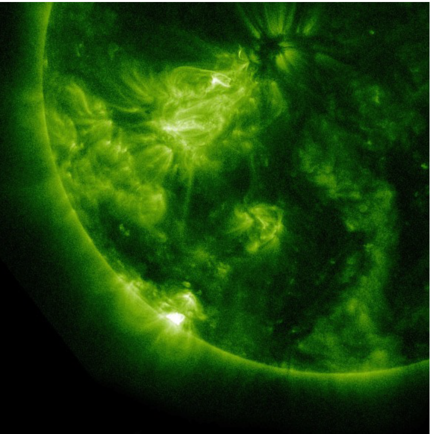
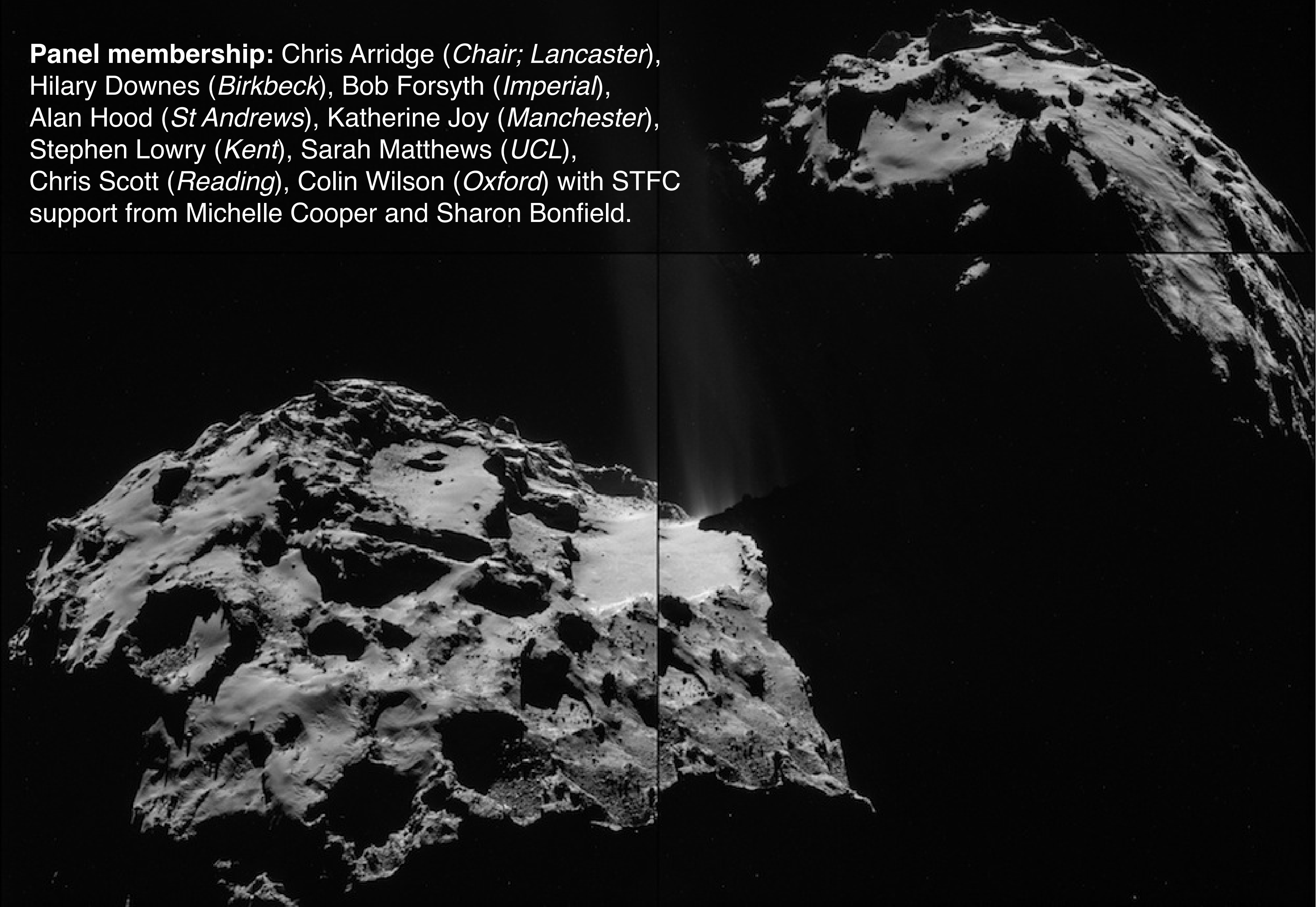


Roadmap for Solar System Research July 2015

Prepared by STFC's Solar System Advisory Panel on behalf of the UK community of Solar System researchers for STFC



Panel membership: Chris Arridge (*Chair; Lancaster*), Hilary Downes (*Birkbeck*), Bob Forsyth (*Imperial*), Alan Hood (*St Andrews*), Katherine Joy (*Manchester*), Stephen Lowry (*Kent*), Sarah Matthews (*UCL*), Chris Scott (*Reading*), Colin Wilson (*Oxford*) with STFC support from Michelle Cooper and Sharon Bonfield.

Executive Summary

1. Under the leadership of Monica Grady, the Solar System Advisory Panel (SSAP) wrote a "Roadmap for Solar System Research" in preparation for the programmatic review that was released in November 2012. This was based on a document written by its predecessor body, the Near Universe Advisory Panel in November 2009.
2. A new SSAP chair was appointed in December 2014 and the Solar System Advisory Panel (SSAP) carried out a "light-touch" review of the previous roadmap during Q2/2015 via a Town Hall Meeting in London on 19 June 2015 and an anonymous community consultation on the previous roadmap. SSAP also included the results of consultations carried out in Q1/ and Q2/2015 by SSAP on computing and in response to the Nurse review of research councils.
3. Solar System science is not an island isolated from other research communities, particularly the Astronomy and Particle Astrophysics communities, and there is potential for overlap in the research aims of the communities. Where possible, this has been indicated in the text.
4. The STFC is not the sole Research Council that has interests in Solar System research. Both the UK Space Agency and the Natural Environmental Research Council (NERC) are involved in different aspects of the research. Applied research in the area of Solar System science is also funded by the Engineering and Physical Sciences Research Council (EPSRC) The SSAP hope that this Roadmap will help these bodies as they also define their research priorities and facilitate cross-research council projects.
5. Three overarching themes are identified which encompass the outstanding scientific questions to be addressed over the next two decades. These themes are: (1) Solar Variability and its Impact on Us, (2) Planets and Life and (3) Universal Processes.
6. There are several cross-cutting activities that are also essential for successful delivery of the goals outlined in this Roadmap. These activities are also relevant to the research activities of the other communities funded by the STFC, and are (in alphabetical order): Data centres and Data archiving; the Grants, Fellowships and Studentships lines; High Performance Computing and Laboratory Equipment and Infrastructure.
7. The Roadmap recognises specific strengths where the UK is particularly well-placed to make significant contributions to the questions, in terms of complementary areas of expertise (observation, experimentation, simulation and numerical modelling). Alongside each set of questions are the specific space missions and facilities (national and international) that are required to help deliver the research goals summarised in the Roadmap. It is important to note that this roadmap does not prioritise one Solar System body above others.
8. There are several recommendations that the SSAP makes to STFC on more general aspects of its programme. These recommendations are as follows:

General Recommendations:

Recommendation 1: *The SSAP recommends that the STFC supports the UK Space Agency's recent membership of ESA's ELIPS Programme with funding to exploit data from the ELIPS facilities in the same way as from other space missions (including bilateral opportunities) and projects, supported via proper peer review via AGP.*

Recommendation 2: *The dual-key approach between the UK Space Agency (UKSA) and the research councils is welcomed and it is important that both bodies are cognisant of, and take into account, the relative priorities of each organisation. Where appropriate, there should be cross-representation on committees responsible for strategic, funding and prioritisation decisions, and this 'dual-key' approach must be monitored and evaluated by regular, publically-circulated reports. SSAP recommends that more be done to clarify the funding mechanisms and processes between UKSA and the research councils.*

Recommendation 3: *SSAP recommends that the STFC supports UKSA in its partnership in ESA's Space Situational Awareness Programme with funding to exploit facilities and carry out research in the same was as in other projects, supported via proper peer review via AGP and PPRP.*

Recommendation 4: *The UK has invested millions of pounds in missions and instrumentation, and the final product of this investment is the publically owned data-set. STFC has an obligation to preserve these data. We recommend that the STFC continues to fund its data centres, such as UKSSDC, at the level required to maintain efficient and effective operation, without prejudicing the security of the data.*

Recommendation 5: *As a <u>minimum</u>, STFC must maintain the Grants line at its current level (cash basis, not percentage of the programme): if it falls any further, the number of PDRA working in the subject will be insufficient to keep the programme going, resulting in a decrease in performance at all levels, and an inability to compete for funding at the international level.*

Recommendation 6: *As a minimum, the STFC must maintain its Fellowship and Studentship programmes at their current levels (cash basis, not percentage of the programme). Fellowships and Studentships are the main pathways for bringing young people into research, technology and academia. The Fellowship programme is an important way of recognising future leaders in the field, who will continue to drive research forward, again to the benefit of the UK. However, there is a significant funding gap in early career fellowships that enable us to identify these future leaders and nurture their independent development and this must be addressed. The skills acquired through studying for a PhD are of great benefit to the UK economy as a whole, not just for those who remain in STFC-funded research.*

Recommendation 7*: SSAP supports STFC's recent computing consultation aimed at developing a clear and appropriate funding strategy for HPC/HTC to allow the UK to remain competitive in the critical area of HPC expertise, and to ensure adequate training for future generations of scientists. Furthermore, it is critical that STFC recognise that the development of* *new numerical models is essential for continued scientific excellence, impact, and international leadership in a wide variety of areas. STFC should consider the development of numerical models in a similar way to the development of new telescopes, space instrumentation, or new detectors for particle physics.*

Recommendation 8: *STFC maintains support for ground-based laboratory experimental, analytical, simulation, fieldwork activities and curation facilities, to enable the UK to maintain its high international profile in the relevant fields, and play a leading role in forthcoming sample return missions.*

Recommendation 9: *That STFC maintains its support for ground-based and space-based telescope operations and instrumentation at a level that will enable the UK to maintain its high international profile in the relevant fields. This support should recognise and balance the competing claims of new developments versus extension of current instrumentation, such that UK scientists are able to access the range of facilities they require to meet their goals.*

Recommendation 10: *SSAP recommends that STFC, NERC and EPSRC work more closely to enable and deliver research that cuts across the remits of the various research councils.*

Specific Recommendations on Prioritisation:

9. Prioritisation of projects and facilities is a complex, difficult and divisive process that is essential for an efficient scientific programme which remains up-to-date, is able to compete in an international arena and successfully delivers its desired outcomes. In putting together the Roadmap, the SSAP took scientific excellence as the main driver, followed by the international significance of the project; the extent of UK leadership and the timeliness of the project.

10. The SSAP has not prioritised specific missions, Solar System bodies, or projects over others: we have not had the information, the time or a mandate from the community to do this. Instead, what we have suggested is a rolling prioritisation based on the status of the projects in question. We suggest a flexible apportionment of resource, which might be possibly along the lines of, for example, 60 % to projects in operation, 30 % to those selected and in development, 10 % to those not yet selected, but requiring input for development. The split of 60:30:10 is given only as an example, and the actual figures should be subject to continual monitoring and adjustment.

11. Exploitation of data from a project continues long after the instrument itself has ended, thus each project should be seen as carrying on beyond the project end. Funds for this stage of research would, presumably come from the Grants line and Fellowships and Studentship programmes.

12. There is still a grey area, possibly not completely understood by the community, where responsibility for funding of projects falls between the remits of the STFC and the UK Space Agency. Thus funding for building a detector for a mission is the responsibility of the Space Agency, but funding for research into generic detector development belongs with the STFC. Funds for such research would, presumably, come from the PRD line, and/or the Grants line and Fellowships and Studentship programmes. We recommend more clarity is provided on this aspect, both by STFC and UKSA, and that communication between the two bodies is enhanced through interaction of their respective advisory panels.

13. There are a large number of projects that have not been included on the Roadmap because they are not funded by the UK, either directly or through international subscription, e.g., NASA's Juno mission to Jupiter. NASA's Solar Dynamic Observatory, and JAXA's Hayabusa 2. Data from such projects are available, and exploitation of these data is a vital part of the community's research effort, both in terms of preparation for future missions as well as helping to deliver answers to our key research questions. The absence of specific mention of these projects must not be taken as an indication of unimportance: they are a crucial part of our research effort. Funds for such research would, presumably, come from the Grants line and Fellowships and Studentship programmes.

14. Internationally-leading and impactful projects can be carried out based on the exploitation and data mining of legacy data sets from space missions and facilities that are no longer operational. SSAP fully supports the funding of such projects via the normal peer-reviewed routes via the Grants line and Fellowships and Studentship programmes.

15. **Given the above considerations that go with the Roadmap, it should be clear that the SSAP rates maintaining (at the very least) the Grants line and Fellowships and Studentship programmes at their current level as its highest priority.**

Introduction

At the heart of the research undertaken by the communities represented by the Solar System Advisory Panel (SSAP) is a drive to understand the origin and evolution of the Solar System, and the nature of the phenomena that influence its dynamics. The remit of the SSAP covers all bodies in the Solar System, from its central star, the Sun, to the outermost fringes, as defined by the Oort cloud that is a reservoir of comets. Within the Solar System is a variety of objects: planets, their satellites and rings, asteroids, Kuiper Belt Objects and comets, plus streams of interplanetary and interstellar dust. Interactions between and amongst Solar System bodies are influenced by gravitational, magnetic and electric fields. Controlling the entire dynamic of the Solar System is the Sun, a complex interplay of plasmas and fields that connect with and influence the behaviour of planetary magnetospheres and ionospheres. The Solar System came into existence some 4.567 billion years ago, and the evolutionary processes that we follow through study of objects within the Solar System should be applicable to, and should direct the study of, other stars and their planetary systems, as well as magnetised plasmas in general.

We are fortunate that over the next five or so years, we will be in a time of enriched Solar System exploration, with ESA's flagship **Rosetta** mission making observations at comet Churyumov-Gerasimenko. Preparations for the launch of the **Trace Gas Orbiter** to Mars in 2016, and its partner **ExoMars** lander in 2018 are well in hand, as are launches of **Solar Orbiter and BepiColombo** in 2018, as well as the start of operations of **JWST**. These are all ESA missions, to which the UK has made a significant contribution in terms of design and instrument build (as well as funds); the scientific community is looking to capitalise on this investment with an exciting programme of research planned, based on exploitation of data from these missions. We are also poised to take advantage of partnerships with other agencies: UK scientific excellence is recognised by invitations to UK scientists to participate in major international consortia, including those established to study the surface and interior of Mars, analyse material returned from an asteroid, explore the jovian atmosphere and magnetosphere and observe solar phenomena.

In order to focus the efforts of the community of Solar System scientists and the expertise they bring to their research, we have defined three themes that encapsulate the sweep of our research goals. These are: (1) **Solar Variability and its Impact on Us**; (2) **Planets and Life** and (3) **Universal Processes**. Within each theme, a series of specific questions has been developed which are pursued through a combination of observation (reliant on both space- and ground-based instrumentation), laboratory analysis and experimentation, simulation and theoretical modelling. Complementing the science themes is a set of **Cross-cutting Activities**, areas of significant importance that are relevant for all three of the themes (indeed, they are relevant for all of STFC's research communities). The questions speak to and extend the 'Big Questions' that currently comprise STFC's Science Roadmap (http://www.stfc.ac.uk/Roadmap/index.aspx). They are also questions of international importance, as they echo priorities that have been recognised in road-mapping exercises undertaken by several international bodies, specifically Astronet (http://www.astronet-eu.org/), and its Working Group ETFLA (the European Task Force on Laboratory Astrophysics). We are also aware of the goals of ESA's Cosmic Visions and Aurora programmes, as well as the intentions of the EU Horizon 2020 framework.

Although the specific request STFC made to the SSAP was to produce a roadmap of the key goals and requirements for Solar System research over the next 15 – 20 years, we have also taken the opportunity to consult with our community to formulate a series of recommendations regarding our wider research programme.

It is within the remit of SSAP to consider Outreach, Impact and Technology Development. These areas were not included in the previous version of the roadmap and not addressed by the previously appointed panel during its tenure. We draw attention to this omission from the Roadmap, so that review panels do not, mistakenly, infer that they are unimportant and so deny them funding. These aspects will be addressed by SSAP and delivered to STFC in Q2/2016.

Overlap with Astronomy and Particle Astrophysics Research Areas

Solar System research overlaps with astronomy in several areas, e.g., in the study of stellar activity, asteroseismology draws on results from helioseismology, and work on solar flares and prominences informs consideration of related stellar features. Similarly, study of solar and planetary dynamos feeds into research on astrophysical dynamos, turbulence in disks, etc. The field of exoplanet research also demonstrates complementarity between the Solar System and Astronomy communities, with each community bringing a different flavour to the research effort. As we move from detection to the characterisation of exoplanets, the skills and knowledge of the Solar System community become central to our understanding of these alien worlds. We are starting to reach the point in this area where we have sufficient confidence in the data to apply some of our most simple Solar System models. This is fundamentally important as some of the newly-discovered planetary systems contain objects for which there is no Solar System analogue (e.g., super-Earths) and hence allow severe tests of our physics. Solar System research also overlaps with the field of Particle Astrophysics, particularly in the study of neutrinos, cosmic rays, interstellar dust, wave-particle interactions, shocks, and other particle acceleration processes. As noted in the previous section, there are several issues which are common to the research communities represented by the different Advisory Panels (data archiving, grants, fellowships and studentships, high performance computing and laboratory instrumentation). In this report, we have brought these areas together under the heading of Cross-cutting Activities, in order to draw attention to their importance.

Relationship with the UK Space Agency and with ESA

UK SPACE AGENCY

The UK Space Agency now funds the development and operation of spaceflight instrumentation developed and built by UK groups; such instruments are not just for ESA missions, but include development and build for bilateral and UK-only missions. It is important that the UK Space Agency strategy is consistent with the science requirements of the missions and instrumentation, as determined by STFC (and other Research Councils, e.g., NERC), to reap the benefits of UK participation in space-based projects in terms of science definition, data exploitation and interpretation, training of PhD students and PDRA, research fellows and outreach opportunities. Additionally, the STFC and UK Space Agency share a common impact agenda that is served through the continued growth of the UK Space Sector and initiatives such as ISIC, the Space Catapult, and the creation of ESA's European Centre for Space Applications and Telecommunications (ECSAT).at Harwell.

The creation of the UK Space Agency has resulted in a change to some of the STFC's funding responsibilities, most particularly the subscription to ESA, which no longer features in STFC's budget line. Whilst consideration of the ESA subscription is not part of this prioritisation exercise, we deem it essential to highlight the importance of ESA to our research goals. The selection of space missions, and the development of spaceflight instrumentation for those missions, are critically important issues for the Solar System science communities, and so remaining a leading member of ESA is a top priority. The UK Space Agency relies upon the STFC (and other Research Councils) for information and advice when setting its own priorities. By ensuring that ESA (and other space agencies') mission-related research is aligned with STFC's road-mapping exercise, the UK Space Agency also has a firm scientific basis for its recommendations. There should also be a reciprocal recognition from the STFC that missions, once they become supported by the UK Space Agency, remain visible in the Solar System Roadmap, when relevant to Solar System research questions. We note that UK Space Agency-supported missions include technical demonstrations that provide pathways to meet future science requirements in addition to mature science missions.

There is some confusion in the community regarding the division in responsibility between STFC and UKSA. For example, UKSA funds some science planning and exploitation funding via ESA's 'Aurora' programme and through bilateral space exploration missions of opportunity (e.g., MSL, NASA, Insight, NASA; Osiris-Rex, NASA). STFC supports fundamental instrument technology development, and UKSA supports more mature instrument development. SSAP have received anecdotal evidence that there is some uncertainty regarding where support from STFC should cease and where UKSA should take over. It is important to resolve this in an internationally-competitive space science environment with implications for space exploration, human spaceflight, and Earth-observation. In parallel with these issues, there is no mechanism within the grant systems of UKSA or STFC to support mission science planning, particularly the type that is required to support instrument development and establish science leadership during a space mission flight hardware programme. The old STFC rolling grant system did provide the opportunity to bid for funds for such activities, but the new consolidated grants do not and UKSA does not consider these activities to be within their remit. It is important that the UK community fully understand the dual-key approach and that sufficient information on funding opportunities is made available.

Recommendation 1 *The SSAP recommends that the STFC supports the UK Space Agency's recent membership of ESA's ELIPS Programme with funding to exploit data from the ELIPS facilities in the same way as from other space missions (including bilateral opportunities) and projects, supported via proper peer review via AGP.*

As part of a desired expansion of the national space programme, the UK Space Agency has joined ESA's Life and Physical Science in Space Programme (ELIPS). This is an optional programme, and acts as an umbrella for a variety of activities, including access to the International Space Station, parabolic flights and drop towers. These facilities enable experiments to be carried out in zero gravity, and also at high gravity and at high speed. Subscription to these facilities provides the UK with access to a laboratory in low Earth orbit, as well as new planetary simulation facilities and detector test beds. This is of great benefit to the Solar System science community as it enhances and extends the range of observations, experiments and simulations that can be undertaken in pursuit of our science goals, across all three of the themes described above. It is therefore important that STFC be aware of this new subscription and provide funding to exploit data from ELIPS facilities(via the same AGP-supported peer-review mechanisms) in the same manner as other space missions and projects, naturally.

Recommendation 2*: The dual-key approach between the UK Space Agency (UKSA) and the research councils is welcomed and it is important that both bodies are cognisant of, and take into account, the relative priorities of each organisation. Where appropriate, there should be cross-representation on committees responsible for strategic, funding and prioritisation decisions, and this 'dual-key' approach must be monitored and evaluated by regular, publically-circulated reports. SSAP recommends that more be done to clarify the funding mechanisms and processes between UKSA and the research councils.*

In order to gain fully from participation in space missions, there must be sufficient funds both to prepare for future missions (modelling, simulations, comparative studies, etc.) as well as to exploit data from current and past missions. To date, as far as the SSAP has been able to judge, there have been clear messages from both STFC and the UK Space Agency about where the boundary of funding responsibility lies. Whilst we very much welcome this aspect of co-operation between the two bodies, the boundary is not always apparent to the community at large. The SSAP takes the opportunity given by this road-mapping exercise to re-iterate the importance of the synergy between STFC and the UK Space Agency, where generic research and development for hardware (e.g., penetrators, detectors) is the purview of the STFC, whilst development, build and operations for specific missions lies firmly with the UK Space Agency. Funding for exploitation of data from space missions, which often arises many years after the original STFC investment in generic R&D and mission selection process, is again very definitely the remit of STFC. It is essential that STFC's funding in these areas remains at a level that ensures continued UK success within ESA missions, and such that our national space programme is able to expand to implement bi-lateral programmes that serve both to test new technologies and deliver science return.

Recommendation 3*: SSAP recommends that the STFC supports UKSA in its partnership in ESA's Space Situational Awareness Programme with funding to exploit facilities and carry out research in the same was as in other projects, supported via proper peer review via AGP and PPRP.*

With space weather now included in the National Risk Register, the UK government recognises the potential impact of an extreme space weather event to the national economy. The UK Space Agency has joined the space weather core element of ESA's Space Situational Awareness (SSA) programme which aims to develop a space weather monitoring and forecasting capability. The impact of space weather at Earth depends critically on a detailed understanding of the generation of solar mass ejections, their propagation through interplanetary space and their interaction with the Earth's space environment. The UK science community are already world leaders in these areas of research and are ideally placed to help develop any instrumentation and forecasting models that would be central to an operational space weather service. These also provide a vital enabler of the Met Office's Space Weather Operations Centre, the European lead for space weather forecasting.

Relationship with other Research Councils

The community represented by SSAP performs a range of cross-disciplinary research that is supported in various areas by STFC, NERC, EPSRC and UKSA. By its very nature, cross-disciplinary areas of research often reside near the boundaries between the remits of the individual research councils, for example:

- Fundamental plasma physics: astrophysical/Solar System plasma physics is funded by STFC, laboratory physics is funded by EPSRC/STFC.
- Space Weather and Solar-Terrestrial Physics: supported by STFC/NERC/UKSA and funding gaps are particularly acute in this area given the role that Space Weather may play in climate change.
- Planetary Science (STFC/NERC, STFC/UKSA), mission related activities (mission science planning, instrument development) are supported by UKSA, science exploitation by STFC.

This type of research has suffered from a lack of funding and the frustration of proposals being passed back-and-forth between research councils until deadlines pass and proposals are summarily rejected. SSAP recognises the difficulties in bridging these gaps, especially in a constrained funding environment, but in our view some formal mechanism is required. We note the mechanisms that appear to exist at the RCUK-level (e.g., the Cross-Council Funding Agreement, and RCUK multidisciplinary research themes) to resolve these issues at research council boundaries and to enable innovative, exciting, cross-disciplinary research. However, these mechanisms sometimes do not appear to filter down to the level of funding panels and so these arrangements do not work as effectively as one might expect.

Space Weather has recently been placed on the National Risk Register for Civil Emergencies, has reached the attention of the Cabinet Office, and recently a new forecasting centre has been set up at the UK Met Office. The UK is leading Europe in this endeavour. Unfortunately this research sits near the boundaries between NERC and STFC. This is because the activity which ultimately drives Space Weather is initiated at the Sun, and is, thus, within the remit of STFC (and UKSA for space missions), through a region of space that may be in the remit of both STFC and NERC in the near-Earth magnetic environment, whilst a large range of effects are often felt in the Earth atmosphere (e.g., radiation effects on aircraft passengers) or even at Earth's surface, which is funded by NERC. Particularly relating to the NERC-STFC interface, it is not always clear where the boundaries lie. In addition, since Space Weather has a particular concern with impacts on technology (both ground- and space-based assets) and society, there is substantial potential for research that involves EPSRC and ESRC. Input from the community suggests that unless one research council is willing to be pro-active and take the lead it is difficult, if not impossible, to activate inter-disciplinary and cross-research council funding. This suggests that arrangements for cross-research council research are not as robust as might be desirable, leading to a demonstrable loss in opportunities for the UK and the UK research community.

Recommendation 10: *SSAP recommends that STFC, NERC and EPSRC work more closely to enable and deliver research that cuts across the remits of the various research councils.*

Structure of the Roadmap

The Roadmap is broken down into six sections. The first is a simple listing of the science questions within the three themes. This is, in effect, a summary of the Roadmap. The next three sections take each of the themes in detail, describing the goals of each theme and the facilities and instrumentation required to achieve the goals. We also detail specific areas where the UK has particular strengths and expertise that support and drive the research themes. The fourth part of the Roadmap covers areas that the three themes have in common, such as the need for high performance computing resources, the importance of studentships and Fellowships, etc. The penultimate part of the Roadmap is a timeline, showing the programme of relevant space missions, and when resources are likely to be required for mission preparation and exploitation. The final section of the Roadmap is a prioritisation of the resources required to deliver our goals, and the rationale behind this ordering.

Roadmap for Solar System Research: The Key Questions

Theme 1: Solar Variability and its Impact on Us

S1. What are the causes, consequences and predictability of solar magnetic variability and the solar cycle?

- S1.1 What is the origin of solar magnetic fields? How do they create the variety of observed magnetic structures?
- S1.2 What causes solar magnetic variability and the solar cycles and how can we predict or forecast this?
- S1.3 How does the structure, evolution and predictability of solar magnetic fields relate to dynamic phenomena?

S2. What are the structures, dynamics and energetics of the Sun?

- S2.1 What is the nature of the coupling between the solar interior, surface and the atmosphere?
- S2.2 Why are there solar structures and dynamics on different length scales and time scales, and what process is responsible?
- S2.3 How, and with what consequences, is magnetic energy transported, stored and released?

S3. What are the underlying processes that drive Sun-planet connections?

- S3.1 How does the solar wind, including transients, evolve through the heliosphere, and how can we predict/forecast conditions at Earth?
- S3.2 How are geoeffective events produced and how can we forecast them?
- S3.3 How are the magnetosphere-ionosphere-thermosphere systems of the Earth and other planets influenced by their interaction with the solar wind?
- S3.4 What are the processes that cause enhancement/loss of radiation belts around planetary bodies?

Theme 2: Planets and Life

P1: How did the Solar System form and evolve?

- P1.1 What was the primordial composition and state of the solar nebula?
- P1.2 What are the processes and timescales of planet formation?
- P1.3 What are the internal, surface and atmospheric properties of Solar System bodies and what processes have affected their evolution?
- P1.4 How does solar radiation affect the formation and evolution of small bodies such as comets and asteroids?

P2: How widespread is life in the Universe?

- P2.1 Is (was) there life elsewhere, and what are its biomarkers? Is (was) there life on Mars, and how can we find it?
- P2.2 Where do prebiotic molecules form and how do they get to where they form life?
- P2.3 What are the requirements for and bounds of habitability in the Solar System and elsewhere?
- P2.4 Where did the Earth's water come from and what is the wider volatile inventory of the Solar System?

P3: What do other planets tell us about the Earth?

- P3.1 What is the impact record of the Solar System, including Earth?
- P3.2 What does the Moon tell us about the origin of the Earth-Moon system?
- P3.3 What can planetary magnetic fields, magnetospheres and atmospheres tell us about changes on Earth?
- P3.4 How can we explore and exploit planetary resources?

Theme 3: Universal Processes

U1. What are the fundamental processes at work in the Solar System?

- U1.1 How do waves behave in inhomogeneous plasmas?
- U1.2 Why and how do instabilities develop in inhomogeneous plasmas?
- U1.3 How are magnetic fields generated and how do they evolve?
- U1.4 What is the nature of turbulence in magnetised plasmas?
- U1.5 How does magnetic reconnection work?
- U1.6 What is the nature of cross-scale coupling in plasmas?
- U1.7 How are energetic particles accelerated?
- U1.8 How do we know what we are seeing?

U2. How do planetary systems work?

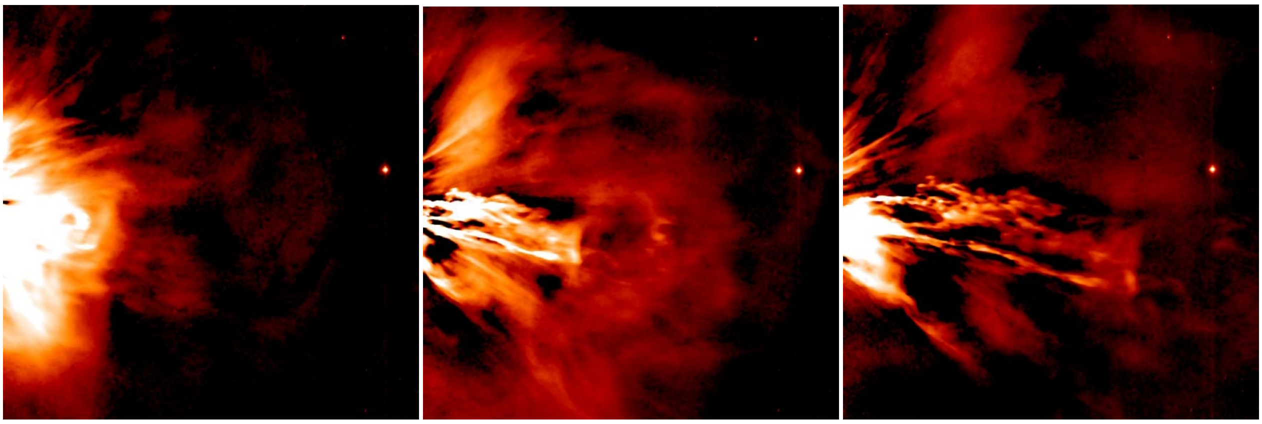
- U2.1 How do fundamental plasma processes vary throughout the Solar System?
- U2.2 What are the processes that have created, modified, and produce activity in the interiors, crusts and atmospheres of Solar System bodies?
- U2.3 How do we build an holistic picture of planetary magnetospheres?
- U2.4 How are Solar system planets archetypes for planets in other planetary systems?
- U2.5 How common are Earth-like planets in other planetary systems?
- U2.6 How stable are conditions in the Solar System?

Theme 4: Cross-cutting Activities (These are listed in alphabetical order, not in terms of priority):

Theme 1: Solar variability and its Impact on Us

Introduction

The Sun is a fascinating and important object for astrophysical and plasma research. It displays a vast number of surprising dynamic physical phenomena. As our closest star, the variability of the Sun can have profound consequences for the Earth and the modern technological systems on which society relies. The impact of the Sun and solar wind on our technology has become known as ‘space weather’, and the UK government has recognised the impact of space weather on the economy by listing it in the National Risk Register (http://www.cabinetoffice.gov.uk/resource-library/national-risk-register). Lloyds of London also recently commissioned a report into the potential risks of space weather and their associated costs (http://www.lloyds.com/news-and-insight/risk-insight). The Met Office have recently established a Space Weather Operations Centre that is leading space weather forecasting in Europe. Solar wind variability, resulting from solar variability, and its evolution throughout the heliosphere plays a significant role in driving dynamics in planetary magnetospheres which are important in understanding the evolution of planetary surfaces and atmospheres.



The evolution of a Coronal Mass Ejection pictured over 24 hours by the UK-led Heliospheric Imagers on the STEREO spacecraft. The bright ‘star’ on the right is Venus. Image credit: Jackie Davies and the HI team (Rutherford Appleton Laboratory)

Through long-term observation and modelling, we are moving towards a complete and detailed understanding of the solar interior and atmosphere and we now see that the Sun exhibits greater variability and complexity than ever imagined. The quality of current observations allows the study of three-dimensional, time-dependent and non-linear behaviour on all length and time scales. This poses enormous challenges for both analysis and theory, requiring the development of innovative methods of observation and modelling. The UK has a proud history of major solar and solar terrestrial discoveries and has the expertise to meet these future challenges. The study of the Sun, our star, is essential for understanding other stars. This includes all aspects of solar physics from the solar interior (e.g. generation and transport of energy and magnetic field, S1.1, S1.2, S1.3), the solar atmosphere (e.g. coronal heating, flares, S2.1, S2.2, S2.3), and the solar wind (S2.3). Methods developed for solar physics, such as magnetic field extrapolation and seismology, are now routinely applied to other stars. Many of the fundamental processes, which occur in astrophysical and laboratory plasmas, are observed remotely in high resolution on the Sun and *in situ* or remotely in planetary magnetospheres, providing a unique opportunity for understanding magnetic field generation and evolution, particle acceleration, instabilities, reconnection, heating, plasma waves and turbulence.

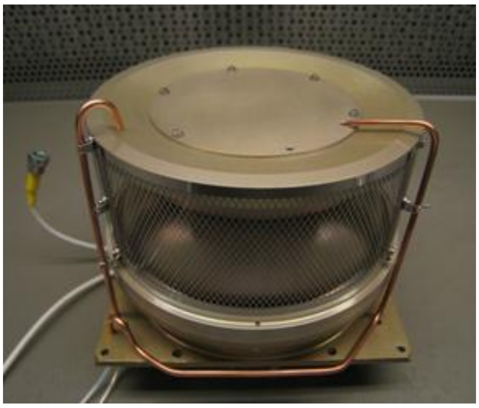
In order to address the risks associated with space weather, it is important to understand the processes that drive solar variability and improve our ability to predict the occurrence, speed and direction of coronal mass ejections (CMEs). These eruptions carry energetic plasma and associated magnetic fields from the solar atmosphere and into interplanetary space where they influence the environment around planetary bodies in a variety of ways. The launch of a CME can enhance the radiation environment for spacecraft and aircraft, while its arrival at Earth can trigger a geomagnetic storm, driving geomagnetically-induced currents into ground-based power grids, disrupting satellite timing and location signals and interfering with radio communications. The consequent heating of Earth’s upper atmosphere and the resulting atmospheric expansion enhances atmospheric drag on low-altitude spacecraft. Magnetic flux in the heliosphere affects the cosmic rays impacting earth’s atmosphere, which in turn affect, for example, cloud cover and albedo (S3).

The mechanisms by which the Sun, solar wind and CMEs influence the other planetary bodies in the Solar System varies, from the entirely solar wind-driven magnetosphere of Mercury to the largely internally-driven magnetosphere of Jupiter. The induced magnetospheres of Mars and Venus provide a degree of shielding of the atmosphere to loss processes *via* their interaction with the solar wind. The fact that Venus has a thicker atmosphere than Mars, yet is subjected to a larger degree of solar wind forcing reveals the complexities in understanding how the Sun and solar wind influences these systems (S3). Understanding the processes that drive the solar variations, the production of heliospheric transients and their impact on planetary environments requires detailed observations, both multi-wavelength and *in situ*, covering a wide range of spectral, spatial and temporal scales. To maintain such a comprehensive suite of observations, enabling a study of the complete Sun-Earth or Sun-planetary system in the required detail, the STFC must liaise closely with space agencies, research councils and industry to ensure that the science they fund meshes seamlessly with other national and international programmes to ensure that all required measurements are made from the solar interior and solar atmosphere through to the space environments of the planets and down to the terrestrial bedrock.

UK Expertise relevant for Theme 1

The UK has more than 40 research groups that are active in solar, solar-terrestrial and solar-planetary research (totalling more than 200 researchers) and holds a world-leading position within the international community in instrumentation, observational data analysis, magnetohydrodynamics (MHD) and kinetic theory, plasma physics and planetary plasma science. A sample of UK highlights and expertise for Theme 1 are listed below.

- UK research groups have a long heritage in solar wind and heliospheric physics through world leading contributions to, among others, the Ulysses and STEREO missions, and include expertise in exploiting both *in situ* and remote sensed solar wind data, and the associated theory and modelling.
- The UK has several hardware groups developing instrumentation for space- and ground-based projects, resulting in the UK taking PI roles on instruments that contribute to the success of several international space missions and ground-based facilities. Participation of UK physicists is actively sought in major new projects. For example, the UK now has major roles in four of the instruments for Solar Orbiter, due to be launched in 2018. In ground-based instrumentation, the success of the ROSA instrument has led to UK leadership in providing visible cameras for the U.S. Daniel K. Inouye Solar Telescope (DKIST).
- Our pioneering theoretical work in MHD and kinetic theory is valued worldwide, including advances in large-scale simulations through, for example, the DiRAC High Performance Computing facility.
- UK groups are internationally leading in the provision of atomic/molecular data for the interpretation of atomic/molecular spectra from spectrometers and CHIANTI is the preferred atomic physics package throughout the international solar community.



The Electron Analyser System for the Solar Wind Analyser on Solar Orbiter, currently being built at MSSL. Image credit: MSSL.

- The UK currently hosts state-of-the-art models of the coupled magnetosphere-ionosphere-thermosphere jovian and saturnian systems. These are currently being extended to understand physical processes including magnetic braking, auroral emissions, and the transport of energy and angular momentum.
- The UK has considerable expertise in simulations of wave-particle interactions and their application to radiation belt production/loss, important for the forecasting of space weather.
- Through the use of ground- and space-based observatories such as UKIRT and HST, the UK has built an international reputation for the remote study of giant planet magnetospheres and ionospheres through the analysis of auroral images and spectra and their theoretical interpretation.

Only through a strategic approach to mission and facility involvement, data analysis, theory and modelling, and adequate investments in both staffing and HPC hardware, will our leading and productive role be maintained.

S1. What are the causes, consequences and predictability of solar magnetic variability and the solar cycle?

The Sun's atmosphere and its behaviour are controlled by its magnetic field, which owes its existence to dynamo action in the solar interior and transport of the field from the interior to the atmosphere. The Sun varies on a wide range of time scales, from the sudden rapid release of energy and mass over a few seconds, to the propagation of MHD waves and oscillations throughout the solar atmosphere over minutes, and to solar cycles over a decade. Variations over hundreds of years can be detected through proxies in tree rings and polar ice sheets. The main goal of S1 is to identify and unravel all the physical processes responsible for such a wide range of solar variations with the possibility of predicting or forecasting the specific processes that generate space weather.

Firstly, understanding the origin of solar magnetic activity requires a detailed description of how dynamo action arises through the interaction of magnetic fields with rotation, convection, shear flows and stable stratification (S1.1, S1.2, S1.3). What causes the structure and development of the solar tachocline and creates differential rotation? Does the large-scale magnetic field arise through the interaction of turbulence with rotation or *via* magnetic instabilities? Why does the solar cycle vary? The recent extended solar cycle minimum was unexpected and at odds to all cycle predictions. What was special about the last cycle? The large-scale magnetic fields generated by the dynamo are transported to the solar surface by magnetic buoyancy, leading to sunspots whose structure is determined by the interactions between the magnetic fields and the surrounding convective motions. Key questions include (S1.2, S1.3, S2.1): How does buoyancy interact with downward transport *via* the magnetic pumping of convective downdrafts? How does the complex interlocking comb structure of sunspot penumbrae form? Why is this stable? What is the link between magnetoconvection and the small-scale features in sunspot umbrae (umbral dots)? This theoretical underpinning of the origin of magnetic activity is constrained by our knowledge of the solar interior through helioseismology. The current experiments have just been going for long enough now for the first gravity modes (oscillations that provide information of the density and temperature near to the centre of the Sun) to become detectable. Continued longstanding ground based helioseismology experiments (e.g., BiSON, GONG) together with the space-based instruments on SOHO, Hinode and SDO guarantees new results in our understanding of the Sun's interior.

Secondly, magnetic fields emerge on all spatial scales, ranging from active regions to small ephemeral regions (S1.2, S1.3, S2.1). What is the form of the field in the solar interior and what are the physical processes involved? Are the small-scale magnetic fields in the quiet Sun a result of magnetoconvective processing of fields rising from the main dynamo at the tachocline or do they owe their existence mainly to a local small-scale dynamo driven by near-surface convective motions? We need to improve our fundamental understanding of how the interior magnetic field couples to the solar atmosphere and how the emerged magnetic fields are subsequently processed in the photosphere. How are the many different coronal magnetic structures, such as active region loops, prominences and coronal holes, formed?

Thirdly, how does the structure, evolution and predictability of coronal magnetic fields relate to dynamic phenomena (S1.3)? The extreme diversity of dynamic solar phenomena means that they evolve on a wide range of timescales and lengthscales. For example: fast dynamical evolution occurs in flares, spicules, surges, coronal hole jets, CMEs (once the magnetic field is destabilized); more moderate evolution takes place during active region formation, active region outflows, coronal holes, polar plumes, magnetic carpet and small scale emergence; slow evolution of the global coronal field's structure and its open flux, quiescent and active-region prominences (until they erupt). This is a subset of observed solar phenomena from SOHO, STEREO, Hinode and SDO. How does the Sun create such different scales? Once we understand their magnetically-controlled formation, magnetic characteristics and drivers, we can then investigate their dynamical evolution in more detail.

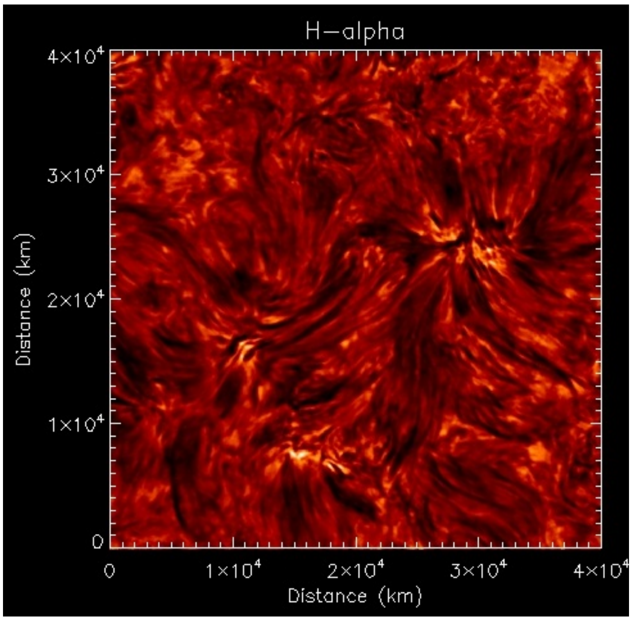


Image chromospheric spicules in Hydrogen alpha observed with ROSA showing the structure of the dynamic chromosphere down to the smallest spatial scales. Credit: Queens' University, Belfast.

Key missions and requirements for S1:

- BiSON, SoHO, Hinode, HMI/SDO (and in the future Solar Orbiter, Solar-C and HiRISE) provide global and local heliosiesmology measurements as well as vector magnetograph measurements to measure accurately the emerging flux.
- Hinode, SOHO, STEREO, SDO and IRIS missions are key to understanding of physical processes in emerging and developing magnetic fields across all spatial scales.
- The Solar Orbiter mission, with its unique orbit, will provide a view of the poles to allow helioseismic measurements of that unexplored region – this will probe the fundamental behaviour of the magnetic cycle in the Sun.
- ROSA's multi-wavelength capability will continue to provide high-cadence observations of waves and oscillations from the photosphere/chromosphere at high spatial and temporal resolutions. In addition, DKIST (and in the future Solar-C and EST) will resolve, with unprecedented sensitivity, individual magnetic flux concentrations, observing their emergence, structure and dynamics, measuring their field strengths and direction.

S2. What are the structures, dynamics and energetics of the Sun?

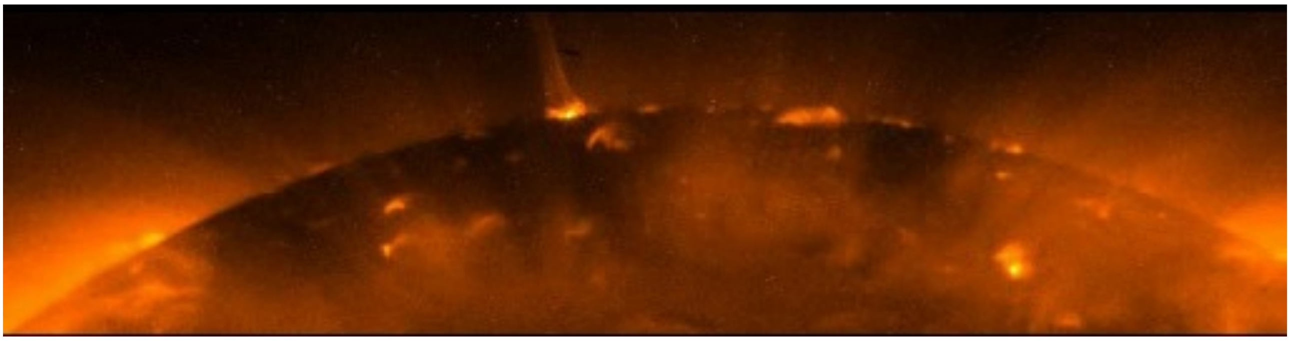
The magnetic fields, which thread the solar surface fill and structure the solar atmosphere. The interaction of plasma and magnetic field produces a wide range of dynamic phenomena. Traditionally, the solar interior and the different levels of the solar atmosphere have been treated as separate regions because of the limitations of previous observations. However, the wealth of new multi-wavelength observations, through both space and ground-based instruments, are giving us a simultaneous view throughout the various atmospheric layers. The time is now right to study how these layers are coupled together (S2.1). The new high-cadence, high-resolution observations from the Hinode and SDO satellites and from the ground-based DST/ROSA instrument have shown how dynamic the entire solar atmosphere is. Transient and explosive events, such as nanoflares to microflares, spicules, CMEs and flares, occur throughout the solar atmosphere, at all scales (S2.2). Flows are prevalent. and waves and oscillations are omnipresent. Key questions are: What is the nature of the coupling between the solar interior, surface and the atmosphere (S2.1)? How is mass, momentum and energy transported from the convection zone to the corona and solar wind (S2.3)? How does the lower atmosphere regulate this transport (S2.1, S2.3)?

The distribution of the surface magnetic flux is now known to follow a power law over many decades, with many small-scale magnetic elements of 10^{16}Mx, the present resolvable limit, and fewer large-scale sunspots of 10^{22}Mx. Coronal active region loops are conjectured to consist of many threads, with the elemental thread presently still unresolved. However, DKIST, with a spatial resolution of 25 km at the photosphere and 150 km in the corona, will provide a step-change in resolution. Key theoretical questions include: Why are there solar structures on different length scales and time scales, and what process is responsible (S2.2)? How do these solar magnetic fields evolve dynamically (S1.3, S2.2)? What is the magnetic nature and properties of the elemental thread and why? What determines such scale-invariant distributions, how far do they extend, and which processes are responsible (S2.2)? How are the different scales coupled in dynamic events (S2.2)? What are the characteristic magnetic topologies across the scales and how do they change (S2.2)?

An underlying process involved in all solar atmospheric phenomena is the transfer of magnetic energy not only from its source in the interior but also into thermal energy, kinetic energy and the acceleration of particles. Transfer from the interior is either directly by the emergence of magnetic fields or through the propagation of waves/oscillations along magnetic structures (S2.3). Important theoretical questions include: What role do small and large scale flows at the level of the photosphere play in the build up of energy and the re-organization of atmospheric magnetic fields into complex energy releasing structures (S2.3)? How is this energy transported and distributed in closed and open magnetic field regions (S2.3)? The release of magnetic energy can be fast and highly dynamic, as in flares, CMEs and other eruptions, but it can also be less dynamic, as in heating (either due to wave damping or nanoflares). Why and how does energy release occur both over small (few metres) and large (solar radii) length scales leading to solar flares and CMEs (S2.1, S2.3)? How do waves propagate in a highly stratified and structured magnetic environment (S2.3)? How is the plasma in in the upper corona accelerated to produce the solar wind (S2.3)? How do fields, flows and particles interact in the solar atmosphere (S2.2, S2.3)? How does the global magnetic field store energy over periods of months to years (S2.3)? Understanding these processes require direct incorporation of observational data into theoretical models to first reproduce and understand the physics behind these complex systems and then to predict them.

To transfer magnetic energy into other forms of energy (S2.3), the key questions relate to where, when and how much energy is transferred. What is the relative significance of the two main energy release mechanisms in coronal and chromospheric heating: reconnection and waves? What are the mechanisms that remove the magnetic flux/energy from the Sun? What triggers solar eruptions and can we predict them? How do solar magnetic fields dissipate energy at all length scales and time scales? What are the non-thermal processes that heat the solar atmosphere? What is the nature and implications of the coupling of MHD and kinetic scales for nanoflares/flares/eruptions?

Many signatures of solar activity are produced by energetic particles (S2.3). Energetic accelerated particles are ubiquitous in astrophysical plasmas, and all types of solar activity are associated with particle acceleration. Magnetic reconnection acts as an acceleration mechanism, but how this operates at a particle or kinetic level is still unknown. There is a massive disparity of scale, in that plasma simulations can be used to investigate acceleration processes on the scale of the reconnection region, but the flare site has a much larger scale, encompassing active region structures. Plasma modelling is required to understand fundamental questions of particle acceleration, such as the interplay between reconnection and turbulence, but more global modelling is required to understand fully the role of large-scale magnetic structure and interactions with lower parts of the corona. There are also problems of interpretation, since particle propagation and emission effects mediate the observational signatures, needing a multi-wavelength approach to disentangle their properties. CMEs are associated with solar energetic particle events measured by spacecraft at 1 AU, which fill a substantial portion of the heliosphere contributing to the radiation environment in the Solar System. Shocks are known to be efficient acceleration sites for energetic particles, and those formed ahead of CMEs are a natural explanation for solar energetic particle events. Testing theories of not only the shock acceleration processes, but also propagation and time evolution effects, requires modelling of the inner heliosphere. It is also necessary to know the initial state of the energetic particle populations, and this can depend on previous activity events and flare accelerated particles. Because of the efficiency of energetic particles emitting in radio, optical, ultraviolet and X-ray wavelengths, they serve as the unique signatures of the physical processes and, without them, our understanding of the solar atmosphere would be rather limited (S2.3).



X-ray jets seen at the north pole of the Sun by the X-ray telescope onboard Hinode, in response to newly emerging magnetic fields reconnecting with the background field. Credit: Hinode X-Ray Telescope.

It has traditionally been assumed that the solar coronal plasma is in local thermodynamic and ionisation equilibrium, but with the new highly dynamic observations, we need to take a different, more challenging approach to modelling the atomic processes and solar plasma. We foresee a worldwide interest in non-equilibrium processes in the next few years. Theoretical modelling of some dynamic solar features requires non-equilibrium ionization. Observations from future ground- and space-based instruments will enter a domain where we cannot ignore non-equilibrium and non-thermal effects. For example, IRIS, a next-generation spectrometer with much improved spatial (0.3") and temporal resolutions, is designed to study the dynamic interface between the chromosphere and the corona, including structures not in local thermodynamic equilibrium. The questions we need to address are: How do non-equilibrium processes affect the plasma modelling *and* diagnostics? How can we improve the kinetic and plasma models for regions where flows are prevalent, and where ion and electron distributions may not be in equilibrium? Can we adapt atomic packages, like CHIANTI, to take account of non-equilibrium processes?

It is through the synergy of improvements in observations, theory and simulation with High Performance Computing (HPC) that we will solve these major problems. Once the underlying physical processes are understood, we will be able to make predictions.

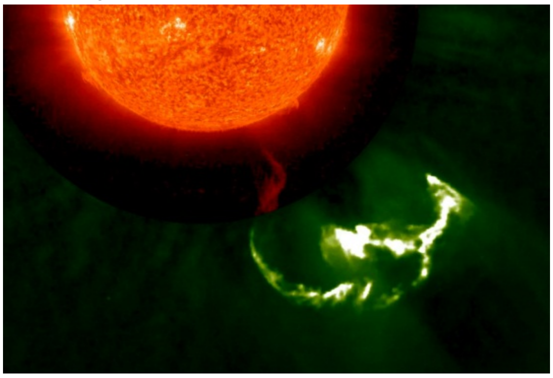
Key missions and requirements for S2:

- The Hinode and SDO missions provide high-resolution data on the flows and magnitude of the magnetic field that drives activity at all scales. The UK-led spectrometer EIS provides critical information on plasma parameters such as flows as the magnetic field varies. This is complemented by the long-established UK-led SOHO/CDS instrument that has provided EUV spectral imaging for 17 years and will continue with involvement in IRIS

- RHESSI continues to provide outstanding data on high-energy solar events, sites for particle acceleration, and in the future, Proba3 (Fresnel Lens) will image the hottest flare plasma, at sub-arcsecond spatial scales that approach fundamental structural coronal scales. SPARK is designed to target the whole range of particle acceleration, from suprathermal electrons to relativistic ions, through the combination of imaging and spectroscopy.
- STEREO provides a heliospheric imaging capability, led from the UK, which is unique in the study of CMEs from onset to Earth impact, feeding into studies of coronal structure and evolution as well as issues such as SEP production.
- ROSA observations of solar flares provide exceptional imaging of the fine structure of chromospheric filaments and allows us to relate those with post-flare eruptions and CMEs. ROSA can determine the importance of waves as fundamental carriers of energy through the solar atmosphere.
- LOFAR, together with other ground- and space-based instruments that observe the Sun in radio, optical, EUV, and X-ray wavelengths, will study dynamical aspects of solar activity, such as solar flares.
- Solar Orbiter will provide ‘encounter’ type science by providing high-resolution imaging and spectroscopy during the unique orbit – this will allow us to probe the solar atmosphere at close to fundamental scales.
- The Solar-C mission focuses on analysing energy flow spectroscopically all the way through the solar atmosphere. This is not achievable with current instrumentation and will make huge steps forward in understanding fundamental processes
- The energy released in solar flares is stored in stressed magnetic fields. DKIST, and later EST, will provide accurate magnetic field measurements in the photosphere, chromosphere and corona and determine the pre- and post-CME magnetic field configuration. The magnetic fields of prominences and eruptive filaments will also be measured to coronal heights.
- HiRISE with its outstanding spatial and temporal resolution, will provide highlights to the micro-physics underlying magnetic coupling between the solar photosphere and corona, with emphasis on the dynamics of the transition region.

S3. What are the underlying processes that drive Sun-planet connections?

The solar wind and its magnetic field can have a profound influence on the environments of planetary bodies in the heliosphere. It is thus critical that we understand both the origin at the Sun, and the evolution of the wind and magnetic field, in order to recognize the variations that we see *in situ* and their subsequent impact on the Earth and other Solar System bodies (S3.1). Such knowledge is essential to underpin further research into predicting the propagation of solar wind transients (CMEs, high speed streams and interaction regions) in a space weather context. Key questions include: What is the global structure of the solar corona and the near-Sun solar wind? How and where do the solar wind plasma and magnetic field originate in the corona? What are the different origins of fast and slow solar wind? How do solar transients drive heliospheric variability? What are the drivers and effects of solar wind turbulence, and how and where are shocks formed? To answer these questions, it is essential to make *in situ* measurements of the solar wind plasma, fields, waves, and energetic particles close enough to the Sun that they are still relatively pristine and have not had their properties modified by subsequent transport and propagation processes. A key element in understanding these phenomena is the combination of observational data and theoretical models to reproduce the characteristics of these complex systems and then to predict them. For example, MHD models of the solar wind can be used to model the structure and evolution of high speed streams and stream interaction regions through the inner heliosphere, and the propagation of CMEs through this complex environment, interacting with the solar wind stream structure and even other CMEs. However, the current models assume that the solar wind is in thermal equilibrium. Does the fact that the solar wind is a non-equilibrium plasma affect the propagation of CMEs and solar wind streams?



FA combination of two images from the STEREO EUV imager and solar coronagraph, showing a prominence breaking away from the solar surface in October 2012. Credit: NASA-GSFC.

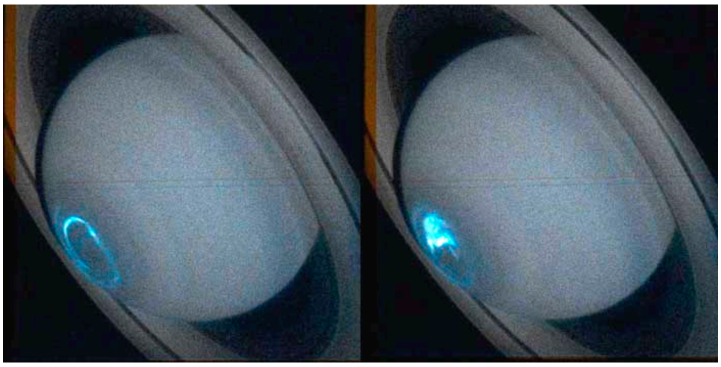
With the advent of space borne heliospheric imagers, such as those on STEREO, our ability to track solar wind transients has been greatly improved. The techniques developed for tracking solar wind transients in these wide-field cameras have enabled preliminary predictions to be made of the arrival of the observed transient at a given location, be it a spacecraft, the Earth or another planet. It is clear from these predictions that while some events could theoretically be tracked with a precision and latency sufficient to provide a useful warning at Earth, the vast majority are not. In particular, it is more challenging to track those events that interact with each other or propagate at speeds that differ significantly from that of the ambient solar wind. Accurate forecasting of solar wind conditions and the arrival of potentially geoeffective transients at Earth therefore requires not only a basic ability to detect and track these features but also detailed understanding of the universal processes that govern their interaction (Theme 3). For it to be useful to operators of ground- or space-based systems, a space weather forecast requires: an understanding of the background solar wind conditions into which any transient may be launched; an estimate of when a transient will erupt; initial estimates of the speed, direction of propagation and density of the transient; estimates of the expansion rate and longitudinal extent; understanding of how a transient will interact with the solar wind; whether a shock front will develop that will lead to enhanced particle acceleration ahead of the transient.

While advances have been made in tracking the speed and density of solar wind transients and estimating their time of arrival at Earth, their effect on the Earth’s space environment cannot be anticipated sufficiently far in advance to provide useful warnings. The main reason for this is that the strength of their coupling with the Earth’s (or another planet’s) magnetic field, their geoeffectiveness, is strongly dependent on the highly variable direction of the magnetic field in the transient. If this is opposite to the Earth’s field, this maximises the efficiency with which the two fields can merge through magnetic reconnection, allowing energy and plasma to be stored in a planetary magnetosphere. Additionally, a steady solar wind with the appropriate orientation can also produce geoeffective events in ways that are not fully understood. The concept of geoeffectiveness as extended to the magnetospheres of other planets is also of importance in generalising this concept to understanding the role of physical parameters (such as the strength of a planetary magnetic field and properties of the incident solar wind plasma) in controlling geoeffectiveness (S3.2). Despite its importance, the only way currently to predict this quantity at Earth is *via in situ* measurements from the ACE and DSCOVR spacecraft, orbiting the L1 point approximately 0.01 AU upstream of the Earth. Such measurements provide advanced warning of the geoeffective nature of an event only about 40 minutes prior to its arrival at Earth.

Key missions and requirements for S3.1 and S3.2:

- Widely spaced *in situ* solar wind observations from the two STEREO spacecraft, in combination with ACE at L1 and other interplanetary spacecraft such as Venus Express and Messenger are currently contributing to our understanding of the large-scale structure of the solar wind. Combinations of data from ACE, Wind, DSCOVR, Cluster and Themis/Artemis are suited to smaller-scale multi-point studies of the solar wind.
- Solar Orbiter builds on our UK strengths and will revolutionise our knowledge of the solar origin and inner heliospheric evolution of the solar wind by combining *in situ* observations closer to the Sun than ever before, both in and above the ecliptic plane, with high resolution multi-wavelength imaging and spectroscopic observations. The extensive investments that the UK has made in this mission must be fully exploited.
- Operational space weather missions have been studied to determine the optimum configuration for routine space weather forecasting. One possible configuration involves placing a heliospheric imager at L5 would allow exploration of whether such instrumentation could be used in routine space weather forecasting. This concept was the subject of a recent UK Space Agency-funded feasibility study (HAGRID). The Carrington concept led by Airbus DS (UK) places both in situ and remote sensing instrumentation at L5 to increase the lead-time on forecasting solar activity, improve the accuracy of predicting Earth-directed CME arrival times, and provide a 3 to 4 day forecast of solar wind conditions before they rotate to the Earth.
- Further development in modelling and simulation of solar wind evolution is also essential, including non-equilibrium plasma effects. Good near-real time models of the inner heliosphere based on near-real time solar and heliospheric observations are needed and we need to improve our scientific understanding to make these accurate enough to be useful.
- Developing techniques to measure the direction of the magnetic field and particle properties embedded in a transient well ahead of its arrival at Earth (S3.2) would be a major advance and would be of great strategic value to future space weather forecasting capabilities. This could be achieved in the following ways:
    - Deployment of a fleet of spacecraft in highly elliptical Earth orbits which, between them, always have a spacecraft significantly upstream of the Earth in the solar wind (Space Weather Diamond).
    - A single spacecraft orbiting much closer to the Sun than the L1 point using a solar sail to balance the forces necessary to keep it upstream of the Earth.
    - Use a ground-based radio telescope such as LOFAR to measure the Faraday rotation of the signal from astronomical radio sources as it passes through the solar wind.

The interaction of the solar wind, and any embedded transients, with a planet is mediated by the coupled magnetosphere-ionosphere-thermosphere system, which facilitates the transport of energy and angular momentum between a planet and its surrounding environment (S3.3). Under different levels of forcing from the solar wind, different parts of this system become important in mediating and transferring the stress and energy imparted onto the Earth. These interactions are highly non-linear and are of fundamental importance in understanding space weather events. The complexity and non-linearity of this system is enhanced at the giant planets by the strong role played by internal plasma sources, such as Io at Jupiter and Enceladus at Saturn, and the enforcement of (partial) co-rotation of the magnetospheric plasma thus extracting energy and angular momentum from the parent planet. The magnetospheric configurations of Uranus and Neptune differ significantly from those of the gas giants because of the large offsets between the spin and magnetic axes at both planets and Uranus' large obliquity. Although these effects must lead to unique configurations for solar wind-magnetosphere-ionosphere-thermosphere interactions and interior plasma transport, almost nothing is known about the seasonally-dependent consequences. Clearly, the solar wind-magnetosphere-ionosphere-thermosphere system varies considerable across the Solar System thus providing a laboratory to study the relative importance of each component.



HST images of a strengthening aurora on Saturn, resulting from solar wind pressure (F. Crary et al., Nature (2005) 433, 695-696).

The influence of energetic particles on Earth's atmosphere is a good example of the consequences of the Sun-planet connection. Energetic particles accelerated near the Sun and in the Earth's magnetosphere during geoeffective events precipitate into the atmosphere. The most energetic particles penetrate further into the atmosphere before transferring their energy and heating the atmosphere. The depth at which this energy is deposited has a bearing on the extent to which the atmosphere expands with deeper penetration causing weaker expansion (since there is more atmosphere above to lift). Somewhat unexpectedly therefore, weaker geoeffective events may have a greater impact on atmospheric expansion, with important applications to secondary effects such as satellite drag. A related important question in the study of giant planet magnetospheres is why their thermospheres are much hotter than can be explained by current models of solar and auroral heating. These issues highlight missing physics in our description of planetary thermospheres or the presence of unknown energy sources.

One of the great challenges in understanding the dynamics of planetary magnetospheres and their interaction with the Sun is dealing with the vast range of scale sizes involved. The auroral substorm cycle is a good example of the challenges presented by understanding a process that occurs across a range of scale sizes when the energy stored within the magnetosphere is transferred into the Earth's atmosphere, focussing a volume many times that of the Earth, into an area around the size of a continent and mediated by electric current systems that may be present on the scale of 10s of km. Understanding the process by which solar wind energy is transferred into the Earth system requires techniques that cover both large-scale observations made by spacecraft and ground-based facilities together with measurements of the detailed interactions between particles and magnetic fields at much smaller scales. A detailed understanding of the transport of energy from the solar wind into the Earth magnetosphere and then into the Earth's atmosphere will provide vital input to scientific subjects beyond the scope of STFC science. The modulation of ionospheric layers, thermospheric composition and circulation, the global electric circuit and long-term change in the Earth's atmosphere are all subjects being studied by NERC-funded scientists using facilities such as EISCAT and SuperDARN. It is important to ensure that science at the boundaries of research council remits is enabled through consultation between research council strategies Study of the magnetosphere-ionosphere-thermosphere system also has applications beyond our Solar System. The associated current systems play a key role in the generation of auroral radio emissions that may be used as a remote diagnostic of magnetised exoplanets, as already demonstrated in the detection of auroral emission in brown dwarfs. This is a growing theoretical area in which the UK has a lead and the growing capability of ground-based radio observatories, as well as space-based observatories, will lead to important discoveries in this area. Key scientific questions include: How do magnetospheric structure and dynamics arise from the interaction with the solar wind and interplanetary magnetic field? What is the role of magnetospheric substorms in solar wind-magnetosphere-ionosphere coupling and how are they triggered? What differentiates geomagnetic storms from other geomagnetic activity and what causes them? How are giant planet thermospheres heated? Can the expansion of the atmosphere due to magnetospheric activity be accurately predicted? How does magnetospheric activity couple to the ionosphere and atmosphere, and how do these regions influence magnetospheric behaviour?

Dramatic image of the aurora borealis taken in Kvaløya near Trømso, Norway. Image credit: Bjorn Jørgensen (http://www.suntrek.org/blog/the-northern-lights-aurorae-borealis

Quasi-permanent radiation belts have been found at almost all the magnetised bodies in the Solar System and are known to be dynamic, responding to forcing from the solar wind and possibly internal processes at the giant planets whose magnetospheres have a high degree of internal control (S3.4). At Earth these radiation belts, and particularly their variability in spatial distribution and intensity, are important factors to understand since they pose risks to satellites and astronauts and are a key component of Space Weather. At other locations in the Solar System they also pose risks to spacecraft, for example they are critical mission drivers for JUICE. In general it is important to understand how these radiation belts are generated, maintained and lost. The acceleration of a "seed" population of particles up >MeV energies, by interactions between waves and particles, is an active area of research in which the UK plays an important role. However, the origin of these seed particles is an open question particularly in giant planet magnetospheres (see also U1.7). Precipitation of radiation belt particles into the atmosphere of a planet is a general process by which radiation belts can decay, thus affecting the atmosphere, possibly over long time scales. It is critical to continue the theoretical and observational investigation of radiation belt variability and particle acceleration in order to fully develop our system-level understanding of Space Weather and to gain a general understanding of charged particle acceleration in the universe. The variability of radiation belts is also important for understanding habitability, particularly of moons embedded in such radiation environments. Key questions include: Are wave-particle interactions critical in generating radiation belts? What are the energy and plasma sources and sinks for planetary radiation belts, do these vary between different planetary magnetospheres? What are the seed populations for generating radiation belts and how are they produced? How do the terrestrial radiation belts respond to quiescent solar wind driving and solar wind transients/CMEs? Do the radiation belts of the giant planets respond to solar wind driving? Modelling and exploitation of future, current and heritage data sets on radiation belts at Earth and the outer planets is crucial in answering these questions. Exploitation of public data from NASA missions (e.g., Van Allen Probes, Juno) with a radiation belt measurements in concert with data from UK-led instruments will also be important in addressing these questions.

Key missions and requirements for S3.3 and S3.4:

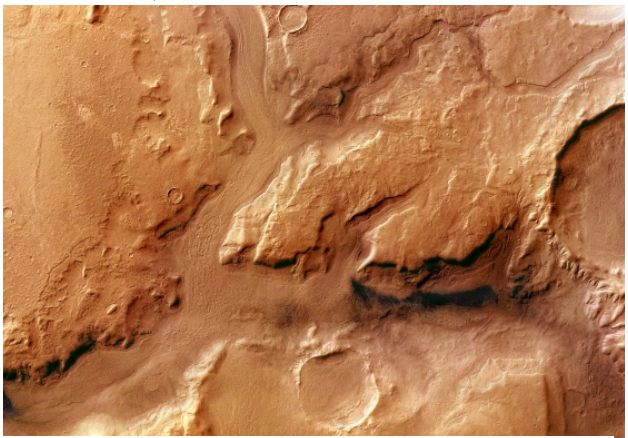
- The development of Space Weather forecasting relies on understanding processes and structures over vastly different scales in the magnetosphere, from small-scale current systems to the global magnetosphere. The proposed SMILE mission will pave the way for global magnetospheric imaging and the studied CENTINEL mission is part of the roadmap for developing a fleet of magnetospheric monitors. Smaller-scale current systems and structures will be probed by the SWARM and NASA MMS missions, and continue to be studied by Cluster. The proposed Alfvén+ mission will continue this work. At the boundary between the remits of NERC and STFC lie projects investigating the transfer of solar wind energy to the Earth's atmosphere then to the Earth's surface. To enable such projects to continue, support is required for exploitation of data from EISCAT and SuperDARN, and the development of new facilities, such as EISCAT_3D.
- Continuous auroral monitoring (e.g., *via* RAVENS) is also important in understanding the global magnetosphere since these emissions map out to very large volumes in the magnetosphere.
- Funding for the exploitation of data from giant planet missions (such as Cassini, and eventually Juno and JUICE), and remote telescopic studies, is essential in understanding the magnetosphere-ionosphere-thermosphere systems at giant planets and how internal magnetospheric processes change this coupling. The eventual exploration of the ice giants *via* an

orbiter (e.g., Uranus Pathfinder) is essential to complete this picture. Funding for remote sensing studies and to pursue modelling and data analysis is required to support such future mission development.
- Funding to exploit data from Messenger will enable the UK to meet important goals in magnetosphere-ionosphere-thermosphere coupling and to prepare for BepiColumbo. Funding for data exploitation from JUICE will also enable the study of small magnetospheres *via* the JUICE orbital phase of Ganymede.
- A critical issue in understanding solar wind influences on giant planets is the lack of an upstream solar wind monitor. Current work uses modelled propagations of solar wind conditions at 1 AU. The eventual development of an upstream monitor for an outer planet mission will be an important step in understanding the magnetospheres of the giant planets.
- The UK has expertise in modelling the acceleration of charged particles in the radiation belts of Earth and Jupiter. Continued funding of this research will maintain the UK's position as a lead in this important area.
- NASA's Van Allen Probes is a dedicated radiation belt mission, and the UK has a unique position in our ability to combine Cluster and Van Allen probe data to understand the production and loss of the terrestrial radiation belts. Funding for Cluster and for exploitation of publicly available Van Allen data will enable us to exploit this position.
- Exploitation of data from Juno, Cassini, JUICE and a future ice giant orbiter will enable the complete exploration of planetary radiation belts to give us a better understanding of the production, energisation and loss of radiation belts.

Theme 2: Planets and Life

Introduction

The origin of the Solar System and the possibility of life beyond the Earth are questions that have occupied the minds of scientists for many years; they are also questions that are of great interest to a more general public, and inspire future astronomers and planetary scientists. Significant progress is being made into understanding our distant past and our place in the Universe. The UK planetary science community is engaged in a variety of fundamental planetary science investigations targeted at understanding the Solar System; knowledge gained from these studies has direct application to the understanding of the formation of exoplanetary systems. How the Solar System formed and evolved reaches into the heart of planetary science. In understanding the materials that have formed and modified the planets, knowledge of the transfer and inventory of volatiles within the Solar System are important factors. Understanding the interior, atmospheric, surface and magnetospheric structures of planetary bodies within the Solar System is crucial to providing constraints on the volatile budget. We also have an increasing knowledge of geology and geomorphology of many of the terrestrial planets and satellites in the Solar System and what processes affect them. However, even our understanding of surfaces and surface-atmosphere interactions of the best-studied bodies, Mars and Venus, is still far from complete. For example, the sedimentary rock record of Mars is only now beginning to be investigated through high-resolution orbital investigations and rover observations, and new high resolution images and spectral datasets of airless bodies like Mercury and the Moon, are revealing the geologically complex nature of small rocky worlds.



The Reull Vallis outflow channel on Mars. Credit: ESA

The UK community is considerably active in the search for evidence for past or present life beyond Earth, especially the search for life on Mars. Notwithstanding the significant emphasis that has, appropriately, been placed on study of the red planet, our understanding of the habitability of planetary environments is now moving beyond consideration of Mars and the "Goldilocks" zone of habitability. For example, investigation of the warm environments inside the icy moons of the giant planets is extending our understanding of the bounds of habitability. Research continues into determining the biomarkers that are the signs of life, and how these signs degrade because of environmental effects. Establishing the geological framework of Solar System bodies underpins future understanding of the evolution, habitability and current environment of terrestrial planets and satellites. Questions such as "How widespread is life in the Universe?" cannot be addressed without knowledge of the geological and environmental contexts of a planetary body, set within a chronological framework. Once such an understanding is gained, the knowledge can be applied to future exploration prospects, from orbital global-scale studies to *in situ* micro-scale investigations. Over the past decade, discoveries of exoplanet populations have revealed a wide variety of planetary systems, many very different from the Solar System: no longer are 'hot Jupiters' the norm as exoplanets – an increasing number of terrestrial-type and 'super-Earth' planets are now also known. A complete investigation of the Solar System is essential to provide a basis for comparison to enable understanding of exoplanetary system formation. For giant exoplanets, it is already possible to start to determine their atmospheric composition and structure, and the presence of moons. But much more will be required to understand how they work in both familiar and extreme environments. Fascinating new water worlds are being discovered that may be scaled-up versions of icy moons such as Europa and Enceladus. An interesting and important corollary of such research is that study of different classes of terrestrial planets will also inform us about the evolution of our own planet.

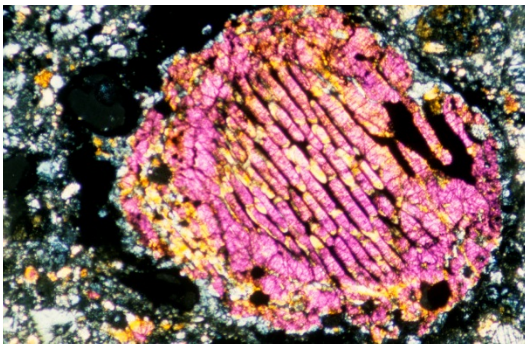
Studies of other planets yield information about some of the major events faced by our civilisation on Earth, such as magnetic field reversals, asteroid and comet impacts, resource depletion, and climate change. Information about planetary dipoles and magnetospheres can shed light on the changing dipole of the Earth (magnetic reversals) and its resulting changing magnetosphere. The atmospheres of other planets (e.g. Venus, Mars) give us insight into climate change that has occurred (and is still occurring) on Earth. Studies of Near-Earth Objects and missions to asteroids and comets will yield data about the nature and dynamics of Earth-crossing bodies, which may be of major importance in understanding the potential for major impacts on Earth. Furthermore, as we exhaust the resources of our own planet, we may ultimately need to explore, inventory, understand the origin and exploit the resources of other planets.

UK Expertise relevant for Theme 2

The UK has around 30 research groups active in planetary science research, totalling approximately 200 researchers. It is recognised as a leading exponent of the laboratory-based analysis of extraterrestrial materials, as well as remote sensing of planetary atmospheres and surfaces, small body dynamics and exoplanet detection. The field of astrobiology is an important sub-discipline within planetary sciences; the UK was amongst the first to recognise the subject as a cognate area, and is still a major international driver of the subject.

- The UK has some of the best equipped laboratories in the world for the analysis of extra-terrestrial material, and UK expertise in this field is world-renowned. The UK CAN (UK Cosmochemistry Analysis Network) is an example of how access to facilities is well-established between different laboratories nationwide; it is also a leading partner in a complementary EU-funded scheme under the Europlanet umbrella.
- The UK also provides major contributions to mineral physics at high pressures and temperatures, such as those experienced by metal and silicate segregating during the formation of the cores of terrestrial planets. Through the use of facilities such as Diamond and ISIS, the UK has international leadership in the laboratory study of planetary ices and volatiles which are of key importance in understanding the interiors of planetary bodies.
- The UK is a world leader in laboratory astrochemistry, directing the EU ITN LASSIE (Laboratory Astrochemistry and Surface Science in Interstellar Environments). UK astrochemists are world-renowned for their contributions especially in ice chemistry and physics, particularly in fundamental surface science experiments and the associated theory relevant to planetary, cometary and protoplanetary environments.
- The UK has a strong legacy of planetary remote sensing and observation, with UK scientists participating in research and modelling of data from Venus, Mars, comets, the Moon and Mercury. UK teams have developed instruments for several missions (including Mars Express, Mars Climate Sounder (on MRO), Venus Express and Cassini) for characterization of the composition and dynamics of planetary atmospheres. They have also played major roles in developing software for climate statistics and numerical models for the climates of Mars, Venus and Titan.
- The UK is a world leader in the study of planetary magnetospheres and their interactions with moons, rings and the parent planets through participation in Mars and Venus Express, Cassini, Juno, JUICE, and related studies at Earth.
- Astrobiological research is a major forte of UK scientific activity. In terms of attempting to detect life, UK teams have built miniaturised mass spectrometers, X-Ray and IR spectrometers and environmental sensors. UK groups have also led projects on characterising the nature of life in extreme environments on Earth, and characterised microorganisms in samples exposed to space conditions in orbit. A specialist astrobiology laboratory has recently been established in the Boulby potash mine, 1 km underground, where it will host experiments on extremophiles.
- The UK currently leads the world in ground-based transit surveys for exoplanets (e.g., WASP, SuperWASP, WFCAM Transit Survey, NGTS) and has pioneered the low-cost discovery of exoplanets. The UK is heading the ARIEL and Twinkle missions, which will characterise these systems as planetary bodies. In microlensing surveys, UK researchers have produced software tools that allow efficient targeting and scheduling of potentially important objects. Several groups are undertaking internationally-recognised observational and theoretical studies of exoplanet atmospheres. The UK has also developed leading positions in asteroseismology and its application to planet host stars.
- Observation of planets in the process of formation using sub-mm wavelength instrumentation is a recognised strength of UK scientists, as is the complementary discipline of numerical modelling of planet formation.
- The UK is taking a significant part in the development of Europlanet, the European planetary science network, led from within the UK. Europlanet, and particularly its annual European Planetary Science Congress, provides a focus for European co-operation and dissemination of its science to the wider community, policy-makers and the general public.

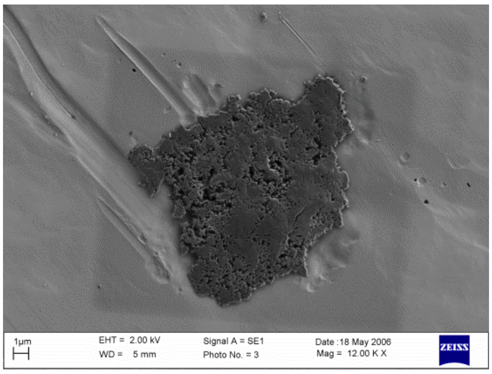
P1: How did the Solar System form and evolve?



Thin section of a chondrule from a primitive meteorite, viewed through crossed polars. The chondrule has a thick rim, showing that it accumulated smaller dust grains whilst still warm. Field of view = 1 mm.

Our knowledge of the origin of all planetary systems requires systematic and detailed study of the Solar System, which contains the only presently-known abode of life, and investigations of exoplanetary systems whose architecture is very different from that of our own. We need to understand in what ways Solar System planets are archetypes for bodies in other planetary systems. To this end, we undertake studies of early Solar System material, in the form of asteroids, comets, primitive meteorites, and interplanetary dust-particles. Within meteorites, we can isolate pre-solar grains (derived from stellar sources that existed prior to the birth of the Solar System), refractory grains (the earliest solid particles formed in the Solar System), chondrules (produced during high temperature flash heating events when the Sun was very young), and fragments of planetesimals that were formed and destroyed in the early history of the Solar System (P1.1 and P1.2). Laboratory analysis of these components allows us to derive very precise timescales for the evolution of the solar nebula and the subsequent evolution of pre-planetary bodies. Material remaining from the formation of the Solar System (comets, asteroids, Trans-Neptunian Objects) is also affected by changes in the evolution of the Sun, and may have had a major role in distributing material throughout the Solar System. Outstanding problems in understanding the early history of the Solar System include: (1) What was the primordial state of the solar nebula? (2) How did the evolving Sun affect the evolving planets? (3) How did dust and ice stick together in order to grow into planetary bodies? (4) What were the timescales for accretion of the planets? These questions can be addressed *via* studies of meteorites derived from differentiated asteroids, lunar and martian samples (including future sample-return missions), as well as observation of ancient planetary surfaces such as those of Mercury, Callisto and the Moon.

Following accretion of dust into small planetesimals and then planets, planetary interiors, atmospheres and magnetospheres developed (U2) eventually resulting in the structures observed today. Determining the structure and composition of the main bodies in the Solar System (P1.3) is a key diagnostic for understanding the primordial structure and composition of the solar nebula, identifying where these planets formed, and the processes of planet formation. The subsequent evolution of the planets after their formation is dependent on the size, location and composition and so it is critical to characterise the planets (P1.3) and understand the impact history of the Solar System in order to understand the processes by which they have evolved (P1.4). Observations of exoplanetary systems show us that the orbital architecture of the Solar System is not common and it thought that the planets have undergone orbital migration through tidal interactions between planetesimals, planets and the protoplanetary disc. However, the question of how the planets and other bodies arrived at where we find them today (P1.5) has not been comprehensively answered. Many of the exoplanet systems that have been discovered are very different from the Solar System. In particular, the size, the eccentricity and the relative inclinations of the planetary orbits show that their evolution must have been shaped by forces and events that our system did not experience, or did not experience to the same extent. Modelling the evolution of planetary systems to discover which of the processes were dominant in producing the observed planetary configurations will also help us to understand how the Solar System itself evolved.



Electron microscope image of a particle from Comet Wild II embedded in aerogel then flattened onto gold foil

The evolution of a planetary surface is recorded in the surface observed today, from internal dynamics to surface and atmospheric processes. The diversity of planetary evolution within our Solar System is best demonstrated by the results of geological remote sensing, *in situ* robotic studies and in the future by human assisted exploration. A greater understanding of the evolution of Mars has been made possible by access to very high resolution images and topographic data coming from orbiters including Mars Express and Mars Reconnaissance Orbiter. These same methods can be used to understand the geological and geomorphological evolution of other solid bodies in the Solar System, e.g., MESSENGER at Mercury (crucial in preparation for the forthcoming BepiColombo mission), Lunar Reconnaissance Orbiter (LRO) at the Moon, Rosetta at comet 67P/Churyumov–Gerasimenko. Study of the interior structure of Mars will be the prime goal of the future Insight mission. *In situ* studies of planetary are also important in our understanding of their evolution, although so far, only the Moon and Mars(and, briefly, Titan, with the Huygens lander and comet 67P by the Rosetta lander) have benefitted from the deployment of instrumentation capable of providing appropriate information. Although we are able to study planetary and asteroidal bodies by remote methods, and also through analysis of meteorites, measurement of material returned from specific locations on Mars or the moons of Mars (e.g., ESA Phobos sample return), as well as from a specific asteroid (e.g., Marco-Polo-2D), and new unsampled sites on the Moon (e.g., ESA-Luna 28, Chang'e 5), remains key goals of planetary science research that are essential for understanding fundamental questions about Solar System evolution and planetary habitability (P1.3, 1.4).

Hypervelocity impacts are ubiquitous throughout the Solar System: craters are seen on every solid surface and occur at all size scales. They are thus a major evolutionary driver of surfaces throughout the Solar System and understanding the physical processes that occur in the high pressure and high temperature regime that occurs during an impact are necessary to understand the compositional makeup of planetary surfaces. Laboratory work using light gas guns has shown that such impacts can change mineralogy and both create and destroy organic molecules. Such work has helped to underpin the analysis of cometary and interstellar dust samples brought back by the Stardust mission. Because of the nature of the collection device, the material was shocked upon capture - and disentangling the effects of shock from the original material has been a major result from these analyses. Further, MSL is currently exploring the geology in Gale impact crater - and it is very likely that many of the samples will have a shock history. However, there are limitations to the physical size of a gun, so hypervelocity impacts on planetary scales have to be simulated using hydrocodes. By coupling the results from the experimental work (including measurements of equations-of-state and material strengths) into modelling we are gaining insight into planetary scale impact events: the formation of moons, the disruption of small bodies, differentiation of impacted bodies etc. This modelling work is being extended to look at how a material changes through shock (phase transitions, shock synthesis, etc.) which is the next step in interpreted data from future sample return and *in situ* space missions (such as ExoMars, JUICE, and small body missions like Rosetta). Our knowledge of the physical and compositional properties of cometary nuclei and related populations, including Kuiper Belt Objects, is limited.

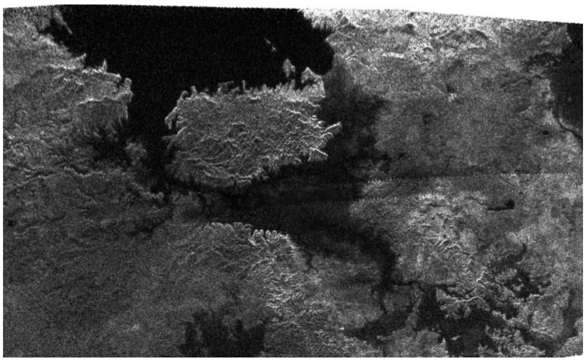
Solar radiation is as fundamental as gravity in driving the physical and dynamical evolution of small asteroid bodies (P1.6). Yet many areas in the theoretical and observational study of these phenomena, and the full extent of their wider implications, have yet to be explored. Some examples include: (1) How are the physical and compositional properties of asteroids influencing the strength of these radiation-induced forces, and over what timescales are they effective? (2) How important an effect is the interaction between solar radiation and small bodies in the delivery of small bodies to Earth, and thus to the evolution of life on our planet (see below)? (3) How dynamic is the shape and internal structure of small asteroids as a result of radiation-induced forces acting on them, and is this the main mechanism in the formation of binary or multiple-asteroid systems? These are questions that detailed theoretical studies, observational programmes and spacecraft missions will endeavour to answer.

Key missions and requirements for P1:

- State-of-the-art laboratories are essential for the successful analysis of extraterrestrial material, which contains components dating from the earliest stages of planetary formation. Material will come from future asteroid body sample return missions Marco-Polo-2D, OSIRIS_Rex, Hayabusa 2, ESA Phobos sample return, as well as meteorites, micrometeorites, interplanetary dust particles and previous sample return missions (P1.1).
- Observational studies of protoplanetary disks using ground-based (e.g., SCUBA2 on JCMT) and space-based facilities (e.g., HST, JWST) are required to complement numerical modelling and experimentation. HPC is required for the numerical modelling (P1.1).
- To understand the composition of primitive objects and the physical processes involved with the modification of these bodies as they are transferred across the Solar System, the Rosetta mission is vital. Just as Rosetta builds on Giotto and Stardust, Rosetta will, in turn, feed into missions such as the New Horizons mission to Pluto, plus a proposed mission to a main belt comet (Castalia) and proposed sampling of comet delivered ice-rich deposits at the lunar poles (Luna 27 and Luna 28) (P1.1).
- The only method by which the absolute age of planetary materials can be determined is by direct measurement in the laboratory, requiring state-of-the-art instrumentation. For relative chronologies, high resolution mapping of planetary surfaces is necessary, to obtain representative counts and dimensions of craters. This requires the current missions Cassini, Mars Express, MRO, and Rosetta, as well as future missions, including ExoMars Trace Gas Orbiter, BepiColombo, EnVision, Juno, JUICE, Uranus Pathfinder, New Horizons to Pluto and Castalia (P1.2).
- The currently-operational Mars Express continues to return excellent data on the surface morphology of Mars, as does the NASA-funded MRO mission. Compositional data from the surface is coming from MSL. Data from these are feeding forward to what is the highest priority in the Mars strand of the Roadmap: the coupled ExoMars Trace Gas Orbiter and ExoMars lander missions (both funded missions) and future MREP programme (post-ExoMars). Gas Orbiter will examine, in greater detail than ever before achieved, the structure and composition of Mars atmosphere, whilst the ExoMars lander will drill below Mars' surface to investigate, again for the first time, subsurface deposits protected from solar irradiation. Both of these missions are scientifically valuable in themselves, but also acts as significant milestones towards a Mars Sample Return Mission (P1.3, P1.4). Planetary escape from Mars is currently being studied by NASA's MAVEN mission.
- To determine the surface morphologies of planetary bodies, good imagery is required at high spatial resolution. High-quality data from both the inner and the outer planets are returned by several recent missions: Cassini, MESSENGER and Rosetta. Future missions which are necessary to continue the data flow, and augment images with compositional data, include BepiColombo at Mercury, EnVision to Venus, Juno and JUICE at Jupiter at its major natural satellites, Uranus Pathfinder, New Horizons to Pluto, and Castalia (P1.3, P1.4).
- The dynamical evolution of the Solar System requires study by ground-based facilities, including ESO-VLT, ING, JCMT and UKIRT, as well as through complex modelling of aggregation, requiring HPC and chronology studies of meteorite samples and those returned by missions (P1.5).
- The interaction between comets and asteroids and solar radiation and the solar wind requires the analysis of data from Rosetta, as well as remote observations of comet 67P/Churyumov–Gerasimenko using ground-based facilities. Samples returned from asteroidal missions will contain signs of radiation damage on grain surfaces (P1.6).

P2: How widespread is life in the Universe?

The Solar System exhibits a great diversity of planetary environments, many of which contain some or all of the essential requirements for life as we understand it: liquid water, an energy source, nutrients, and stable sheltered environments. The more we explore Earth, the greater is the diversity of habitats where life has been identified to exist. Using the survival of life on Earth as a guide for where life might exist beyond Earth directs us to explore many of the planets and satellites within the Solar System where similar conditions exist (or have existed in the past). The detection of extinct or extant life relies on the detection of appropriate biomarkers, and a key question currently being explored is what are these biomarkers and how are they influenced by different environmental effects such as oxidising chemistry and radiation (P2.1). A key point in the development of life is the formation of prebiotic molecules; the chemical processes that produced these molecules, and the environments where they formed (interstellar space, asteroids, comets) are not completely understood. Recent discoveries have identified potential formation mechanisms and environments in the atmosphere of Titan. It is not yet clear whether tectonic and/or volcanic activity is required for life to form. Research will lead to a more complete understanding of these processes and how life forms from simple prebiotic molecules (P2.2).



Radar image taken by instrumentation onboard Cassini of a hydrocarbon lake on the surface of Titan. The central island is ~ 150 km across. Image credit: ESA

Our understanding of habitability includes the warm environments inside the icy moons of the giant planets (P2.3). This is of clear relevance for our understanding of exoplanetary systems and the search for extinct or extant life beyond Earth. Whether there is or was life elsewhere in the Solar System depends largely the presence of liquid water (although research into alternative life chemistries is on-going), the history and inventory of liquid water in the Solar System, and the manner in which water was delivered to the inner planets, including the Earth, and whether interactions between the interior and atmosphere of a planet are requirements for life (see also P2.4). We need not only investigate places within the Solar System in which there is or was liquid water and sheltered habitats (e.g. Mars, icy satellites), but also areas where ice-water has been sequestered since early Solar System times, such as the poles of Moon, craters of Mercury, Main Belt Comets and other cometary populations, and the Kuiper Belt.

The search for life beyond Earth has historically concentrated on studies of Mars, which meets (or met) all of the essential requirements for life. It also offers a chance to investigate the abiotic-prebiotic-biotic transition that is not possible on Earth. The stratigraphic record of Mars provides a rich record of the history of the planet, revealing time periods and processes vital to understanding the formation and evolution of early life. Exploration of Mars includes the main objectives: (1) to characterise past and present habitability and search for evidence of life; (2) to characterise ancient and recent climates and climate processes; (3) to characterise the nature and evolution of surface and interior processes. A structured exploration programme designed to address questions of habitability and the subsurface is required, such as a progression from Mars Express, through MSL to ExoMars TGO and Rover, leading to a Mars Sample Return mission. Investigations of analogues and simulations are complementary to mission exploitation. The key science investigations required to address the issue of habitability involve understanding the geological, geochemical, photochemical and radiochemical processes that control atmospheric, surface, and shallow crustal chemistry, particularly where it bears on the provision of chemical energy and the availability (abundance, mobilisation, and recycling) of bioessential elements and molecules. It is also crucial to ascertain the nature and abundance of possible chemical energy sources that can drive organic and biological chemistry. It is also important to understand the role of global and local magnetic fields in providing environments that can protect (pre-) biotic molecules and life-forms themselves.

These questions and investigations are particularly pertinent in the study of icy moons surrounding the giant planets. The presence of heat inside the volumes of icy planetary bodies provides the necessary energy to drive organic chemistry leading to life. The presence of oxidants is an essential component to the question of habitability and observational and laboratory studies characterising the radiolytic processes in planetary ices are essential in understanding the generation of oxidants on the surfaces of the icy moons that orbit the giant planets. A strongly linked question is the role of tectonic and volcanic/cryovolcanic processes in cycling the surfaces of terrestrial and icy bodies, thus transporting surface oxidants into interior oceans. These same oxidants and radiolytic processes are also important in degrading the signatures of extant life.

It is possible that at least part of Earth's oceans were derived from water delivered to Earth by cometary and asteroidal impacts. Identifying the source population for this water is a key scientific investigation with important UK leadership. The key measurable is comparing the D/H ratio of cometary and asteroidal populations. Until recently, the D/H ratio of comets was thought to be incompatible with that of Earth's oceans. A new population of volatile-bearing bodies was recently uncovered in the Asteroid Belt which may have formed *in situ*. The Main Belt Comets (MBC) now represent an opportunity to sample volatile material – readily accessible by spacecraft (e.g., Castalia) – that formed at its present location in the Solar System. The poles of the Moon provide an accessible archive of hydrated asteroids and comets delivered in the past to the Earth-Moon system (e.g., Luna 27 and 28). Such data would be hugely valuable for early Solar System formation models and furthermore, isotope measurements could help establish a source for Earth's water. Other key questions include: (1) How could such bodies have remained *in situ* throughout the lifetime of the Solar System? (2) How widespread are the MBCs? (3) What drives their activity, and how important are inter-asteroid collisions in exposing volatile material? (4) How are volatile budgets modified during planetary collision processes? Only on-going theoretical modelling and remote observations, combined with *in situ* analysis, can we begin to understand the true nature of the MBC population. Further remote and *in situ* studies of comets and asteroids (such as Rosetta and a future main belt comet mission) and also analysis of ice at the poles of the Moon, are necessary to answer these key scientific questions in the evolution of Earth and the emergence of life on Earth.

Halley's comet in 1985, during its closest approach to the Sun. Credit: ESA.

Identifying other locations in the Solar System with liquid water is an essential step in understanding the wider volatile inventory of the Solar System. In understanding the materials that have formed and modified the planets, knowledge of the inventory of volatiles within the Solar System is an important factor. We do not yet know what the volatile inventory of the Solar System is, or the distribution of volatiles within and between the planets and their moons (P2.4). It is now well established that water once flowed freely on Mars but the key question is now what fraction of that volatile inventory has been lost to the solar wind and heliosphere, and what fraction has been stored in the crust of Mars. Both modelling of climate change and water-loss processes, and a better understanding of these processes in terms of the environmental history of the planet are required. Understanding the interior, atmospheric, surface and magnetospheric structures of planets and moons within the Solar System is crucial to providing constraints on the volatile budget. We need to understand why the giant planets (and their numerous moons) are so different from each other, in order to constrain models of planet formation. Finally, we have little understanding of how solar radiation and solar plasmas have affected the formation and evolution of Solar System bodies, from small bodies such as comets and asteroids, to full-scale planets. Measurements of the composition of asteroids, comets, small bodies and the giant planets (particularly the ice giants) is required to fully understand the wider inventory of volatiles such as ammonia and methane. This requires *in situ* and sounding measurements of the giant planets, remote and *in situ* observations of small bodies, and sample-return missions to various small bodies.

Beyond the Solar System it is important to determine the effect of stellar class on these processes. In terms of planetary systems elsewhere in the Galaxy, we do not yet understand how habitability relates to star-type, and have little in the way of planet population statistics which are required to provide a powerful test of models of planet formation and the potential for habitability. The search for terrestrial planets including super-Earths will provide us with the data for such studies. Finally, we also need to know whether our definition of life is appropriate for all life (for example, is liquid water necessary or are there alternative life chemistries?)

Key missions and requirements for P2:

- The search for life on Mars is a flagship project that is currently benefitting from the successful MSL mission and the ongoing Mars Exploration Rovers, but looking towards the Mars 2020 rover. Building on this mission are the coupled spacecraft Trace Gas Orbiter and ExoMars lander. The former will determine the composition and structure of Mars' atmosphere, looking for biomarkers, or any other signatures that might indicate the existence of a martian biology. Instruments on ExoMars will search below Mars' surface for biomarkers, and also determine the extent and depth of the permafrost layer, parameters required to determine the extent and location of an habitable zone in the martian near-surface (P2.1).
- The (currently foreseen) ultimate goal of searching for life on Mars is a Mars Sample Return mission. Sample return from Phobos, a moon of Mars is also an important goal. The return of material directly from Mars would allow much more detailed and sophisticated analyses to be carried out on the material in a controlled environment (P2.1).
- A necessary requirement for any sample return mission, whether from an asteroid, a comet, the Moon or Mars, is an appropriate Sample Curation Facility to undertake curation and storage of the material, and to house the instrumentation essential for preliminary examination of the returned samples (P2.1).
- The search for life beyond the Solar System is presently only possible through investigation of exoplanetary systems, such as would be undertaken by the ARIEL and Twinkle missions to characterise the atmospheres of transiting exoplanets (P2.1) and also for the search for magnetic fields around exoplanets via SKA.
- Determining the environment of formation of prebiotic molecules, the reaction chemistries they follow and the products of the reactions requires laboratory infrastructure for simulation and analysis of appropriate molecular species, as well as HPC to model reaction pathways (P2.2).
- The direct return of a sample from a primitive asteroid, such as by the Marco-Polo-2D, Osiris-Rex and Hayabusa 2 (and from Phobos, which is thought to be a primitive asteroid) missions will allow detailed study of an intermediate stage in the transition from prebiotic to biotic molecules, as well as how the organic molecules are bound with inorganic species (P2.2).
- In order to search for life beyond Earth, it is necessary to characterise the nature of life that can survive in extreme environments. One of the ways that this can be done is to undertake experiments in specialised environments, e.g., below ground (as in the BISAL facility) or in space (on the ISS via the ELIPS programme).
- One of the major goals of the Rosetta mission is to investigate the composition of the cometary volatiles, a significant piece of information necessary to help understand the origin of the Earth's oceans and the distribution of water throughout the Solar System. NASA's New Horizons mission to Pluto will be the first mission to visit a Trans-Neptunian Object; data from this mission are a necessary piece of the Solar System volatile story. Participation in ESA missions of collaboration with Roscosmos (Luna-27 and Luna-28) will provide the first opportunity to visit the lunar South Pole (Luna-28), where one of its main science goals will be to search for ice within shaded regions of the lunar surface. Collaborations on the Chinese missions Chang'e-4and other bilateral opportunities will lead to lunar sample return (e.g., Chang'e-5). Similarly, the Uranus Pathfinder mission to the ice giant will fill another gap in our understanding of the distribution and composition of volatiles, as will a mission to a Main Belt Comet (P2.4).

P3. What do other planets tell us about the Earth?

View of Shackleton Crater at the lunar South Pole taken by SMART-1. It is one of the deepest craters on the Moon, and its interior receives almost no direct sunlight. Deposits of water ice from comets may line the floor of the crater. Credit: ESA.

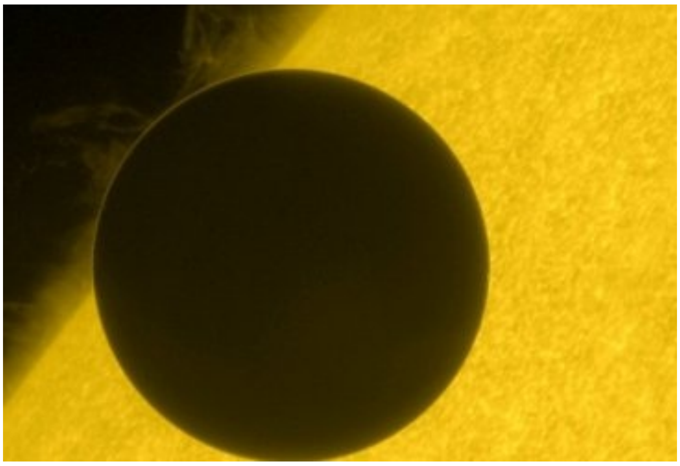
Our increasing understanding of the environments and history of other planets within the Solar System is revealing a great deal of information which can be used to shed light on the origin and evolution of the Earth, including perhaps its near-future. One critical aspect to be investigated is the impact record of the Solar System and the record of large impacts upon the Earth (P3.1). In general, the surfaces of other planetary bodies offer a longer and sometimes cleaner record than that of the Earth in terms of the processes that have operated throughout the history of the Solar System (see also P1.3 and P2.3). The early crustal history revealed on other bodies records not only external processes (e.g. impact cratering, solar wind scavenging) but also internal processes (e.g. possible plate tectonics, volcanic activity) that are not available or accessible in the terrestrial record. Impact cratering is a fundamental planetary process, an understanding of which is essential for our knowledge of planetary evolution. Yet our knowledge of impact processes is based on a combination of theoretical modelling, small-scale laboratory impact experiments, and field studies of generally poorly-preserved terrestrial impact craters. The Moon provides a unique record of essentially pristine impact craters of all sizes (from micron-sized pits up to 1000-km impact basins). Sample collection from and *in situ* geophysical studies of pristine lunar craters of a range of sizes would greatly aid in our understanding of the impact cratering process. The Moon is an extremely large satellite in comparison to the size of its host planet, such that the Earth-Moon system is unique within the Solar System. Studies of the Moon can tell us about the origin of our (as yet) unique "double planet" (P3.2). Material ejected from the early Earth by impacts may still be present on the Moon, and may yield information about the early history of the Earth during its first 500 Myr. Likewise debris and isotopic signatures found on the Moon from asteroid and cometary collisions in the past will tell us about the sources of impactors through time, helping to provide constraints for dynamical models of Solar System evolution ascertain the causes of impact spikes in the inner Solar System.

Studies of planetary atmospheres shed light on the evolution of Earth's atmosphere. How do planetary environments respond to differing energy input in terms of climate, atmospheric chemistry, meteorology, cloud formation and atmospheric circulation? The presence of heavy organics in the nitrogen-rich atmosphere of Saturn's largest moon Titan and their possible evolution into "tholins" has prompted the discussion of Titan as a prototype for the atmosphere of the early Earth. Future studies of Titan's atmosphere and the driving of both the atmosphere and atmospheric chemistry by solar insolation and the deposition of energy *via* charged particle precipitation is important in understanding the potential role these processes played in the atmosphere of Earth and the "seeding" of the primordial soup by the precipitation of tholins. The atmospheres of other planets (e.g. Venus, Mars) can also give us insight into non-anthropogenic climate change that has occurred (and is still occurring) on Earth. These issues lead to clear scientific questions enabling us to understand more about the Earth as a planetary system and its evolution (P3.3). Key scientific questions include: How effectively is solar wind energy extracted by a pole-on magnetosphere and what implications does this have for the coupled solar wind-magnetosphere-ionosphere-thermosphere system? Is Titan's atmosphere a suitable analogue for the early Earth? Do other planetary dynamos exhibit reversals? What role has and does the Earth's magnetosphere play in modulating climate?

The Solar System presents a diverse set of planetary magnetic fields produced by dynamo action in their interiors (see also U1.3), and by remnant crustal magnetisation from extinct dynamos. We do not have a general understanding of planetary, stellar and astrophysical dynamos and the continued study of planetary magnetic fields is essential for understanding changes in the Earth's dynamo and magnetic field over a variety of time-scales. The Earth's magnetosphere is the most studied in the Solar System but because of the limited range of controlling parameters (such as field strength, solar wind properties, plasma sources) the range of physical processes that can be investigated is necessarily limited. The study of planetary magnetospheres throughout the Solar System is important to generalise our understanding of planetary magnetospheres and understand more extreme dynamics in the Earth's magnetosphere. The geomagnetic reversals the Earth's magnetosphere is suspected to have had a "pole-on" configuration, significantly modifying the input of solar wind energy into the magnetosphere-ionosphere-thermosphere system. The magnetospheres of Uranus and Neptune have such pole-on configurations during parts of their orbit and diurnal phase and so represent the only opportunity to study such configurations *in situ* where we can test terrestrial palaeomagnetospheric models.

Planetary magnetospheres provide valuable laboratories for studying fundamental planetary plasma processes, which naturally leads to a better understanding of the Earth's magnetosphere and space weather, whilst yielding internationally-renowned science in its own right (P3.4). The magnetosphere of Mercury is an example of a "clean" solar wind-magnetosphere interaction without the influence of a significant atmosphere or ionosphere. In this case the solar wind has direct access to the surface, driving sputtering processes that can produce a tenuous atmosphere. Key questions about Mercury's magnetosphere include: What is the relationship between Mercury's atmosphere and the upstream solar wind conditions? Why does Mercury's magnetosphere respond so strongly to solar wind forcing? Although results from NASA's MESSENGER mission has been important in helping to understand Mercury, ESA's BepiColombo mission, with an orbit much closer to Mercury than MESSENGER's, will deliver significant data that will aid in addressing questions about Mercury's structure, composition and geological evolution, as well as about its magnetosphere. Mars and Venus do not have global scale magnetic fields and so their magnetospheres are induced by interaction between the solar wind and the ionosphere. The configuration of these induced magnetospheres and how they respond to the solar wind and solar cycle appears to be crucial in influencing atmospheric loss rates, but we have a poor understanding of the underlying processes. This is obvious from the observation that Venus is exposed to a higher degree of solar wind forcing by virtue of its location closer to the Sun, yet Venus has a thicker atmosphere than Mars. It is not clear if this results from active atmospheric regeneration at Venus, or if there is a magnetospheric explanation.

Plasma interactions can also affect the surfaces of planetary bodies through processes such as sputtering. The interaction of the solar wind with comets is another example of an induced magnetosphere. The interaction of solar wind transients with cometary magnetospheres produces large-scale deformations in the magnetospheric tail and can also cause these to become detached, thus playing a role in the loss of volatiles from the comet. Key science questions include: How are the induced magnetospheres influenced by solar wind and solar cycle forcing? What are the atmospheric loss rates as a function of upstream solar wind conditions, the solar cycle, and short-term variations in solar EUV output? How are cometary magnetotails detached by solar wind transients? How does the solar wind and solar cycle driving influence the comet-solar wind interaction and affect the rate of loss of volatiles and dust? How have plasma interactions affected planetary evolution?



The transit of Venus in 2012, captured by Hinode. Credit: JAXA

The magnetospheres of the giant planets are currently the focus of considerable international and UK interest and present large laboratories for the study of a wide variety of plasma and planetary processes. The two key factors that distinguish giant planet magnetospheres from others in the Solar System are the importance of mass or plasma sources internal to the magnetosphere and rapid rotation of these planets. Rapid rotation is imparted onto the magnetospheric plasma by currents connecting the ionosphere with the magnetosphere as part of the magnetosphere-ionosphere-thermospheric system. Rapidly rotating magnetospheres are valuable analogues for rapidly rotating astrophysical objects that cannot be studied *in situ*. Much of the dynamics of giant planet magnetospheres has an origin in moon-magnetosphere and ring-magnetosphere interactions, e.g., the interaction between Io and the jovian magnetosphere. Jupiter's magnetosphere is the harshest planetary radiation environment in the Solar System and a key question is how charged particles are energised to produce this environment. Both the jovian and saturnian magnetospheres display evidence of periodicities at periods longer than that of the rotation period of the planet and unravelling the physical origin of these modulations at Saturn is a key focus of the Cassini mission with considerable UK involvement. Missions to the giant planets have also highlighted the importance of dusty plasma physics in our Solar System. Key science questions on giant planet magnetospheres include: Why are their thermospheres so hot? How does non-steady mass loading affect the magnetosphere? What knowledge from moon-magnetosphere interactions can be applied to the interactions with the Moon, Mars, Venus, comets and other small bodies? How is plasma heated in giant planet magnetospheres? What is the physical origin of planetary period oscillations in Saturn's magnetosphere? What role does the solar wind play in driving dynamics in giant planet magnetospheres? How does Ganymede's mini magnetosphere interact with the jovian magnetosphere? To what extent do dusty plasma processes participate in complex chemical processes leading to the formation of very heavy ions and pre-biotic chemistry?

The exploitation of planetary resources has recently become of international interest and UK expertise can play an important role in this effort (P3.5). Key areas in which the UK can play a role involve the determining the inventory of planetary resources in the Solar System and developing the expertise in reaching such bodies the UK space industry can play a major role, supported by the UK planetary science community, and sample-return missions represent the technological steps towards such exploitation.

Key missions and requirements for P3:

- The impact record of the Solar System can best be established by detailed, high resolution mapping of planetary surfaces from orbit and chronological studies of planetary materials (meteorites and asteroid returned samples, lunar samples, martian samples). This requires the current missions Cassini, Mars Express, MRO, and Rosetta, as well as future missions, including the Trace Gas Orbiter at Mars, BepiColombo, EnVision to Venus, Juno, JUICE, Uranus Pathfinder, New Horizons to Pluto and Castalia, and investment in analytical laboratory equipment for sample analysis studies (P3.1).
- Simulation studies of impacts require the facilities associated with membership of ELIPS and high powered computing capabilities.
- Establishing the environment of the early Solar System is an essential step in understanding the origin and evolution of the Earth and other planetary environments in the Solar System. The Moon may preserve a pristine record of this environment and lunar missions, such as Luna 27, 28 and Chang'e-4/5, will be important in exploiting this important source of information (P3.2).
- Characterising and studying plasma physics in planetary magnetospheres, and interior/surface/atmosphere/magnetosphere coupling processes at all the planets in the Solar System is a key goal to develop a general understanding of planetary magnetospheres, as well as to address key universal processes (Theme 3). Missions include: Cassini-Huygens, Venus Express, Mars Express, BepiColombo, Rosetta, JUICE, Uranus Pathfinder, and remote observations using UKIRT, ING, JWST and E-ELT. Funding to exploit data from Juno and HST are also critical (P3.3).
- Determining the interaction of flowing plasmas with airless moons and those with thick atmospheres is also important to further our understanding of surface and atmosphere evolution, requiring the exploitation of data from Cassini-Huygens, Venus Express, Mars Express, EnVision, BepiColombo, JUICE, lunar missions, and Uranus Pathfinder (P3.3).
- Characterising the atmospheres of Solar System planets and exoplanets is important in meeting the goals of P3; missions such as Cassini-Huygens, Mars Express, Venus Express, EnVision, ARIEL and Uranus Pathfinder along with remote observations from ground-based facilities including UKIRT, JWST and E-ELT are essential. (P3.3).
- Study of planetary atmospheres and their interactions with their parent planetary bodies and magnetospheric environments requires participation in the Cassini, Mars Express and Venus Express missions, plus future participation in Juno, JUICE, Europa Clipper and ARIEL, modelling and the use of HPC, and access to ground- and space-based observatories. Future capability to place solar wind monitors upstream of a giant planet magnetosphere will be important to properly characterise the response of a giant planet magnetosphere to the solar wind. (P3.3).
- The advancement of our knowledge of planetary dynamos is somewhat limited by the observations of the intrinsic magnetic field of the planets. High quality magnetic field measurements at Solar System bodies via missions such as BepiColombo, Juno, JUICE and Uranus Pathfinder are essential in furthering our understanding.,(P3.3).
- In order to exploit planetary resources, detailed maps of the surface of different planetary bodies are required. Specific missions that can address this topic include (currently): Cassini, Mars Express, MRO, LRO, and Rosetta, as well as future missions, including the Trace Gas Orbiter at Mars, BepiColombo at Mercury, EnVision to Venus, Juno, JUICE, Uranus Pathfinder, New Horizons to Pluto and a Main Belt Comet mission. ExoMars and InSight (Mars), Luna 27 and 28 and Chang'e-4, and 5 (Moon), Phootprint and Osiris-Rex and Hyabusa-2 (asteroids) will probe the surfaces of the accessible bodies, to detect water and other potential resources (P3.4).

Theme 3: Universal Processes

Complementary to the science questions in Themes 1 and 2 are a series of questions about fundamental physical and chemical processes, an understanding of which is essential to deliver the science goals of our Roadmap. The questions are also important science questions in their own right, and the UK demonstrates considerable international leadership in moving towards answering these questions. Because the scope of this theme is so broad, in terms of application of the different processes to specific situations or environments, it is impractical to list areas of UK excellence, or missions or facilities that are key to answering the questions.

U1. What are the fundamental processes at work in the Solar System?

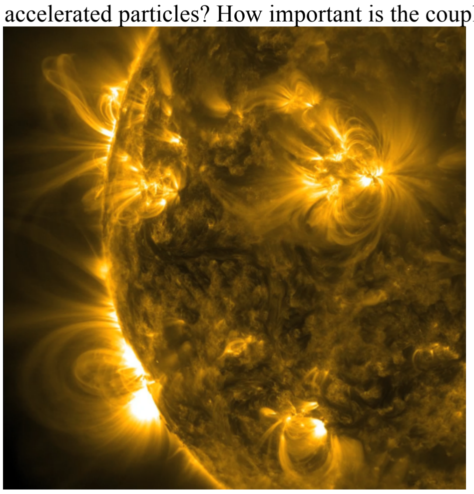
U1.1 **How do waves behave in inhomogeneous plasmas?** Waves, and wave-particle interactions play an important role in transporting and converting energy in a wide variety of Solar System contexts, from waves in the interior, photosphere, chromosphere, and corona of the Sun, to the solar wind, to planetary radiation belts. They offer important diagnostic information as they propagate through the highly-structured plasma medium, now seen in the current generation of high-precision Solar System observations, giving enormous potential for solar, stellar and other astrophysical seismology. The key scientific questions to answer are: What are the mechanisms for, and efficiency of, wave generation and guiding? How does wave scattering, conversion, dispersion and dissipation occur in regular and random dynamically evolving plasma inhomogeneities? What is the role of waves in inducing and triggering of powerful energy releases and in particle acceleration? How important is enhancement or suppression of nonlinear effects, including self-organisation, in structured plasmas?

U1.2 **Why and how do instabilities develop in inhomogeneous plasmas?** The stability properties of magnetized inhomogeneous plasmas are key to predicting the onset of dynamic eruptions and the collapse of length scales to create current sheets. In the complex magnetic structures of astrophysical plasmas, we need to address the following key questions: When and why does the magnetic field generate current sheets? When and why do magnetic eruptions occur? If boundary motions continually energise the magnetic field, to what state does an unstable magnetic field relax?

U1.3 **How are magnetic fields generated and how do they evolve?** Dynamo action and magnetoconvection occurs throughout the Universe, under widely different plasma conditions. Hence, theoretical advances in understanding all the complex interactions between plasma motions and magnetic fields in general has wide-ranging applicability. Key questions include: How does the dynamo saturation mechanism determine the spatiotemporal behaviour of large-scale magnetic fields (such as periods of reduced activity like the Maunder Minimum of the 17th Century)? How are strong stable planetary internal fields generated and why do they only reverse on long timescales? Is there any evidence for reversals in planetary fields beyond Earth? How do ice giant dynamos generate highly asymmetrical fields? Can dynamos work efficiently at small magnetic Prandtl number, when the field dissipates on scales much larger than the turbulent flow? What is the energy source for dynamos when the energy budget is tightly constrained? Sunspots are the result of the transport of dynamo generated magnetic fields by magnetic buoyancy to the solar surface but their structure is determined through the interaction of magnetic fields with convection. The existence of starspots is well-established, so solar-like dynamo and magnetoconvective processes are also occurring in these more distant objects. Furthermore, other late-type stars are known to exhibit cyclic magnetic activity. Key questions include: what is the similarity between sunspots and starspots? Is the solar dynamo typical of that of a late-type star?

U1.4 **What is the nature of turbulence in magnetised plasmas?** Turbulence naturally occurs in magnetised plasmas and planetary atmospheres, where it transports and deposits energy and heat, between different plasma scales, as well as controlling the propagation of energetic particles from flares and even galactic cosmic rays. Turbulence can drive solar wind energy into the Earth's magnetosphere and heat plasmas in planetary magnetospheres. It occurs throughout the Solar System, and is ubiquitous in astrophysical plasmas. However, it remains poorly understood: How does the magnetic field affect the turbulence cascade? How is turbulent energy dissipated at ion and electron scales? How does turbulence evolve, when unforced or driven? Resolving these questions will improve our predictions of solar wind speeds and mass fluxes, solar particle events at the Earth and variations in the galactic cosmic ray flux, and understand the general question plasma heating in planetary magnetospheres.

U1.5 **How does magnetic reconnection work?** Magnetic reconnection occurs in solar, space, astrophysical and laboratory plasmas, converting magnetic energy into thermal energy, bulk kinetic energy and driving energetic particle acceleration. This process has been well-studied in the Earth's magnetosphere but the application of these concepts to other Solar System environments has not been as comprehensively studied due to a lack of *in situ* data and changes in the controlling parameters, for example the presence of multiple plasma populations and very different ambient plasma conditions. It enables the magnetic field to globally restructure, but three-dimensional reconnection is significantly different to the process in two dimensions. 3D reconnection does not occur at a point, but continually and continuously throughout a diffusive volume and the sites of reconnection are much more varied. Through exploitation of data from other planetary magnetospheres and remote studies of the Sun we can understand better the conditions for the onset of magnetic reconnection. Key questions include: What are the best ways of identifying reconnection sites? What are the consequences of reconnection for the global system? How does reconnection partition the magnetic energy into thermal, kinetic & accelerated particles? How important is the coupling between macroscopic & microscopic scales during reconnection? How do reconnection rates depend on ambient plasma conditions?



Loops above active regions of the Sun, viewed by the EUV imager of the SDO in Oct. 2012. Credit: NASA/GSFC.

U1.6 **What is the nature of cross-scale coupling in plasmas?** Solar System plasmas exist under a range of conditions (from fully collisional to collisionless). In many situations, physical processes on microscopic scales (described by kinetic theory) influence what we observe on macroscopic scales (MHD), and vice versa. This cross-scale coupling is not yet understood because of the vast difference in length and time scale ratios (10^6 -10^{10} for typical Solar System plasmas). Hence theories of plasma heating, particle acceleration/transport and the interpretation of observations, e.g. of solar radio emission, are incomplete. Another fundamental point is the transition from the collisional to the collisionless regime. For example, laboratory reconnection experiments, along with theoretical and numerical modelling, have demonstrated clearly that, as the plasma transits from collisional to collisionless, the rate of reconnection increases substantially. Does this imply for Solar System plasmas that transport coefficients increase by orders of magnitude because of collisionless processes (micro-turbulence) as the collisional/collisionless transition is crossed and what effects does this have on the macroscopic scale? Key questions are: How is magnetic reconnection enhanced and how are charged particles accelerated as length scales collapse through the collisional to collisionless regime? How do shock waves evolve through the cross-scale coupling? How do fluid discontinuities lead to the generation of high frequency Langmuir waves, accelerate particles and produce radio emission?

U1.7 **How are energetic particles accelerated?** Acceleration and propagation of energetic particles, interacting on various physical scales, remain a major theoretical challenge in plasma physics. It is observed in solar flares, magnetic reconnection, at interplanetary shocks and planetary bow shocks, planetary radiation belts, and energetic particle populations observed in planetary magnetospheres. Some of the key processes, e.g., wave-acceleration of radiation belt particles, are relatively well understood. However, a detailed understanding of the acceleration of particles from low to very high energies is not yet available. Improved understanding of particle acceleration and propagation, e.g., in solar flares and at shocks, is directly relevant to the study of galaxy clusters, extra-galactic jets, magnetospheres of pulsars and planetary magnetospheres, and the cosmic magnetic explosions that result in gamma-ray bursts.

U1.8 **How do we know what we are seeing?** Laboratory astrophysics must be an integral part of current and new investments, as recommended by ASTRONET, in order to capitalise on current and future Solar System missions. The UK has traditionally been leading atomic and molecular calculations with HPC, to provide data to the wider astrophysical (and fusion) communities. The UK is leading atomic data provision with CHIANTI, now the reference database for ions, and universally used in solar physics, but also widely used by the astrophysical community. Spectroscopy features prominently in all major solar ground and space missions (IRIS, Solar Orbiter, Solar-C). Spectroscopy of the solar atmosphere provides the only way we can remotely measure the plasma state such as densities, temperatures and chemical abundances. Line widths and Doppler motions provide information about the processes responsible for plasma dynamics. The UK has a strong expertise in solar spectroscopy, and has significant involvement in several Solar Orbiter instruments, including the SPICE spectrometer, an instrument that ESA decided to fund given its fundamental importance for the overall science of the mission.

U2. How do planetary systems work?

U2.1 **How do fundamental plasma processes vary throughout the Solar System?** With our understanding of the fundamental physical and chemical processes that are found in the Solar System and beyond, how do these fit together to give a system-level understanding of planetary systems? The fundamental plasma processes described in U1 vary in their importance and efficacy throughout the Solar System, e.g., the atmospheres of Mars and Venus are quite different and exposed to similar erosion processes *via* the solar wind. This process should be more efficient at Venus because of higher solar wind pressure, but Mars has the more tenuous atmosphere. It is critical to understand how these plasma processes vary throughout the Solar System. Key questions include: How does the efficiency of magnetopause magnetic reconnection differ from the Earth's magnetosphere to those of the giant planets? How do atmospheric erosion processes change with solar wind conditions? How do ionospheres vary with distance from the Sun?

U2.2 **What are the processes that have created and modified the crusts, interiors and atmospheres of Solar System bodies?** To understand the formation and evolution of the Solar System more completely, and to interpret the specific properties of Solar System bodies that we find today, we must understand the basic processes that have created and modified the crusts, interiors, and atmospheres of Solar System bodies. Such processes include, and are not limited to, impacts, magmatism and volcanism, aqueous alteration and irradiation. Through comparative planetology observations we learn not only the local history of specific planetary bodies, but also the wider history of the entire planetary system.

U2.3 **How do we build an holistic picture of planetary magnetospheres?** Although it is well appreciated that the magnetospheres of Jupiter and Saturn are dominated by the angular momentum exchanges with the planetary atmosphere and by the gas/plasma outputs from inner moons, major issues remain to be resolved before a global picture of these environments will emerge. Exploration of ice giant magnetospheres and a more complete investigation of Mercury's magnetosphere is essential to complete this exploration and build a full system-level picture of how planetary magnetospheres work in general. Key science questions include: How is plasma transported throughout these systems, resulting in variable magnetodisc structures, magnetosphere-ionosphere coupling current systems, and related auroras? What physical processes occur within the powerful gas-giant auroral particle acceleration regions? What is the physical origin of the dual-period oscillatory phenomena in Saturn's magnetosphere, and is there a counterpart at Jupiter? What are the major solar wind-magnetosphere coupling processes in these systems, how do they influence the outer magnetosphere and the formation of the extended tail, and what are their auroral signatures?

U2.4 **How are Solar System planets archetypes for planets in other planetary systems?** A key goal of planetary science is not only to determine the nature of the planetary environments in our own Solar System, but to form a foundation of knowledge from which related aspects of exoplanetary systems can also be understood. This necessitates understanding how the planets in our Solar System can be used as archetypes for planets in other planetary systems. Key science questions include: To what extent are the giant planets representative of exoplanets? How does varying solar insolation and planetary heat flux affect the atmospheres of planets? How unique is the orbital architecture of our Solar System?

U2.5 **How common are Earth-like planets in other planetary systems?** A critical question with wide importance, both scientifically and societally, is to identify how common Earth-like planets are in other planetary systems. Addressing this question will require reading the detailed record of the formation of the terrestrial planets in our Solar System that is preserved in primitive material, so that the dependence of the formation of an Earth-like planet on the particular environment in which our Solar System formed can be assessed.

U2.6 **How stable are conditions in the Solar System?** Within the Solar System, we find a variety of planetary environments whose characteristics vary on a number of timescales that are beginning to be revealed by ongoing and repeated observations. Key science questions include: How stable are the environmental characteristics such as radiation and impact flux? What is the seasonal variability of planetary atmospheres, on what timescales do planetary systems change? On what timescales do habitable zones last and what implications does this have for the onset, development and frustration of life, particularly related to planetary bombardment? What configurations of planetary orbits and evolutionary processes give rise to a stable system?

Theme 4: Cross-cutting Activities

C1. Data Centres and Data Archiving

Having gathered data from the many missions, facilities and models, it is of great importance that these data are made freely available to the community in order that they can be exploited fully. Storing data is not just a matter of putting data files on a publicly accessible website, it also involves gathering and storing all information that explains where the data come from, how the measurements were made and what processing has been carried out on them. Historical data sequences are of tremendous value in understanding the context of modern observations. Many are preserved in their original form, as printed text or photographic plates. Many high-profile experiments, while of fundamental importance, are not bound to a particular time and, if there were the political or scientific will, could be recreated long after the original experiment had ended. This is not the case with data gathered for environmental monitoring purposes. Many of the datasets gathered for solar and space environment monitoring form time-series or come from a specific epoch of particular significance. These data are irreplaceable and should be treated as such. The Solar System provides a wonderful opportunity to study extreme astronomical environments at relatively close quarters. Unlike traditional laboratory experiments, however, it is almost always impossible to influence the medium being studied. Instead, the range of environmental conditions and specific events of interest are captured through a mixture of long-term and targeted observations. When developing a theoretical model, it is very important that a sufficiently wide range of data has been taken, preserved and made available so that it can be exploited in constraining the theory.

The STFC's scientific data policy, published in 2011, requires all STFC-funded activities, facilities and grant proposals to have a data management plan. It states that data should normally be managed and made publically available through an institutional repository. The policy also states that STFC expects the original data to be retained for the longest possible period. For data that, by their nature, cannot be re-measured, effort should be made to retain them in perpetuity. The STFC data policy can be found at http://www.stfc.ac.uk/About+STFC/37459.aspx.. It is, therefore, important that STFC supports data archiving facilities to an adequate level to ensure secure and easy access to Solar System science data sets, in perpetuity. STFC and AGP also must recognise that long-term data storage (both for missions and HPC) requirements extend beyond the three-year consolidated grant lifetime.

While STFC missions (some now funded by the UK Space Agency) archive their data through existing and proposed data centres (e.g., UK Solar System Data Centre; Solar and Heliospheric Centre), this process is funded through the post-launch support for each mission. Core funding for such data centres is minimal. Nor are there the resources to secure archive material from before the digital age. As technology advances and the rate of data collection increases with it, the issue of sustainable data preservation is one that needs to be addressed sooner rather than later. SSAP considers that centralisation of data repositories where STFC takes responsibility for the long-term preservation of data, would be better than incoherent local archiving of data associated with each STFC-funded project.

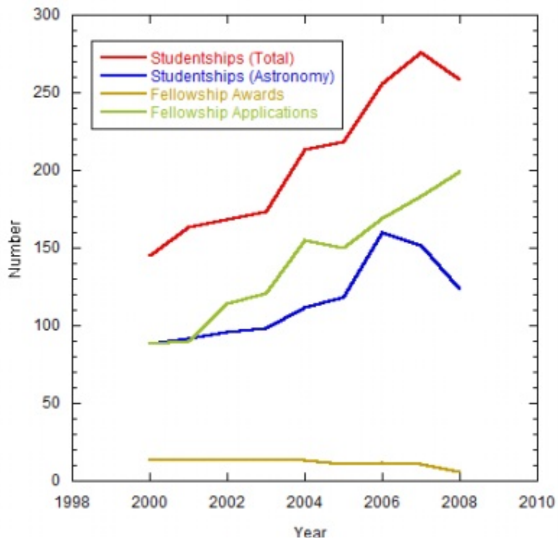
Recommendation 4: *The UK has invested millions of pounds in missions and instrumentation, and the final product of this investment is the publically owned data-set. STFC has an obligation to preserve these data. We recommend that the STFC continues to fund its data centres, such as UKSSDC, at the level required to maintain efficient and effective operation, without prejudicing the security of the data.*

C2. Grants, Fellowships and Studentships

Grants: The best analytical facilities in the world are useless if they have no staff to exploit them and no technical support to ensure that they are maintained and developed. Similarly, the most detailed programme of space missions is fruitless if there is no-one to interpret and exploit the data obtained. Thus the highest priority of the panel is to recognise the importance of the grants line, and the Fellowship and Studentships programmes. The Grants line funds exploitation of data from projects, provides technical and secretarial support for infrastructure, as well as resource for travel, consumable items and small items of capital equipment, including computing. All these are essential for the successful delivery of STFC's scientific programme; however, the most significant cost against the Grants line is that of salaries. The fEC component for academics named in a grant replaced the dual-funding model for research several years ago, and has, supposedly, enabled institutions to direct research monies into the specific areas that have raised the funds. This benefits the Research Councils, as it ensures that they support staff and infrastructure that are delivering on their priorities. It also benefits the institutions, as they can use the external peer-review of submitted proposals to recognise excellence and thus use it as a mechanism to channel funding to the appropriate recipients. The function of the Grants line to provide fEC for academics is important, but not as vital, in terms of delivery of research outputs, as funding for post-doctoral research associates (PDRA). The SSAP feels that this aspect of STFC's programme is one of its highest priorities.

Recommendation 5: *At a minimum, STFC must maintain the Grants line at its current level (cash basis, not percentage of the programme): if it falls any further, the number of PDRA working in the subject will be insufficient to keep the programme going, resulting in a decrease in performance at all levels, and an inability to compete for funding at the international level.*

Fellowships and Studentships: The functions of the Fellowship and Studentship programmes are slightly different from each other, and from that of the Grants line. Fellowships and Studentships are the main pathways for bringing young people into research, technology and academia. The Fellowship programme is an important way of recognising and training future leaders in the field, who will continue to drive research forward, to the benefit of the UK and its ability to compete effectively at international levels. They also form the next generation of academics. Studentships introduce young people to the research community, and equip them with a variety of high-level skills in communication, data manipulation and presentation, that have application way beyond what might be a relatively-narrow research topic. The skills acquired through studying for a PhD are of great benefit to the UK as a whole, not just for those who remain in STFC-funded research. Over the past few years, funding for STFC has gradually declined in real terms, and, from a maximum in 2006/07, the number of studentships and fellowships awarded has also declined Also shown is the steep increase in the number of applicants for Fellowships – showing that we are not able to fund an increasing number of gifted researchers each year.



Number of Studentships and Fellowships awarded since 2000. Data from STFC website (http://www.stfc.ac.uk/webstatistics/stfcStatistics.aspx?)

It is not just STFC that is failing – a recent independent inquiry by the Higher Education Commission into postgraduate education (http://www.policyconnect.org.uk/hec/research/postgraduate-education; published 23rd October 2012) found that the UK was failing to recognise the importance of this aspect of its education system. The report notes: *'A vibrant system of postgraduate education is vital if Britain is to achieve its ambition to be "the leading knowledge-based economy of the world."……globalisation and changes in the UK's industrial base mean that postgraduate degrees are more important than ever before in getting ahead in the labour market'.* Because the recommendations of this inquiry are so apposite, we reproduce two of them here, taken from the Executive Summary of the report:

'Our international competitors are increasing investment in research and development at a faster rate than the UK………We should look closely at the amount of funding we are investing in postgraduate research and benchmark this against the rest of the world. Recommendation 6: UK industry, government and universities should increase the amount they invest in research and development activities, in line with the UK's major competitors.

Academia is a profession which brings with it the opportunity to have an impact on the cultural life of the nation. We believe it should be accessible to anyone with sufficient ability. The research councils, learned societies and universities should ensure there are enough doctoral studentships to replenish the research base……….Particular attention needs to be paid to funding for research masters degrees, which are becoming increasingly important for gaining admission to doctoral research programmes, and from which the Research Councils have largely withdrawn funding. Recommendation 7: Funders, in partnership with learned societies, should reflect on whether they collectively fund enough studentships to replenish the research base in each discipline, rather than relying on self-funded individuals'

Based on its own consultation with the community, the SSAP recognises that the Fellowship and Studentship programmes form a vital part of STFC's overall portfolio, and that any diminution of numbers in either programme would have a detrimental effect on the UK research profile, beyond any short-term benefit that might be achieved by cost-cutting. A further issue is the lack of funding for early career fellowships that enable us to identify and nurture future leaders. The Royal Astronomical Society has provided temporary (limited) funds to mitigate the effects of this shortfall, but this is not sustainable in the long-term and this gap must be closed.

Recommendation 6: *As a minimum, the STFC must maintain its Fellowship and Studentship programmes at their current levels (cash basis, not percentage of the programme). Fellowships and Studentships are the main pathways for bringing young people into research, technology and academia. The Fellowship programme is an important way of recognising future leaders in the field, who will continue to drive research forward, again to the benefit of the UK. However, there is a significant funding gap in early career fellowships that enable us to identify these future leaders and nurture their independent development and this must be addressed. The skills acquired through studying for a PhD are of great benefit to the UK economy as a whole, not just for those who remain in STFC-funded research.*

C3. High Performance Computing

High Performance Computing (HPC) is essential for Solar System research and, indeed, for all STFC-funded theoretical research. The increase in computing power means that models that were originally no more than a cartoon or simplified to a 1D or 2D situation, can now be undertaken in full 3D and fully nonlinearly. Almost all the scientific questions defined in the preceding sections are dependent on HPC facilities. Specific examples include, but are not limited to, study of the following: (i) dynamo modelling, magneto-convection, flux emergence and global coronal field evolution (S1); (ii) MHD wave propagation in inhomogeneous plasmas, MHD instabilities, magnetic reconnection, coronal heating and particle acceleration (S2 and S3); (iii) heliospheric and magnetospheric simulations, plasma wave generation and wave-particle interactions (S3); (iv) modelling impacts, ring and accretion disc dynamics, and orbital evolution (P1); (v) modelling planetary atmospheres (P1, P3) and (vi) across the full range of universal processes (U1-U3). We give just one example of the type of problem in Solar System science that requires HPC: the UK has traditionally been, and continues to be, a recognized world leader in computational magnetohydrodynamics (MHD) modelling. This requires the numerical solution of eight coupled, nonlinear, partial differential equations, resulting in codes which must be able to resolve small length scales, in order to describe, for example, the onset of turbulence or the breakup of a current sheet during magnetic reconnection. Additional physical processes, (e.g., optically-thick radiative transfer) and instrument response functions can be included in the codes, so that it is now feasible to compare directly the outcome of theoretical simulations with high-resolution observations. Kinetic theory requires solution of the plasma distribution function (a function of seven independent variables of space, velocity and time), and Particle-In-Cell methods bridge the gap between kinetic and MHD scales.

In addition to the HPC needs of simulations, data analysis also requires significant HPC resources. Currently, space missions generate around 1 TB of data per day, and accessing and processing these data is a major undertaking. Hence access to appropriate HPC facilities is essential for the successful analysis and interpretation of observational data. In our quest to exploit, understand and interpret the data from our observational facilities, a full theoretical description is dependent on HPC simulations. These become more sophisticated and computationally-demanding as observational facilities scrutinize the Solar System in greater detail. HPC facilities should be seen as an analogy to an observational facility, and both are essential for our goal to understand the Solar System.

The recent investment in DiRAC II was an unexpected windfall from BIS (http://www.stfc.ac.uk/24711.aspx) and STFC must ensure this investment is used wisely. There are two main models for HPC provision, either place all the computer nodes at one site or maintain several, smaller but still extremely powerful, machines at different campuses and invite the hosts to enhance the machine. There should be a coherent plan for hardware refresh, since hardware improvements are advancing at an impressive rate. A sustainable strategy for HPC is an essential requirement for the UK to remain at the forefront of research, and this applies to all science and not just that funded by STFC. In addition to the hardware, PDRAs and students are required. The UK has a strong tradition of writing and developing its own codes. This tradition is a major benefit to students, both those who wish to stay in the field, and those who enter other fields, since students with good HPC skills are highly sought after in non-academic positions. Continued training in HPC, through annual summer schools, will ensure that our computational methods remain up-to-date.

However, it is extremely important to recognise the impact of a lack of funding for the development of numerical models, the development of junior scientists trained in these techniques, and the lack of human resources and programming support in these areas. Whilst many models can produce scientific results for years without major upgrades, eventually significant new developments are required to keep pace with science and our international competitors. It is critical that such major model developments are adequately supported to maintain UK leadership and competitiveness in a range of fields. It is SSAP's view that STFC should consider the development of numerical models in a similar way to the development of new telescopes, space instrumentation, or new detectors for particle physics. These developments take time, requiring development of the basic formalism, considering the numerical aspects, implementation, testing (on smaller-scale facilities enable capabilities to be checked, hence the requirement for a range of HPC facilities), and documentation. These developments take time, often longer than a 3 year consolidated grant period, and during this period publication rates will drop. This must be recognised by grants panels.

Recommendation 7: *SSAP supports STFC's recent computing consultation aimed at developing a clear and appropriate funding strategy for HPC/HTC to allow the UK to remain competitive in the critical area of HPC expertise, and to ensure adequate training for future generations of scientists. Furthermore, it is critical that STFC recognise that the development of new numerical models is essential for continued scientific excellence, impact, and international leadership in a wide variety of areas. STFC should consider the development of numerical models in a similar way to the development of new telescopes, space instrumentation, or new detectors for particle physics.*

C4. Laboratory Infrastructure

Exploration of the Solar System, seeking answers to the questions posed in the three themes, is undertaken by a combination of observation, theory, simulation and experimentation. The last, experimentation, can be carried out remotely, by instruments on-board spacecraft, or mounted on landers (e.g., the instrumentation carried by the Rosetta spacecraft and its lander, Philae). However, the number and duration of such experiments may be pre-programmed, and dictated by technical and engineering factors, e.g., the amount of power available, rather than by scientific considerations. Laboratory-based experimentation is the only way for direct and unambiguous determination of key characteristics of planetary materials, such as age and composition. The benefits of laboratory experiments include the ability to modify methods and techniques as appropriate, the capacity for repeat measurements to gain high accuracy and precision, the opportunity to gain extra information by applying complementary techniques, and enabling inter-comparison between different materials and laboratories. There is also the added benefit of being able to archive samples for analysis in the future, when new techniques become available.

The SSAP recognises the important role that national and international laboratory facilities, such as the Diamond Light Source, have for its research. However, whilst we draw attention to such facilities, it is not within our remit to assign priorities to their operation, or, within the context of this Roadmap, to comment on possible new developments (e.g., construction of specific beamlines, etc). The SSAP also recognises that STFC is guided by (although not dictated by) the ESFRI roadmap for large facilities (http://ec.europa.eu/research/infrastructures/index_en.cfm?pg=esfri-roadmap), and again, we express our support for that road-mapping process.

The UK has a long history of supporting laboratory infrastructure at the university level. Over the past decade, this has resulted in the formation of national consortia to share expensive equipment. As a result of the development of state-of-the-art laboratory instrumentation, many groups are part of international consortia such as Europlanet (http://www.europlanet-eu.org/). Support of laboratory instrumentation has enabled the UK to take part in high profile sample analysis programmes such as preliminary analysis of material returned from a comet by the Stardust mission, from the solar wind by the Genesis mission and from an asteroid by the Hayabusa mission. It is important that the UK maintains its high profile in such international consortia, especially as the UK Space Agency, along with its international counterparts at ESA, NASA, the Chinese Space Agency, Roscosmos and JAXA are currently designing missions to return material from asteroids (Marco-Polo-2D, OSIRIS-Rex and Hayabusa 2) and also the Moon, Mars and Phobos. UK scientists are already playing important roles in the science teams of these missions. Alongside analysis of materials from recent direct sample return missions are internationally-recognised programmes of excellence in the analysis of Apollo and Luna samples, meteorites (including from the Moon and Mars) and interplanetary and interstellar dust.

In addition to instrumentation for sample analysis, the UK houses laboratories for undertaking simulation studies. The UK has a suite of world-leading impact facilities, split over several institutions, which include one of the fastest two-stage light gas guns (LGG), capable of impact velocities of up to 8 km s^{-1}. This instrument is also capable of simulating hot and cold temperature environments. There is also a pivoted LGG that can be moved from the horizontal to the vertical, for impacts onto granular surfaces and liquid targets (one of only two in the world), and guns that can fire centimetre-sized projectiles, which represents the forefront of LGG technology. The UK are key players in computer simulations of impact events using hydrocode modelling, as well deriving empirical equations of state for a range Solar System materials for use in these models. These facilities serve as a community resource for impact scientists from the UK and from other international groups. The UK is also home to a variety of chambers that simulate different environments, from the cold, near-vacuum of space to the heated atmosphere of Venus. These are used to test instruments, to perform simulations of surface and atmosphere interactions for different planetary environments, and also to investigate ice dynamics, gas-grain collisions and the chemistry of interplanetary and interstellar space.

The expertise that the UK scientists have in laboratory instrumentation bears fruit in two ways. Firstly, of course, is their ability to analyse samples in ground-based laboratories. Alongside this though comes the complementary development of instrumentation for space missions. In conjunction with analysis of returned samples, is a requirement to curate them, a process which encompasses preliminary examination, material selection and distribution as well as storage of material for future generations. Through the UK Space Agency, UK-based laboratory experimentalists have expressed a desire to lead the European sample curation programme for material returned from future missions, and an EU programme (e.g., EUROCares) study is being led by the NHM-London, along with a consortium of UK and European partners. Selection and curation of analogue materials by this facility will also aid development of future *in situ* experiment packages and sample return mission designs.

Recommendation 8: *STFC maintains support for ground-based laboratory experimental, analytical, simulation, fieldwork activities and curation facilities, to enable the UK to maintain its high international profile in the relevant fields, and play a leading role in forthcoming sample return missions.*

C5. Telescopes

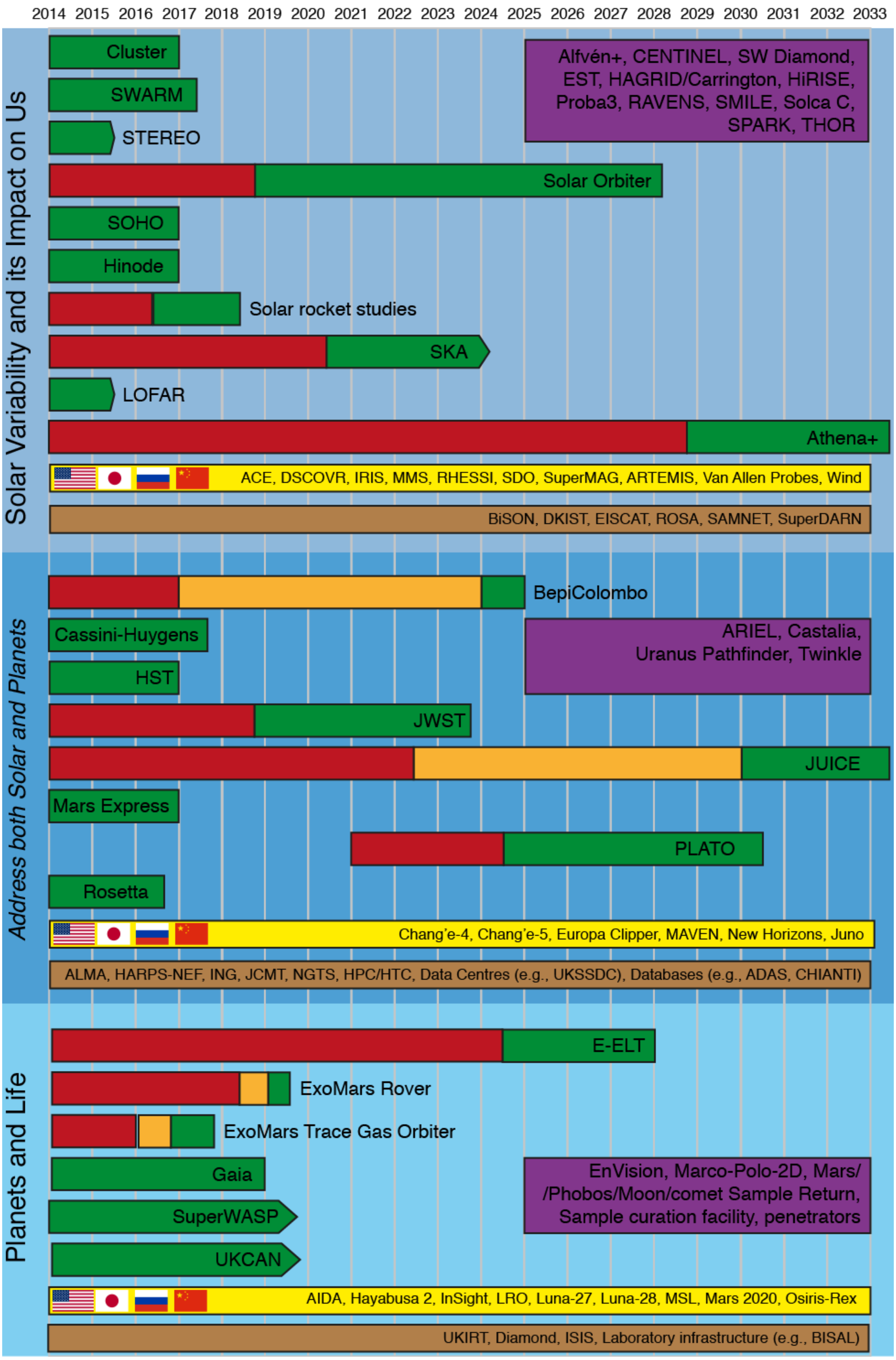
The SSAP recognises that a detailed consideration of telescope operations and the relative prioritisation of instrumentation is beyond its remit, and is part of the remit of the Astronomy Advisory Panel. The UK's telescope provision has also been the subject of several independent reviews over the past few years, and the SSAP is aware of the recommendations that have come from the reviews (e.g., the Ground-based Facilities Report of 2012; http://www.stfc.ac.uk/Resources/PDF/GBFRFinal.pdf). However, Solar System science requires telescope observations of Solar System bodies, across the complete wavelength range; such observations are essential in meeting almost all of the science goals described in Themes 1 and 2. Hence we have included this very general consideration of telescope facilities as one of our cross-cutting issues. These facilities present many opportunities to complement results from space missions and related projects. Examples where telescope instrumentation is essential to achieve the required results include: higher-spectral resolution data than available from space missions; long baselines of observations; global imagery to place spacecraft observations into context; to complement and support spacecraft data, and to provide data that are sometimes not available because of payload selection for a particular spacecraft. Reference is made to individual telescopes at various places in the discussion of specific science questions, and these are also included in our table and timeline. It is essential that STFC continues funding for both ground- and space-based telescope facilities at an adequate level to support the science programme laid out in this report. It is also essential in supporting the goals laid out in the report from the Astronomy Advisory Panel. It must also be noted that even after instruments cease operation, there are still opportunities to exploit data generated by those instruments, requiring support from the appropriate funding lines. Investment in the development of new telescopes, instrumentation and data reduction and processing techniques are key in the advancement of UK Solar System science, and we welcome the opportunities that the UK will gain through its partnership in both the SKA and E-ELT projects.

Recommendation 9: *That STFC maintains its support for ground-based and space-based telescope operations and instrumentation at a level that will enable the UK to maintain its high international profile in the relevant fields. This support should recognise and balance the competing claims of new developments versus extension of current instrumentation, such that UK scientists are able to access the range of facilities they require to meet their goals.*

Missions and Facilities key to Solar System Research

Missions and facilities are considered in two categories: (1) those that the UK directly supports, either through instrument build and/or membership of science team, and (2) those with no direct UK support, but which provide data for exploitation (italicised in the table). Both categories are equally vital for the successful progress of Solar System scientific research. The figure overleaf indicates a timeline of missions, facilities and projects that are relevant for the two main themes (also applicable for theme three). In this diagram the red, orange and green bars represent development/build, cruise, and operational phases respectively. The purple boxes indicate future projects that have been proposed but not yet selected. The yellow and brown boxes indicate international facilities and ground-based observatories/other facilities respectively. Projects such as LOFAR and SuperWASP have angled edges to indicate that the project end date is unknown.

Theme	Question	Mission or Facility			
		Currently operational	**Near-term operational (2016 - 2019)**	**Medium-term operational (2019 - 2022)**	**Long-term operational (2022 - 2032)**
Solar Variability and its Impact on Us	What are the causes, consequences and predictability of solar magnetic variability and the solar cycle?	SOHO, STEREO, Hinode, BiSON, ROSA	Solar rocket studies	Solar Orbiter, Solar-C, DKIST, HiRISE	SPARK, PLATO, EST, Carrington
		SDO			
	What are the structures, dynamics and energetics of the Sun?	SOHO, STEREO, Hinode, LOFAR, ROSA		Solar Orbiter, Solar C, DKIST, HiRISE	SPARK, Proba 3, EST, SKA
		RHESSI, IRIS, SDO	*HiC*		
	What are the underlying processes that drive Sun-planet connections?	EISCAT, SuperDARN, STEREO, LOFAR, Cassini/Huygens, Cluster, MEX, SWARM, SAMNET	EISCAT_3D	Solar Orbiter, CENTINEL, HAGRID	BepiColombo, JUICE, SMILE, Uranus Pathfinder, SW Diamond, THOR, SKA, Alfvén+, PLATO, RAVENS, Athena+, Carrington
		ACE, Wind, DSCOVR, THEMIS/Artemis, Van Allen Probes, MMS, MAVEN, SuperMAG, HST	Juno, Chang'e-4		
Planets and Life	How did the Solar System form and evolve?	Cassini/Huygens, SuperWASP, MEX, UKIRT, JCMT, ING, HARPS-NEF, UKCAN, Rosetta, Gaia, HST, ALMA	NGTS, JWST, ExoMars Lander, ExoMars Trace Gas Orbiter, Sample curation facility	Twinkle	BepiColombo, Uranus Pathfinder, Castalia, Marco-Polo-2D, JUICE, E-ELT, Mars/Phobos/Moon/comet Sample Return, EnVision, ARIEL, PLATO
		MSL, MAVEN, New Horizons, LRO	InSight, Osiris-Rex, Juno, Hayabusa 2, Chang'e-4, Chang'e-5	Mars 2020, Luna 27	Luna-28, AIDA, Europa Clipper
	How widespread is life in the Universe?	Cassini/Huygens, MEX, Rosetta, Gaia, UKCAN, HST, ALMA	JWST, ExoMars Lander, ExoMars Trace Gas Orbiter, Sample curation facility	Twinkle	Uranus Pathfinder, Castalia, Marco-Polo-2D, JUICE, E-ELT, Mars/Phobos/Moon/comet Sample Return, EnVision, ARIEL
		New Horizons, MSL	Osiris-Rex, InSight, Hayabusa 2, Juno	Luna-27, Mars 2020	Luna-28, Europa Clipper
	What do other planets tell us about the Earth?	Cassini/Huygens, MEX, Rosetta, Gaia, UKCAN, HST, ALMA	JWST, ExoMars Lander, ExoMars Trace Gas Orbiter, Sample curation facility	Twinkle	BepiColombo, Uranus Pathfinder, Castalia, Marco-Polo-2D, JUICE, E-ELT, Mars/Phobos/Moon/comet Sample Return, EnVision, ARIEL, PLATO
		New Horizons, MSL, LRO	InSight, Juno, Chang'e-4, Chang'e-5	Luna-27, Mars 2020	Luna-28


2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033
Solar Variability and its Impact on Us
Cluster
SWARM
STEREO
Solar Orbiter
SOHO
Hinode
Solar rocket studies
SKA
LOFAR
Athena+
Alfvén+, CENTINEL, SW Diamond, EST, HAGRID/Carrington, HiRISE, Proba3, RAVENS, SMILE, Solca C, SPARK, THOR
ACE, DSCOVR, IRIS, MMS, RHESSI, SDO, SuperMAG, ARTEMIS, Van Allen Probes, Wind
BiSON, DKIST, EISCAT, ROSA, SAMNET, SuperDARN
Address both Solar and Planets
BepiColombo
Cassini-Huygens
HST
JWST
JUICE
Mars Express
PLATO
Rosetta
ARIEL, Castalia, Uranus Pathfinder, Twinkle
Chang'e-4, Chang'e-5, Europa Clipper, MAVEN, New Horizons, Juno
ALMA, HARPS-NEF, ING, JCMT, NGTS, HPC/HTC, Data Centres (e.g., UKSSDC), Databases (e.g., ADAS, CHIANTI)
Planets and Life
E-ELT
ExoMars Rover
ExoMars Trace Gas Orbiter
Gaia
SuperWASP
UKCAN
EnVision, Marco-Polo-2D, Mars/ /Phobos/Moon/comet Sample Return, Sample curation facility, penetrators
AIDA, Hayabusa 2, InSight, LRO, Luna-27, Luna-28, MSL, Mars 2020, Osiris-Rex
UKIRT, Diamond, ISIS, Laboratory infrastructure (e.g., BISAL)

Prioritisation of Projects

One of the most important outcomes from the Roadmap is that it allows the community to recognise its research goals and how they can be prioritised to take greatest advantage of the funding available from the STFC (as well as the UK Space Agency, ESA, ESO and other funding sources). Any prioritisation process is painful, and has the potential to divide a community, rather than unite it. The SSAP consulted widely for input during the roadmapping exercise, and has drawn heavily on the experience gained from its predecessor panel, the NUAP. It would have been too easy to produce a wish-list, rather than a roadmap. But we have remained cognisant of the necessity of pragmatism in a time of financial turbulence, and so have kept our roadmap to, what we believe, are realistic goals, within a landscape where progress towards our longer-term challenging aspirations can still be maintained. In putting together the Roadmap, the SSAP took scientific excellence as the main driver, followed by the international significance of the project; the extent of UK leadership and the timeliness of the project. We have produced a roadmap (Figure), with key space- and ground-based projects as the parameter employed to illustrate the milestones required to define the direction of our research over the next two decades.

The SSAP has not prioritised specific missions or projects over others. We have not, for example, rated continued involvement with Solar Orbiter over or behind our contribution to JUICE: we have not had the information, the time or a mandate from the community to do this. Instead, what we have suggested is a rolling prioritisation based on the status of the projects in question. The international community frequently has the same science goals as the UK and if a favoured mission is not selected, it is extremely likely that a new mission will be proposed to cover that science area. We must remain flexible to adjust to such a situation In the Figure, the different projects are coloured, according to this status. We suggest a flexible apportionment of resource, which might be possibly along the lines of, for example, 60 % to projects in operation, 30 % to those selected and in development, 10 % to those not yet selected, but requiring input for development. The split of 60:30:10 is given only as an example, and the actual figures should be subject to continual monitoring and adjustment, but it would ensure that funds are distributed across the programme, both in terms of subject area and timeliness. In making this recommendation, the SSAP recognises several additional details:

- Exploitation of data from a project continues long after the project itself has ended, thus each project should be seen as carrying on beyond the project end. Funds for this stage of research would, presumably come from the Fellowships, Grants and Studentship lines.
- There is still a grey area, possibly not completely understood by the community, where responsibility for funding of projects falls between the remits of the STFC and the UK Space Agency. Thus funding for building a detector for a mission is the responsibility of the Space Agency, but funding for research into generic detector development belongs with the STFC. This is why missions such as MoonLITE (in the last version of the roadmap) appear in the roadmap: they represent an opportunity for generic detector/instrument development. Funds for such research would, presumably, come from the PRD line, and/or the Fellowships, Grants and Studentship lines.
- There are a large number of projects that have not been included on the Roadmap because they are not funded by the UK, either directly or through international subscription, e.g., NASA's Juno mission to Jupiter; NASA's Solar Dynamic Observatory. Data from such projects are available to the community, and exploitation of these data is a vital part of the community's research effort, both in terms of preparation for future missions as well as helping to deliver answers to our key research questions. The absence of specific mention of these projects must not be taken as an indication of unimportance: they are a crucial part of our research effort. Again, funds for this research would, presumably come from the Fellowships, Grants and Studentship lines.

Given the above considerations that go with the Roadmap, it should be clear that the SSAP rates maintaining (at the very least) the Fellowships, Grants and Studentships lines at their current level as its highest priority. An increase in the number of Fellowships (particularly at a junior as well as senior level) and Studentships (but **not** at the expense of the Grants line) would be a welcome response to the recent report from the Higher education commission (cited previously) that the government is not doing sufficient in terms of postgraduate training and opportunities.

Front cover image credits: Sun seen by SDO (NASA); Saturn observed by Cassini (NASA/Space Science Institute); Comet 67P/Churyumov-Gerasimenko (ESA/Rosetta/NAVCAM).