Revised by SSAP, Birmingham, 6 Sept 2006

PPARC's Strategy for Solar System Science: 2006-16

1. Introduction

1.1 The purpose of this strategy is to provide a scientific framework for PPARC to allow: the Science Committee to make informed decisions over the allocation of resources; the Grants, Projects Peer Review, and Fellowship Panels to know and respond to PPARC's science priorities; and the UK science community to be aware of these priorities, as a framework for its research activities.

1.2 The objective of the PPARC solar system science programme is to understand the nature, origin and evolution of the Solar System, to use that basic knowledge to underpin the investigations of other planetary systems, and to understand how conditions can evolve to sustain life.

1.3 This strategy has been drawn up by the PPARC Solar System Advisory Panel in consultation with the UK solar system community.

1.4 The study of many environments in the Solar System requires knowledge of a variety of fundamental physics and the way in which physical processes, often occurring on very different spatial and temporal scales, interact.

1.5 Over the next ten years, solar system science in the UK will see greater changes than any of the areas covered by PPARC. Two particular changes result from major funding announcements and the review of PPARC's overall programme:

- Our enthusiastic shaping of, and participation in, ESA's Aurora programme give British solar system scientists the opportunity to take a world lead in understanding Mars and conditions that may, or may not have, harboured Life. For the longer term, ambitious projects laid out in Cosmic Vision places other worlds also at the centre of scientific study. The challenge is to establish the conceptual framework and to provide the intellectual and material resources to grasp the scientific opportunities of these programmes.

- At the same time, PPARC science is scaling back some of its traditional studies of the solar-terrestrial interaction, particularly those making use of ground-based facilities. It is clear, however, that we cannot expect to understand other planets – in the solar system and beyond – without understanding our own planet Earth. The UK solar-terrestrial physics (STP) community represents an enormous investment, of intellectual effort and capital expenditure, during which international collaborations of great significance and inestimable value have been developed. In re-orientating its science priorities, PPARC cannot afford to squander any of these precious resources.

1.6 This review of PPARC's solar system strategy starts from the fact that the UK has a vibrant science community in this area that is highly regarded internationally. In the last few years, UK scientists have participated in some of the most exciting measurements and theoretical developments in solar system science: of the surfaces, atmospheres and near-space environments of Saturn's moons such as Titan and Enceladus using the Huygens probe and Cassini orbiter; of the internal dynamics of the Sun, using helioseismology data from the SoHO spacecraft and the BiSON network; of the structured, 3D dynamics of collisionless plasmas using the four Cluster spacecraft; evidence for frozen seas on Mars; and the analysis of samples returned from a comet and from the solar wind. (see SSAP Strategy Review for further details.)

1.7 UK scientists must clearly continue to make major discoveries and provide critical insight into key problems in both fundamental physics and solar system science. To achieve this, the UK must have access to world-class facilities, have a strong theory and modelling programme and take leading roles in international science programmes. Limited funding means that decisions to fund individual projects must be taken with the broad UK strategy in mind; and the international programmes to which the UK contributes, such as the ESA science programme, must be shaped to support this strategy.

1.8 UK scientists, their knowledge and know-how, are much sought after for collaborative ventures. As well as ESA programmes, there are opportunities for collaborations with other international partners.

1.9 Many questions in solar system science involve expertise that crosses the traditional boundaries between research councils. Whatever the final structure resulting from the reorganisation of the research councils, appropriate cross-council collaboration needs to be much more effective than it has been to date.

1.10 This strategy covers a decade, but will be re-examined annually by the Solar System Advisory Panel and updated as necessary.

2. The Nature of the Solar System

2.1 The Solar System is both an object of investigation in its own right and a test-bed for our understanding of other stars and their planetary systems. It provides us, too, with a laboratory for physics and chemistry on a grand scale, but one that is still directly accessible to *in situ* studies. Thus the questions we ask here have wide applicability across the whole of astronomy. The UK's priorities for solar system science are soundly based on the strengths of our community, matching those strengths to the scientific questions that urgently need addressing.

2.2 The Solar System is diverse, complex and dynamic. It ranges from the Sun and planetary interiors, surfaces and atmospheres, to small bodies, and the interplanetary environment. This scientific diversity requires a wide range of disciplines to understand it, including physics, chemistry, and the application of Earth Science disciplines to other

Solar System bodies. The bringing together of these disciplines provides opportunities for cross-fertilisation and the opening up of new interdisciplinary fields, including those that span traditional research council boundaries.

2.3 Plasmas dominate most of the Solar System and are responsible for some of its most spectacular behaviour, such as solar flares, coronal mass ejections and the aurora. Solar system scientists have the opportunity to study several fundamental plasma processes in exquisite detail using remote sensing instruments and in situ spacecraft observations. The resulting knowledge can be applied to help us understand the effects of these processes throughout the Universe.

2.4 Cross-scale coupling, or the interaction between several physical processes, acting on several spatial and temporal scales, produces the rich complexity of phenomena observed in the Solar System. It is not possible to understand and predict the effects of these phenomena without taking into account these interactions. Couplings are often highly nonlinear, so it is not possible simply to consider the average behaviour at each scale: a multi-scale approach must be taken. The prevalence of cross-scale and cross-boundary couplings in the Solar System has given scientists in these fields great experience of analysing complex, structured and dynamic environments often with limited data sets. Such expertise is crucial for understanding many practical problems on Earth, such as climate change.

2.5 The diversity and complexity of the Solar System mean that there are some scientifically mature areas in which many individual processes are well understood. This allows us to address the challenges of complex coupled systems, including the interaction of various processes, and understanding micro-scale processes that have a system-wide effect. The reservoir of UK expertise in these areas makes our scientists much sought-after international collaborators. The UK must get scientific and/or financial just return on resources and investment represented by the equipment and facilities that the solar system science community has produced.

2.6 Other topics, particularly in planetary science which is often still in an exploratory phase, provide us with the opportunity to make major advances in our general understanding of planetary systems. Here again, UK scientists have developed innovative techniques and instruments from which due scientific and/or financial return must be obtained.

2.7 Three of PPARC's key science questions are core to solar system science (see http://www.pparc.ac.uk/roadmap/rmhome.aspx):

- How does the Sun affect the Earth?
- Are we alone in the universe?
- How do galaxies, stars and planets form and evolve?

2.8 Solar system science also makes an important contribution to another of PPARC's questions:

- What are the origins and properties of the energetic particles reaching the Earth?

2.9 While answering these questions, the Solar System community advances our knowledge of many widespread, universal ubiquitous processes that occur throughout the Universe such as shocks, particle acceleration, turbulence, dynamos and accretion.

3. Addressing the PPARC Science Questions

3.1 How does the Sun affect the Earth?

3.1.1 Our Sun provides the energy that allows life to exist on Earth. It is the dominant energy source for the Earth, dwarfing that produced by mankind: in an hour, the Earth receives more energy from the Sun than we generate in a year from fossil fuel and nuclear sources. A knowledge of how solar energy is transferred to the Earth, and in particular how variations in solar output produce changes in our climate, is therefore essential to predict our future. Our understanding of the Sun-Earth interaction is enhanced by comparison with other planets: for example, the Earth’s climate history with those of its neighbours, Venus and Mars.

3.1.2 Solving these general problems demands understanding of the physical processes at work in the Sun and their variation in time; the resulting solar output in the form of radiation, particles, and magnetic fields, and the details of the coupling of this output to, and effects on, planetary bodies, both magnetised and unmagnetised.

3.1.3 Once more, it is not possible to provide an effective answer the general question of how the Sun affects the Earth without answering several more detailed questions. At the forefront of these are:

- What is the structure of the Sun, from its core to the outer corona and how are different regions coupled in terms of magnetic fields, dynamics and mass and energy transfer?
- What processes heat the corona and drive the solar wind, and how are they reflected in their dynamics, morphology and composition?
- How does energy couple from the solar wind to the Earth, and on what spatial and temporal scales?
- How does solar variability affect the Earth – its magnetosphere, its atmosphere and its overall climate?

3.1.4 In order to answer the above questions, we also need to understand several key physical processes, such as:

- The physics of magnetic reconnection and its effects on the Sun, at the Earth and beyond
- The physics of plasma waves, instabilities and turbulence, and their interactions with particles

- The coupling of phenomena on the scales of electrons, ions and fluids, in space and time and across boundaries
- The interplay between the physics and chemistry of planetary atmospheres, driven by solar forcing, and its effects on local and global structure and dynamics

3.2 How do galaxies, stars and planets form and evolve?

3.2.1 The Solar System provides the *only* directly accessible laboratory to address this component of PPARC's science strategy. Solar system science provides vital knowledge to the wider astronomical community and generates important constraints for understanding the many extra-solar planetary systems that have been discovered.

3.2.2 Our Solar System is enormously heterogeneous. Classification provides a vital framework for solar system studies, but every body that has been visited by spacecraft or studied remotely by ground-based or Earth-orbiting observatories, and every sample that has been analysed in the laboratory, has its own particular characteristics. This means that reductionist approaches are less applicable in solar system science than in other areas of PPARC's remit. It is by understanding individual characteristics and their differences from body to body that we understand the underlying processes that are at work. This approach highlights the importance of comparative planetology.

3.2.3 Many important questions arise from the question of understanding how planetary systems form and evolve. Of particular importance to such studies for the UK's solar system science community are:

- How did the Solar System form, both as a system and as individual bodies, and what does this tell us about the formation of other planetary systems?
- How do geological processes and global geochemical cycles produce and interact with planetary atmospheres?
- What kinds of volcanic, tectonic and surface processes operate throughout the Solar System, and how can more complete understanding of these processes contribute to improving our knowledge of planetary origins and evolution?
- How do magnetised and unmagnetised planetary bodies interact with the solar wind; what processes are at work in the formation, maintenance and evolution of planetary magnetospheres?

3.2.4 In order to answer the above questions, we also need to understand several key physical processes which occur in the Sun and planetary bodies, such as:

- The processes responsible for the formation and evolution of the Solar System – collisions, accretion, cooling, heating, melting and crust formation
- The operation and effects of dynamos
- The mechanisms, timescales and effects of convection
- Ion/neutral coupling in atmospheres and its effects

3.3 Are we alone in the universe?

3.3.1 Of all the questions to be answered by PPARC scientists, this question is the one that arouses the greatest public interest, and is the hardest to answer with any scientific certainty. It is at the centre of the ESA Aurora programme, and addressed by many other international, national and local projects.

3.3.2 The coming decade, however, offers genuine opportunities if not for answering this question definitively, at least for defining the conditions for life elsewhere to arise and evolve. In doing this, the UK's solar system science community will play a leading role. To carry out this component of PPARC's scientific roadmap will require UK scientists to match their existing and developing skills to aspects of the search for actual or past life as this is where they can make the most effective contribution.

3.3.3 In particular, we will address the following questions:

- What are the special requirements of life in the formation and evolution of the Solar System and other exoplanetary systems?
- What is the role of water as a (pre)requisite for life?
- How have conditions in the Solar System evolved to make watery habitats available – either now or in the past?
- What are the signatures of past or present life in atmospheres and planetary surfaces?
- What is the range and occurrence of actual and potential life-supporting habitats?
- What is the occurrence, variety and composition of extra-solar planetary systems, and in what ways are they similar to and different from the Solar System?

3.4 What are the origins and properties of the energetic particles reaching the Earth?

3.4.1 The energetic particles that reach the Earth are accelerated at a range of sites throughout the Universe, as well as within the Solar System at solar flares, interplanetary shocks and the termination shock. The Solar System is therefore a unique laboratory in which to study particle acceleration and propagation and UK scientists play a leading role in understanding these processes.

3.4.2 Solar flares can accelerate particles to GeV energies. A unique feature of studying such particles is that they may be detected both by remote sensing through their electromagnetic emission (e.g. by the RHESSI spacecraft) and *in situ* by spacecraft. Determining the process by which the particles are accelerated and how they subsequently propagate, in complex, often turbulent magnetic field configurations, is a challenging theoretical problem.

3.4.3 The heliospheric magnetic field also influences the propagation of cosmic rays from outside the Solar System, and such particles may also be monitored by space instrumentation to help us to understand how they propagate.

4. Funding Strategy

4.1 The UK community has internationally leading scientists and projects across the entire solar system science area. Recognising that resources are finite, however, it is necessary to prioritise science areas, and hence develop a strategic framework for investment decisions. Science programmes must be adequately funded even if this means reducing the number of projects funded. The resulting programme must be balanced across observation (remote and *in situ*), theory, modelling, science exploitation, and infrastructure.

4.2 The nature of solar system science is such that suites of experiments are often required to provide the range of measurements to address critical science problems. Therefore facilities cannot be considered in isolation. The analogy with astronomy would be the need for several instruments and/or multiple wavelength observations of a single object. Suites of smaller instruments around larger facilities or missions can provide important observations and contextual information. The major infrastructure required to deliver the strategy is described in the following section.

4.3 The UK must ensure that it capitalises on past investment. Support should be provided to ensure continued operation and exploitation (through grants, studentships and fellowships). Support for facilities and missions should be continued if it is clear that they will continue to deliver high impact science that meets the science strategy and in which the UK is a major player. Where this is not the case funding should be terminated to free up resource for new activity. Facilities should anticipate that they will be expected to find operational efficiencies with time.

4.4 At the same time, investment is required in new facilities, technologies and capabilities that will position the UK to be undertaking world leading science in the long-term future (2020+). There are exciting new areas of science opening up: space telescopes that will directly observe terrestrial-like planets and interpreting the structure of their stars; Mars Sample Return; the Jupiter exploration programme; lunar exploration initiatives; and multi-spacecraft plasma physics missions. Major opportunities exist, too, to gain unprecedented understanding of the Sun and its influence over the whole solar system environment, both its immediate effects and long-term influences. Indeed, much of these exciting programmes have already been shaped by the inputs we provided, and no effort should be spared to capitalise on our investments of time, ideas and money.

4.5 The UK needs to invest now to be in a position to take a leading role in these challenging missions. Involvement in these programmes will not only allow UK scientists to take a leading role in the science of the Solar System and other planetary systems; it will also inspire the youth of tomorrow, to study science and deliver a knowledge-based society.

4.6 A significant proportion of the PPARC budget goes on international subscriptions. PPARC should ensure that the UK is in a position to exploit that investment. For example the UK subscription level for the ESA science programme is 17%. This provides for the mission infrastructure costs, but not the instrumentation. PPARC should aim to contribute an average of 17% of the overall mission payloads. This does not necessarily mean that the UK should provide 17% of all payloads; hardware contributions should be targeted to missions that are well-aligned with the PPARC strategy. A challenge for PPARC will be to increase its budget to enable this objective to be achieved.

4.7 For whatever reason, the current programmes of fellowships are not providing sufficient young scientists in solar system science areas to maintain a healthy population of researchers. Particular consideration needs to be given, therefore, to the creation of prestigious, longer-term fellowships in solar system science, as have been established for Aurora. Such fellowships, if held in universities, should be seen as a route into tenured positions, and a consideration for awarding them should be institutional commitment to such posts.

5. Infrastructure

5.1 Mission involvement

5.1.1 Access to space-based measurements is a key requirement for all the science priorities. This should be achieved through extension to existing missions where the science value can justify continued expenditure, e.g. Cassini, Cluster, SoHO and Rosetta and capitalising on future missions such as Solar-B, Stereo and MIRI. Major involvement will be required in future space missions that will address PPARC's Solar System Strategy. Upcoming missions for which UK involvement is essential are listed in Appendix A.

5.1.2 The UK needs to invest in technology for forthcoming missions. In some instances this can be done through participation in bi-lateral missions. An example of this is the requirement to support UK involvement in KuaFu (a bilateral with China) in preparation for Cross Scale. To be funded bilaterals need to demonstrate that they deliver specific elements of the strategy not covered by the ESA programme and/or develop technological capability to position the UK for ESA future missions.

5.1.3 It is essential to maintain a critical mass of people in a range of space technology; otherwise the UK will lose its capability to lead space research initiatives. In addition, stronger links with industry should be developed and greater emphasis placed on knowledge transfer. Since the objective must always to be for the UK to deliver world-leading science, the science user community must be involved at the earliest stages of mission definition.

5.1.4 Extrasolar planets place planetary science at the heart of contemporary astronomy. Direct measurements of light from giant extrasolar planets, rather than inferring their properties by the effect they have on their central star(s), have been made for the first time. For Darwin a long-term technology development programme is required in order for the UK to be a major player in this new and exciting area of science.

5.2 Laboratory analysis

5.2.1 Planetary scientists already have samples of some Solar System bodies, and missions to collect a wider range of primitive and processed material have started to return to Earth. This gives scientists an unprecedented opportunity to obtain detailed information about the composition and history of the source body and about conditions prevalent during the formation of the Solar System.

5.2.2 Cosmochemical studies of dust grains and meteorites obtained from space are extremely important in understanding the formation and evolution of the Solar System. The UK has an outstanding reputation for laboratory studies of extraterrestrial material. It is vital to maintain and develop these facilities. In conjunction with the UK's planetary protection capability, it places the UK in a strong position to provide the European Sample Return curation facility. The UK must continue to invest in this area, if it is to achieve this objective.

5.3 Modelling

5.3.1 Investment in programmes to gather data from space- and ground-based observatories must be complemented by appropriate investment in theory and modelling. The UK solar system theory and modelling communities are internationally strong, but resources are needed to maintain and build strengths.

5.3.2 The construction of realistic models, particularly if they are to be coupled (see below), requires a long-term strategy. PPARC has to move to a situation where modelling projects are accorded "mission status", with teams and facilities afforded the same security and longevity as spacecraft and instrument building teams.

5.3.3 A particular priority is to develop and capitalise on the UK's existing expertise in computational magnetohydrodynamics (MHD), and to expand into emerging theoretical fields, including those that are numerically intensive. In the solar-terrestrial case, the future priority is to develop an integrated modelling programme that couples together current isolated models of different parts of the solar-terrestrial environment, from the thermosphere to the solar wind. For solar physics, priorities are to integrate kinetic and MHD approaches to plasma physics, and to develop the numerical techniques necessary to cross 'boundaries' (e.g. chromosphere to corona) and scales.

5.3.4 A further key priority is to support the further development and exploitation of terrestrial and planetary atmosphere models, in which the UK plays a world leading role. These have been used to interpret data and plan spacecraft missions, giving the UK a key role of expertise in many missions, including those without direct hardware contribution. Their coupling to magnetosphere models, where appropriate, should also be supported.

5.3.5 An area that is often overlooked is the provision of atomic and molecular data, required to simulate the microscopic processes that go into models. Support for this work through the grants line should be seen as supporting solar system science goals.

5.3.6 Provision for modelling includes relevant infrastructure - state of the art computer facilities with proper support, the financial resources to buy time on these facilities and, most importantly, manpower through studentships and postdoctoral positions.

5.4 Ground-based facilities

5.4.1 Ground-based observations contribute to all areas of solar system science: solar observations, solar-terrestrial physics and planetary studies.

5.4.2 The BiSON network provides a scientifically leading monitoring capability for helioseismology, providing UK scientists with by far the longest database to study the low-degree, core-penetrating oscillatory modes of the solar interior. Opportunities also exist for UK instruments (e.g. Rosa, currently under construction) and for participation in international projects (e.g. the LoFAR radio array).

5.4.3 The solar wind, magnetosphere and ionosphere provide a unique plasma laboratory. PPARC’s current combination of ground-based STP facilities (EISCAT, CUTLASS and SPEAR) provides a very powerful insight into the way that energy coupling works in geospace. The simultaneous use of different techniques is essential, as it allows complementary measurements of the same phenomena.

5.4.4 EISCAT is the most capable radar in the world for upper atmosphere studies. Only incoherent scatter has the potential to deliver continuous measurements of plasma parameters from the mesopause to the ionospheric topside. EISCAT’s advanced experimental capabilities allow such measurements to be undertaken with spatial and temporal resolutions impossible elsewhere. As such, EISCAT is a vital tool for UK solar system science. For EISCAT to remain scientifically competitive, investment in a new facility will be required early next decade. A science review will be required in 2009 to assess the science benefit of the investment required.

5.4.5 SPEAR enables UK scientists to undertake controlled laboratory-style experiments in modifying the ionosphere, creating artificially generated aurorae and plasma waves, which are observed by EISCAT, CUTLASS and optical instruments. Although SPEAR has the potential for being scientifically productive for many years, PPARC funding will end in 2008. Until this time, the science exploitation of SPEAR must take a high priority. At the same time, PPARC must be active in negotiating a secure future for SPEAR beyond UK funding.

5.4.6 CUTLASS is a key element of the international SuperDARN facility, which provides the ability to image convection flow and plasma irregularity characteristics on a global scale in both hemispheres. CUTLASS provides the essential context for the observations by EISCAT and SPEAR. The planned closure or re-allocation of CUTLASS will have an adverse impact should the UK want to be involved with ongoing and future space missions, such as Cluster and NASA's THEMIS. The loss of the CUTLASS element of SuperDARN would severely limit understanding of how the Sun affects the Earth on the global scale. It is imperative that PPARC ensures that this facility continues, possibly run by another country. In these negotiations PPARC should ensure UK access to SuperDARN data, to enable PPARC to address the question 'how the Sun affects the Earth?

5.4.7 As our understanding of terrestrial high latitudes matures, measurements at lower latitudes will increase in importance. Continuous measurements of the electric field in the vicinity of the footprint of the ring current will play a major role in determining the transport mechanisms of energetic particles in the radiation belts, a major unsolved question. The UK should therefore keep open its options of participating in new international projects, such as StormDARN.

5.4.8 The boundary between the mesosphere and lower thermosphere is critical in understanding the solar influences on the atmosphere and in particular climate change. Progress in this field requires continued PPARC investment in EISCAT, IRIS, coherent radar systems and coupled atmospheric models, together with investment from other research councils in complementary systems such as meteor radars and mesospheric imagers. PPARC must find an effective way of handling work that crosses the traditional PPARC/NERC divide.

5.4.9 Observations in support of the Cassini mission, using existing facilities and instrumentation, show the potential for UK planetary scientists to develop programmes making use of ground-based telescopes. The UK has never had so much world-class telescope time available to it, and we must capitalise on this to get the most out of our investment in space missions. Looking to the future, new instrumentation will be required in support of planned NASA and ESA Jupiter and Mars missions, amongst others. The UK has particular strengths in optical and infrared astronomy, and should capitalise on forthcoming opportunities for new instrumentation.

5.4.10 The UK has taken a leading role in the search for terrestrial-like planets. The existing SuperWASP and RoboNet facilities are discovering new planetary systems. Future progress in this area requires continued support and development of robotic telescope networks to detect and study cool planets down to a few Earth masses. This will place the UK in a strong position to exploit the future Darwin planet-finder mission.

5.5 Data archiving, assimilation and visualisation

5.5.1 Data are expensive to collect but offer a very valuable long-term resource, if professionally managed. PPARC has a duty to ensure that data arising from its investments are properly archived and accessible to at least the UK research community over the long-term. Where possible this should be undertaken by the appropriate international organisation e.g. ESA, ESO and EISCAT, otherwise PPARC should resource a UK grid-enabled data archive. Once data have stopped being collected the data archive should be completed quickly and expenditure minimised. Mirroring data sets should not be considered unless there is a significant and demonstrable benefit to the UK community.

5.5.2 The multiplicity of data sources relating to similar science questions challenges our existing techniques of data handling, comparison and visualisation. Solar system scientists are the first to have made their models available through AstroGrid. In the future, the exploitation of models on demand, and the coupling of models maintained by different groups will need to be effected more systematically through Grid-enabling. Advantage needs to be taken of the opportunities provided by the AstroGrid infrastructure; key issues to be addressed will be data assimilation and data mining. Investment in these developments will be most effective if linked to demanding science problems.

6. Cross-Disciplinary Science

6.1 Within the Solar System strategy there are cross-cutting science topics and approaches that transcend the PPARC science programme. The community should be encouraged to stimulate knowledge transfer across the traditional scientific disciplines. The funding process must ensure that cross-cutting proposals are considered on an equal footing with those lying entirely within the remit of one funding panel.

6.2 PPARC needs to take the lead in ensuring that the UK’s investment in Aurora is fully exploited. To achieve this, an interdisciplinary approach is required and expertise developed through other Research Councils needs to be tapped. Astrobiology will be a growing area of research in the coming decade and cross-council mechanisms to foster this, such as workshops, joint fellowships and studentships should be encouraged.

7. International Context

7.1 The strategy and priorities identified will make a major contribution to the ESA Science Programme and ESA’s optional Aurora programme. Where PPARC strategy is aligned with international programmes, the UK should aim to take an active role, either through our membership of international organisations and/or directly.

7.2 Opportunities for bilateral missions, in particular, can provide significant science return at relatively low cost. PPARC should aim to participate in bilateral missions where appropriate.

8. Knowledge Transfer

8.1 PPARC solar system scientists are involved in knowledge transfer to a variety of users and audiences, ranging from technology transfer to public outreach. This must continue to maximise the wealth-creating potential of the UK scientific and technological base.

8.2 In developing the complex technology required for scientific instrumentation and robotic spacecraft many other sectors of the UK economy benefit. ESA has calculated that the revenues generated by knowledge transfer of space technologies exceed the related expenditure by 15-20 times. Technologies being developed for solar system missions can be applied in the defence, aerospace, transport, power, instrumentation, healthcare, telecoms, IT and software industries.

8.3 The nature of solar system science is such that the training provided produces inter-disciplinary scientists who can work effectively in teams at interfaces between different science areas, crossing research council boundaries, and interacting with industry. This should be encouraged and developed, in particular for new growth areas; for example, consideration should be given to starting a summer school in astrobiology.

8.4 Climate change has enormous economic and social consequences. Its accurate prediction is essential. Solar variability and its role in climate change is identified in the International Governmental Panel on Climate Change report (2001) and in NERC’s “Science for a Sustainable Future 2002-2007” as a key science problem. To address this science problem requires NERC and PPARC to work effectively together across the funding boundaries. The science within this strategy will also create the necessary knowledge base for any future EU or ESA initiatives in space weather.

8.5 The questions of the origin of life, the evolution of conditions that can sustain life in our and other solar systems, are of great cultural and intellectual interest to the general public. PPARC should build on the outreach programme “UK goes to the Planets”, as we move into the Aurora era, to inform and educate the general public and to enthuse the next generation to become scientists and technologists.

Appendix A – Key missions and facilities required to deliver the Strategy where PPARC directly funds build or operations costs

	Existing/in build	**Near-term**	**Long-term**
How does the Sun affect the Earth?	BepiColombo Cassini/Huygens Cluster CUTLASS EISCAT Mars Express SPEAR SoHO Stereo Solar-B Venus Express	EISCAT-3D ExoMars KuaFu MMS SDO operations StormDARN IMGES	Aurora CrossScale Jupiter Europa Mission Solar Orbiter
How do galaxies, stars and planets form and evolve?	BepiColombo Cassini/Huygens Mars Express Robonet Rosetta Stereo SuperWASP UKCAN Venus Express	ExoMars NEO Sample Return Robotic Lunar Exploration IMGES Scout mission proposal	Jupiter Europa Mission Mars Sample Return Saturn Titan Enceladus Mission Solar Orbiter
Are we alone in the Universe?	Cassini/Huygens Mars Express Robonet UKCAN	ExoMars	Darwin Jupiter Europa Mission Mars Sample Return

Note: this is a table of the key facilities and missions only; other, smaller, commitments will also be required over the next decade or two.