSE, and have not investigated the matter in great detail, but are concerned that the UK may be missing out on significant commercial opportunities, both directly, and indirectly from technology spin-off.

(E4) The Political and International Context.

40. For much of the 44-year history of Human Space Flight the USA and Russia (formerly USSR) have been the dominant players. During the Cold War political and military competition were strong drivers. As one participant in the Cambridge debate commented the super-powers sent humans into space "to inspire their friends and impress their enemies". More recently international collaboration has become more important with 15 nations (though not the UK) collaborating on the International Space Station (ISS). However, the ISS development has been hampered by cost overruns and a lack of regular Shuttle flights, with the scientific returns seemingly becoming increasingly distant.

41. New momentum has now been introduced by several developments. President Bush announced a new *Vision for US Space Exploration* in January 2004, with initial aims of returning to the Moon and later going on to Mars. In Europe *Aurora* is being developed, with a manned mission to Mars as its ultimate target. Meanwhile China has become the 3rd nation to put an astronaut into Earth orbit, while Russia and Japan are considering new human space flight initiatives.

42. In the UK a significant change has been the strong support for the *Aurora* Preparatory programme, where a lead role (deploying robotic explorers) would represent a significantly higher national priority for planetary exploration. The UK position on the ISS remains negative, however, with the consequence that there are no Britons in the European Astronaut Corps. It is possible that the *Aurora* programme will converge over time with the US space exploration programme, bringing the HSE element into sharper focus. Alternatively, it is conceivable that Europe could develop a significant independent programme by combining its financial resources with the expertise and facilities still existing in Russia.

43. **In our view any UK decision relating to support of a future HSE effort has to be seen in the international context. How would public opinion in the UK view a situation in 10-15 years time when all the major nations – except the UK - were involved in high profile missions to the Moon or Mars? How significant would the effect be on the career choices of British children and students? Would our industrial competitiveness suffer, or would the reduced public investment lead to a stronger economy? The view of the UK public is clear on this point if the BBC poll can be taken as representative. By a margin of more than 2 to 1 they want the UK to be fully involved**.

(F) Planetary Science on the Moon & Mars

44. There is a natural challenge: The Moon is there; Mars is there; they can be reached by spacecraft - explore them. Given that we are now technically able to do so, the issue is therefore more one of what are the important science questions that can be addressed, and do they need human presence or is remote interaction with local robots enough?

45. Scientific missions to the Moon and Mars undoubtedly can provide unique insights into a range of fundamental questions. Those of most obvious interest and importance relate to: the origins and history of the solar system; whether life is unique to Earth; and how life on Earth began. Encompassing these major questions are far reaching opportunities for scientific discovery in geophysics, geology and planetary sciences.

46. The Moon is potentially a unique museum of the history of the solar system. The Earth's surface is generally young in geological time, and uniformly covered by a dense atmosphere and surrounded by a significant magnetic field. While both are essential for human existence, by shielding the Earth from extraterrestrial rocks and radiations, the atmosphere and magnetosphere also obscure the record of impacts over the 5 billion years of the solar system. The passive environs and surface of the Moon, by contrast, make it an ideal target for solar system historians.

47. The absence of an atmosphere enables rocks and other interplanetary debris to impact the lunar surface without modification by atmospheric interaction. The solar wind has impinged on the Moon throughout its history and thereby the lunar

surface bears witness to the environment of near-Earth space for the some 4 billion years. Such studies will use the uniquely preserved record of solid body impacts on the Moon and the collection of (initially ionised) solar and galactic particles embedded in the regolith.

48. Experience of terrestrial geophysics research has shown that two key requirements for efficient and effective exploration of the Moon will be roaming access to the lunar surface and a drilling capability to several hundred metres depth. The primary science objective would be to better understand the period of planetary formation, linked with the evolution of the solar wind (and hence of the Sun) and the time history of meteor impacts. Studying the geological processes and near surface materials on the Moon, promises unique insights into planetary formation and evolution, and in particular details on the histories of the Earth and the Sun. In practical terms achieving these aims will almost certainly require both major engineering (drilling to depths of hundreds of metres) and detailed surveys over a wide range of locations.

49. A particularly intriguing question that these investigations could address is the possibility that several billion years ago, comet impacts deposited simple organic molecules, perhaps amino acids, in collisions with the Moon. If so the same must have happened on Earth, where the record in these pristine molecules have been lost, but perhaps not before being transformed into ubiquitous life. Such a far-reaching discovery would revolutionise the debate about the origin of life on Earth and its uniqueness, with potentially profound implications for human culture.

50. Barring the serendipitous discovery of organic molecules in the lunar regolith, Mars provides the only reasonably accessible planetary body where the question of extra-terrestrial life could be addressed. To fully explore that question will again require a roaming capability on the Martian surface and a drilling capability to 100's of metres. Proving the negative will require a global survey and drilling to the bottom of the permafrost, whilst a positive result seems certain to drive a relentless search for more examples and the construction of a detailed palaeo- and actual ecology.

51. Analogous to the results from drilling ice cores from Greenland and the Antarctic Ice Cap, cores from the Martian Ice Caps will very likely contain a wealth of information about the history of the Martian atmosphere and climate.

52. Thus on both the Moon and Mars, we have learned that wide-scale exploration and the capability of obtaining samples from deep below the surface will be needed to achieve the science goals. As discussed elsewhere, the advice we have received is that such exploration could not be carried out by robotic means alone: Humans are far better explorers than robots now and seem likely remain so even on the timescale of possible human space missions to Moon and even to Mars.

(G) Astronomy from the Moon

53. The far side of the Moon is a unique environment for radio astronomy in particular, freed from the increasing `noise' from Earth. The absence of an atmosphere also offers many of the advantages of space astronomy. In the optical band, diffraction-limited observations would be possible without the complexity of the active optics essential for large telescopes on Earth, while the whole electromagnetic spectrum, in particular the rich UV, X-ray and FIR wavebands, would be accessible.

54. An array of telescopes and interferometers placed near the lunar pole would provide uniquely deep, wide spectrum observations of the ecliptic polar region, with little need for human intervention. More generally the 'hands-off' operation of current Earth-based telescopes underlines the potential of robotic facilities set up by humans but needing little servicing. Nonetheless, the higher costs of setting up facilities on the Moon, as compared with those on Earth or in space, make it unlikely that astronomers would choose the lunar option unless a human presence was already there for other reasons.

(H) The Human or Robotics Question

55. According to Buckminster Fuller[6]: "*Man is a self-balancing, 28 jointed adaptor-based biped, and electrochemical reduction plant, with segregated stowage of special energy extracts in storage batteries for subsequent activation of thousands of hydraulic and pneumatic pumps with motors attached; 62,000 miles of capillaries, millions of warning signals, railroad and conveyancing systems, crushers and cranes, and a universally distributed telephone system needing no service for 70 years if well managed, the whole extraordinary complex mechanism controlled from a turret in which are located telescopic and microscopic self-registering and recording range-finders, a spectroscope etc*" To this could be added the fact that humanity has evolved to be a highly flexible problem solver that is optimally adapted to dealing with the unexpected by drawing upon a huge database of personal and collective knowledge.

56. Professor Cockell (Open University) in his presentation at the RAS meeting in December 2004 used a personal story to illustrate the power of humanity to adapt behaviour to circumstance in a way impossible for machines which he calls the "Christmas Present Effect"[7]. He recalled that he went into a large retail shop in Cambridge to buy some paper clips, but came out with both the clips and a set of Monopoly ®. In brief his argument for this was – it was close to Christmas, my sister had been a keen player of Monopoly when a child, had a close association with Cambridge, and the monopoly set was specific to Cambridge (which he had not known about prior to the shopping expedition). He therefore bought it as a Christmas present for his sister. The story illustrates a number of human facets that makes humans excellent explorers: pattern recognition skills; libraries of information gathered over decadal time-scales; rapid acquisition of samples and

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[6] Ellery A, *Human versus Robots for space exploration and* development, Space Policy **19**, (2003), 87
[7] Cockell C S, The Value of Humans in the Biological Exploration of Space, (2004) RAS meeting

an ability to recognise data to be of importance which were not part of the original programme. The analogy with searching for unusual objects on the Moon or Mars is instructive. Humans think and act laterally in ways that robots cannot.

57. With this background, it is self-evident that humans are better explorers than machines; this is certainly true now and for the foreseeable future. Machines excel at doing a well defined task reliably in environments inimical to human life, but robotics in practice is far from the public perception, which is largely driven by science fiction and poorly informed enthusiasts. This seems likely to remain so on at least the 20-30 year timescale of immediate relevance. As specific examples we cite the following: Steve Squyres of Cornell (Principal Investigator on the Mars Rover project) at the Cambridge discussion on Sept 6 said, "We are many decades away from robots that can match humans *even in the lab.* Laboratory state of the art tends to be some 20 years ahead of what can be tolerated in space where one has to attempt 100% success". These remarks were mirrored by discussions held with robotics experts from Oxford and Australia[8], some of which are quoted below. In summary, we heard nothing to suggest that robots can replace humans: "we are overflowing with gigaflops, but just don't know how to construct the wetware" is the phrase that one robotics expert used ("wetware" being the jargon for the brain). We were strongly urged not to think about "artificial intelligence" or "robotics", but rather about "automation" and "the acceptable mean time for autonomous action for the task in hand".

58. We concluded from these discussions that a single well defined task required 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

59. The question therefore becomes whether robots alone, or operated interactively by humans remotely, can achieve the particular science aims without the need for humans in situ.

60. Clearly, if the priority is to learn about human response to long-term exposure to the space environment, then humans are needed. If one wishes to learn about the Moon or Mars per se, and the question can be well defined and constrained, then it is possible that a machine could be designed to answer it. However, whether the question as posed was the right one, whether the machine can answer it in the detail required, or on a sensible timescale are essential caveats.

61. 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 will probably require human presence at the site.

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[8] Meeting of the Commission at Oxford University with Robotics experts R Daniel, P Newman and R McAree on 10 August 2005

62. The 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.

63. If it is required to have long-term reliability then human presence to deal with breakdown becomes more necessary (past examples are the Hubble Telescope servicing, and the Shuttle Discovery mission in August 2005). Qualitatively one can summarise that “machines are not good problem solvers”.

64. The strengths and limitations of automation are highlighted by asking whether current technology could recover a 3km ice core from the inland ice-sheet in Antarctica. While in one respect such activity on the moon could be “easier” in the absence of unpredictable weather, on Mars by contrast the severe dust storms could create severe problems. As regards a drilling programme Professor R Daniel[9] summarised this as follows: Provided the drilling rig can be delivered to the site and assembled there an automated drill rig could be designed to do it. “You may need to do it 27 times, with breakages and other unforeseen pitfalls, but eventually you can do it. If you want to take samples, box the core material and come back 6 months later, you can do that too. However, if you want to change strategy as a result of what you are finding or drill another hole close by, then humans need to be there”. A second robotics expert took the view that the automation can be much more sophisticated and the tasks much more complex if there are humans on site to guide real-time operations and 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. The problem in question might not be one that simply involves computation (which could be done on Earth in a “show-stopper” scenario) but might be mechanical or electrical. Dr P Newman observed that “it is trivial for a human to tighten a nut; not so for a machine”.

65. We have concluded that translating state of the art drilling technology to another planetary body (eg to drill the Martian ice-caps, or to recover 100 – 1000m rock cores from the Moon or Mars) will require a combination of automation and on-site humans.

66. It is possible that evidence of life on Mars will be found without human presence if it is widespread on the surface or near sub-surface. Such a discovery would very probably inspire a demand for humans to go to Mars for in-depth investigations beyond the capabilities of robots alone. Whether or not life is found by upcoming robotic missions, continuing searches will eventually focus on liquid water at the deeper layers where the permafrost melts. Since the search for life is a major driver of Martian exploration, again the dedicated deep drilling programme suggests that autonomous robots alone will be insufficient and that humans will be needed in situ.

67. To survey large areas of the Moon or Mars in any reasonable time frame, over widely differing terrain, again rovers operated by humans are required. Humans can answer questions that cannot be defined *a priori*, or which arise during the

[9] Meeting of the Commission at Oxford University with Robotics experts R Daniel, P Newman and R McAree on 10 August 2005

exploration. An obvious question is whether the humans need to be present in situ or can interact with the robot from a base on Earth.

68. The speed at which autonomous rovers can move sets limits to the area that can be explored by that means. The speed on varied terrain is set by the maximum allowable time for autonomous operation before human intervention. To survey 10km x 10km, visiting each 100m x 100m cell in one lunar daytime would need a rover to travel at around 1m/s. We were advised that it is conceivable that humans could control such a vehicle from Earth at this speed but it would be technologically challenging even with "look-ahead"[10]. The reliability of communications between Earth and Moon, eg the possibility of communication drop-outs and the reliability of power sources are also factors. It seems that only on the near side of the Moon could such fast exploration occur with predictive control. In the case of Mars autonomous robots seem likely only to be able to explore over a long path but small area slowly and under human supervision. For more open-ended exploration, then human presence would again be necessary. Given humans presence on Mars for guidance and repair then robotic rovers might be able to roam more widely over the Martian surface collecting samples to be returned to their human operators at the base station.

69. **We have learned that 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 believe that a robotics approach alone could not deliver this now or in the foreseeable future**.

70. **In the case of Mars, where both robotic and human exploration will be considerably more difficult and expensive, it is particularly important that clear scientific goals be defined in advance of a mission. Only when these are specified can a balanced decision on the need for humans in situ be taken. However, the expert evidence we have heard strongly suggests that the use of autonomous robots alone will very significantly limit what can be learned about our nearest potentially habitable planet.**

[10] Technology which presents the operator with a view of what will be encountered by the rover a short time in the "future" to allow for the communications delay time.

(I) Cost and Funding Issues

71. Sending humans into space is expensive. As a generality the cost of undertaking an activity in orbit, or on the Moon or Mars might be ten times more costly if humans are present. The potential for disaster is also greater given the priority of astronaut safety. Paradoxically it is in part the same risk element that underpins the challenge and excitement associated with space travel, factors that contribute significantly to the high public interest in HSE.

72. However, in our view justification for public funding of HSE must be based on an assessment that the scientific objectives are important and can only be carried out judiciously and effectively by humans supported by the best available robotic tools.

73. In considering the funding implications for the UK to change its long-standing position of non-involvement in human spaceflight, we presume the decision would be to play a full, pro-rata role in an international programme, probably working through ESA. The primary target in the 10-15 years is likely to be concentrated on a return to the Moon, while increased robotic exploration will be focussed on Mars and elsewhere in the solar system. A recent NASA study has estimated the cost of establishing a lunar base by 2018-2020 at $100 billion. We assume a parallel ESA programme, perhaps integrated with that of the USA, to set up a European presence on the Moon at a cost of $27 billion.

74. A pro-rata (~15%) share for the UK would average out over 15 years at $270million (£150M) a year. That figure is some 6 times greater than the amount set aside in the 2004 spending review for UK participation in ESA's Aurora programme. It is also of the same order as the current UK spend through PPARC for research in Astronomy and in Particle Physics, and represents a significant percentage (of order 5%) of the overall budget of the UK Research Councils. It therefore appears unlikely – and undesirable - that an internationally significant UK effort in HSE could be funded from the current science vote, though the direct costs of implementing the science programmes might be expected to come via that route. It follows that a positive commitment from the UK Government would take into full account other factors, such as national prestige, economic return, public interest and the inspirational benefits to education.

(J) The Technological Challenge

(J1) Launcher Capabilities

75. The particular technological challenge associated with HSE centres on the ability to send astronauts into space, to carry out their mission and return safely to Earth. Operating for extended periods in low gravity and exposure to cosmic and solar radiation present unique physiological challenges. Long periods away from Earth, as a Mars mission or permanent lunar presence will entail, also raises important psychological issues for the crew. While no current launchers exist capable of mounting even a repeat of the Apollo Moon landings of 35 years ago, re-configuration of existing chemical propulsion systems should be fairly straightforward. However, the reliability, flexibility and higher thrust of nuclear propulsion makes such systems very desirable for a faster and cheaper Mars mission, but have yet to be developed for human spaceflight

76. In September the NASA Administrator, Mike Griffin, outlined NASA's approach to the *Vision for Space Exploration*, which will start out with a return to the Moon by 4 astronauts no later than 2020, and will adopt a conservative technological approach. The Space Shuttle will be retired in 2010 to release resources. Development of the new Crew Exploration Vehicle (CEV), a larger version of the Apollo command and Service modules, will be accelerated for a first launch into Earth orbit in 2012 on a re-configured 4-segment single stage solid rocket. A new heavy lift launcher consisting of an extended Shuttle external tank plus 2 solid rocket boosters will be capable of raising 125 tonnes in Earth orbit. In mounting the first lunar mission the CEV will carry the 4 astronauts into orbit where it will dock with the lunar lander and propulsion stage. Following a 3-day journey to the Moon the astronauts will spend 7 days on the lunar surface before returning to Earth. Subsequent missions will lead to a semi-permanent lunar station being established, which critically will use natural resources for water and fuel.

77. Chemical rocketry could also be used as the basis of a Mars Mission[11], but a more efficient propulsion system will also be highly desirable, particularly if the radiation hazard is to be limited by rapid astronaut transfer from Earth orbit. A nuclear engine based on enriched uranium would offer a relatively safe technology with the required high thrust for rapid interplanetary transfer. (Uranium is inert until activated). The heavy lift vehicle developed for the lunar missions could be used to assemble in Earth orbit the elements of a Mars mission, with the astronaut transfer likely to be preceded by 2 or more transfers of equipment for the landing, on-surface facility and return module.

78. While the current NASA approach, with a return to the Moon as a first step, has been criticized by space travel enthusiasts for being too conservative, it reflects the constraint of assuming only level funding. It also recognizes the critical importance of political and financial support being maintained over the long term. To achieve that sustainability (of support) NASA has accepted the need for greater

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[11] See Turner M J L, Expedition Mars, 2004, p27

commercialisation (i.e. the private sector having a greater role) and international cooperation.

79. China is developing an ambitious space programme, also with the eventual aim of a Moon landing. A second human spaceflight, Shenzou-6, scheduled for October 2005, will send 2 taikonauts for 3-4 days in Earth orbit, with later missions to include docking and space-walks and establishing a Space Station in Earth orbit by 2020.

80. However, beyond the USA only Russia presently has the technology to mount a Moon or Mars mission on a similar 15-25 year timescale. Conceivably a partnership of ESA and Russia could bring together both the technological capabilities and financial resources to undertake a competitive programme of HSE. A true global collaboration would, however, appear to have substantial advantages in terms both of overall efficiency and in obtaining the political benefits of sharing in potentially the major scientific and technological endeavour of the 21st century.

(J2) Radiation

81. The Earth's surface is a rather safe place in terms of radiation: the rocks are old and there is not much radioactivity left in them. The Earth's magnetic field provides major protection from cosmic rays and the solar wind; the atmosphere also provides further shielding equivalent to some 10m of water or 4m of concrete. Once outside these protective shields humans are exposed. The effect of radiation on astronauts in outer space, in transit to the Moon and Mars and on their surfaces, is a serious issue.

82. The external radiation has a chronic component consisting primarily of galactic cosmic rays (GCR), and an acute component from solar flares and coronal holes known collectively as Solar Particle Events (SPE). The frequency of SPE varies through the solar cycle. Extreme SPE, most likely at solar maximum and on the declining part of the solar cycle, could be fatal for any mission at Earth-Mars distance. "Fatal" here could be literally so for some of the astronauts, or at the least for the effectiveness of the mission by seriously impairing their ability to perform. However it is possible to shield against SPE, at least for non-extreme cases, and also to minimise their chance by timing missions during solar minima. By contrast GCR, which consists of high energy ions, leave mass shielding ineffective due to the secondary radiation it induces. The intensity of GCR is reduced by the solar wind, which has an irony: they are less worrisome during solar maximum, which is when the danger of extreme SPE is greatest. The flux of GCR increases with distance from the Sun, which makes them more troublesome in deep space missions. These considerations already suggest that missions beyond Mars appear at present to be out of the question.

83. K Fujitaka[12] estimates exposure to cosmic rays and solar radiation at "normal" solar status will total 1Sv for a round trip to Mars of total duration about 500days. 0.2Sv is typically what a Briton will receive during a normal lifespan. In

[12] Fujitaka k, Int Congress Series 1276 (2005) 124-128

Cornwall, the lifetime dose would be perhaps 0.6Sv.Given the uncertainties inherent in epidemiology, the opinion is that a 1Sv exposure may be acceptable but more than this is increasingly worrying.

84. If astronauts stay on Mars until Mars and Earth are in the correct relative positions for the return journey via a minimum energy Hohmann orbit[13], typically 520 days are spent in space and 455 days on Mars. While on the surface of Mars, astronauts are at risk as they are missing the natural protection of a planetary magnetic field and atmospheric cover that we have on Earth. However, half of the time is night-time where Mars provides a natural protection from solar flares.

85. K O'Brien, quoted in New Scientist[14], estimated that the accumulated dose on such a mission would be enough "to give 10% of men and 17% of women between 25-34 lethal cancers in their lives”. In the absence of extreme SPE, a human visit to Mars is probably feasible within currently accepted radiation dosages for astronauts aged over 40. O’Brien concluded that humans will be unable to travel more than 75M km on space missions - enough to get to Mars but not, for example, to Europa or Saturn.

86. Lunar missions appear to have no problems with radiation doses from GCR and career limits for life-time lunar "colonists" pose no serious constraint in this regard; however, the issue of extreme SPE will require adequate protection and warning procedures while on the Moon’s surface.

87. **In conclusion, there appear to be no fundamental technological barriers to sending humans to the Moon or Mars. Such missions could be mounted using current launcher technology, though a higher thrust propulsion system would offer an important reduction in transfer time and cost for an interplanetary mission. While solar flares and cosmic rays provide significant health risks for humans in space, particularly during interplanetary flight, we are persuaded that human physiology is not a fundamental limitation for missions to Mars**.

[13] See Turner M J L, Expedition Mars, 2004, p81, 87
[14] New Scientist.com news service, 15:01 01 August 2005

(K) Summary

88. We commenced this study without preconceived views and with no formal connection to planetary exploration. Our personal backgrounds made us tend towards an initial scepticism on the scientific value of human involvement in such research   While fully recognising the technical challenge and the high cost, we have nevertheless been persuaded by the evidence presented to us that there is science of profound interest to humankind that can only be pursued on the Moon and Mars by the direct involvement of humans in situ. We accept expert opinion that autonomous robots alone will be unable to realise those scientific goals in the foreseeable future.

89. The wider commercial, educational, social and political benefits add justification to the substantial expenditure that full UK participation in an international programme of Human Space Exploration will require. The BBC poll of public opinion suggests that there would be strong support for such involvement. Recent developments across the world strongly suggest that after a 30-year lull space-faring nations are gearing up for a return to the Moon and then to Mars. It is hard to imagine that the UK, one of the world's leading economies, would not be fully involved in a global scientific and technology endeavours with such strong potential to inspire. We therefore recommend that HMG re-evaluate its long-standing opposition to British involvement in human space exploration.

(L) Acknowledgements

90. We would like to acknowledge excellent administrative support provided by David Elliott and Peter Bond, respectively Executive Secretary and Communication Officer of the RAS. We thank all of those who gave evidence to us or provided written input and the BBC for providing us the opportunity to gauge public opinion through the BBC web site. We are particularly grateful to the organisers of the Cambridge meeting of the American Astronomical Society for their willingness to host the public debate, and to the speakers who participated.

(M) Appendices

Appendix 1 Expert witnesses consulted and contributions received

Mr. D. Ashford (Managing Director, Bristol Spaceplanes Limited)
Mr. S. Ashworth (Fellow, British Interplanetary Society)
Dr. D. Bartlett (Radiation Protection Division, Health Protection Agency Chilton)
Dr. S. P. Braham (PolyLAB, Simon Fraser University, Canada)
Dr. M.J. Clark (Radiation Protection Division, Health Protection Agency, Chilton)
Dr. A. Coates (Head of Space Plasma Physics Group, MSSL, University College London)
Professor C. Cockell (Chair of Microbiology, the Open University)
Dr. I. Crawford (School of Earth Sciences, Birkbeck and University College, London)
Professor R. Daniel (Department of Engineering Science, Oxford University)
Dr. B. Douglas, University College London. Secretary, UK Space Biomedicine Group
Dr. A. Ellery (Head of Robotics Research Group, Surrey Space Centre, University of Surrey)
Professor. B. Foing (ESA Chief Scientist and SMART-1 Project Scientist)
Dr. K. Fong (Director of the Centre for Aviation, Space and Extreme Environment Medicine, University College London)
Dr. J. Garvin (NASA Chief Scientist)
Mr. A. Hicks, (General Secretary of UKISC, United Kingdom Industrial Space Committee)
Mr. B. Hufenbach (ESA Directorate of Human Spaceflight)
Dr. T. Johnson (Chief Scientist, Solar System Exploration Programs Directorate, Jet Propulsion Laboratory, Pasadena)
Dr. P. Newman (Robotics Research Group, Oxford University)
Dr. R. McAree (Department of Mechanical Engineering, University of Queensland)
Dr. I. Reid (Department of Engineering Science, Oxford University)
Dr. M.Sims (Space Research Group, University of Leicester, and Chair of the PPARC Aurora Advisory Committee)
Dr. B. Smith (The Smith Institute, Surrey Technology Centre, Guildford)
Dr. P. Spudis (Applied Physics Laboratory, Johns Hopkins University)
Dr. S. Squyres (Principal Scientist, NASA Mars Exploration Rover and Cornell University)
Dr G. Woan (Department of Physics and Astronomy, University of Glasgow)

Appendix 2 Poll of UK Astronomers

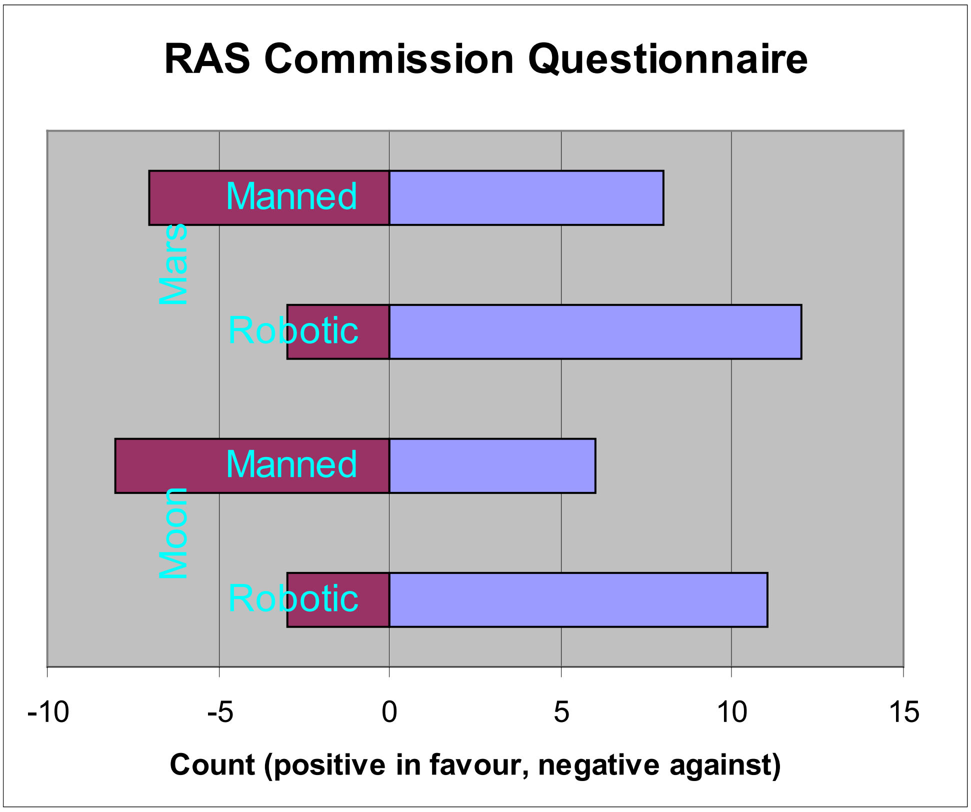
A questionnaire was distributed to all scientists (over 400 in total) attending the National Astronomy Meeting (NAM) at the University of Birmingham in April 2005 and was posted on the web site of the RAS during the month of April. The principal questions and summary of responses follows:

Would you be prepared to see a significant portion of the UK science budget being devoted to answering your scientific question (Q1 above) as part of an international space mission to the Moon

(a) through robotic techniques? Yes/No
(b) Involving in-situ human scientists/technicians? Yes/No

Would you be prepared to see a significant portion of the UK science budget being devoted to answering your scientific question (Q5 above) as part of an international space mission or missions to Mars

(a) through robotic techniques? Yes/No
(b) Involving in-situ human scientists/technicians? Yes/No



The figure above summarises the responses that were received and that provided answers to one or more of the questions. There were a total of 15 responses, which is a disappointingly low rate of response but may reflect the complexity of the issues involved. As can be seen, for robotic exploration there is a strongly positive message for both the Moon and Mars. For manned missions the response is much more balanced with a slight bias in favour for missions to Mars, and the opposite for missions to the Moon.

Appendix 3 Poll of Public Attitudes

1. In June 2005 the BBC web site was used to poll the views of the general public on HSE to the Moon or Mars. Some 20,000 votes were cast.

2. 37% were in favour, only 8% were against but as many as 54% opted for the opaque 'Houston, we have a problem' voting button .

3. A further analysis was made of the 3370 written comments that were received between 15-18 June (when the poll closed). This showed that of those sufficiently interested to do more than hit a voting button 61% were in favour, 26% were against and 13% were undecided.

4. The great majority of responses were from the UK and while a minority of those in the 'yes' camp appeared to back a 'British' effort, most were in favour of the UK working with ESA or NASA.

5. Of those who were opposed to British involvement in Human Space Flight the commonest reason given was that resources should be better spent tackling more immediate problems like poverty in Africa, the funding of the NHS etc.

6. Supporters either pointed out that the costs involved were less than other items currently in the news, such as ID cards, or criticised the lack of vision implicit in a value for money approach e.g. '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...'

Appendix 4 Selected Web Sites

Apollo Expeditions to the Moon, NASA SP-350, 1975
http://www.hq.nasa.gov/office/pao/History/SP-350/cover.html
Chariots for Apollo: A History of Manned Lunar Spacecraft, Washington, D.C., NASA SP-4205, 1979
http://www.hq.nasa.gov/office/pao/History/SP-4205/cover.html

Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions, Washington, D.C., NASA SP-4214, 1989
http://www.hq.nasa.gov/office/pao/History/SP-4214/cover.html

Chandrayaan-1 (First Indian Moon mission)
http://www.isro.org/chandrayaan-1/index.htm

China's Moon Programme
http://www.china.org.cn/english/2003/Nov/79603.htm
http://news.xinhuanet.com/english/2004-11/21/content_2243679.htm

Clementine mission (1)
http://www.nrl.navy.mil/clementine/

Clementine mission (2)
http://www-phys.llnl.gov/clementine/

ESA Aurora Programme
http://www.esa.int/SPECIALS/Aurora/index.html

ESA Aurora Programme brochure
http://esamultimedia.esa.int/docs/Aurora/Aurora625_2.pdf

International Conference on Exploration and Utilization of the Moon (Nov. 2004)
http://www.prl.ernet.in/~ILC6/abs/abs_next.html

International Lunar Exploration Working Group (ILEWG) Forum
http://sci.esa.int/ilewg/

ISAS (Japan) home page – links to Selene, Lunar-A etc.
http://www.isas.jaxa.jp/e/index.shtml

Japanese Solar System Exploration
http://www.jaxa.jp/news_topics/vision_missions/solar/index_e.html

LunaCorp
http://www.lunacorp.com/

Lunar Explorers Society
http://www.lunarexplorers.nl/startframes.html

Lunar & Planetary Institute: Exploring the Moon
http://www.lpi.usra.edu/moon.html

Lunar Prospector
http://lunar.arc.nasa.gov

NASA National Space Science Data Center
http://nssdc.gsfc.nasa.gov/

NASA Exploration Systems Directorate
http://www.exploration.nasa.gov/

NASA Vision for Exploration
http://www.nasa.gov/missions/solarsystem/explore_main.html

President's Commission on Moon, Mars and Beyond (2004)
http://govinfo.library.unt.edu/moontomars/index.htm

Smart-1
http://sci.esa.int/smart-1

The European Union and space
http://europa.eu.int/comm/space/index_en.html

UK Aurora Home Page
http://www.aurora.rl.ac.uk/Default.htm

UK Space Policy 2003-06
http://www.bnsc.gov.uk/assets/channels/about/5818%20BNSC%20Brochure.pdf

United Nations - Office for Outer Space Affairs
http://www.oosa.unvienna.org/treat/ost/ost.html

U. S. Senate Hearing on Lunar Exploration, 6 November 2003
http://www.senate.gov/%7Ecommerce/hearings/witnesslist.cfm?id=987

U.S. Congressional Hearing on The Bush Vision of Future Exploration
http://www.nasa.gov/pdf/55862main_ok_house_hearing_transcript.pdf

Center for Strategic and International Studies Report: The Human Space Exploration Initiative
http://www.csis.org/hse/