Roadmap for Solar System Research
October 2012

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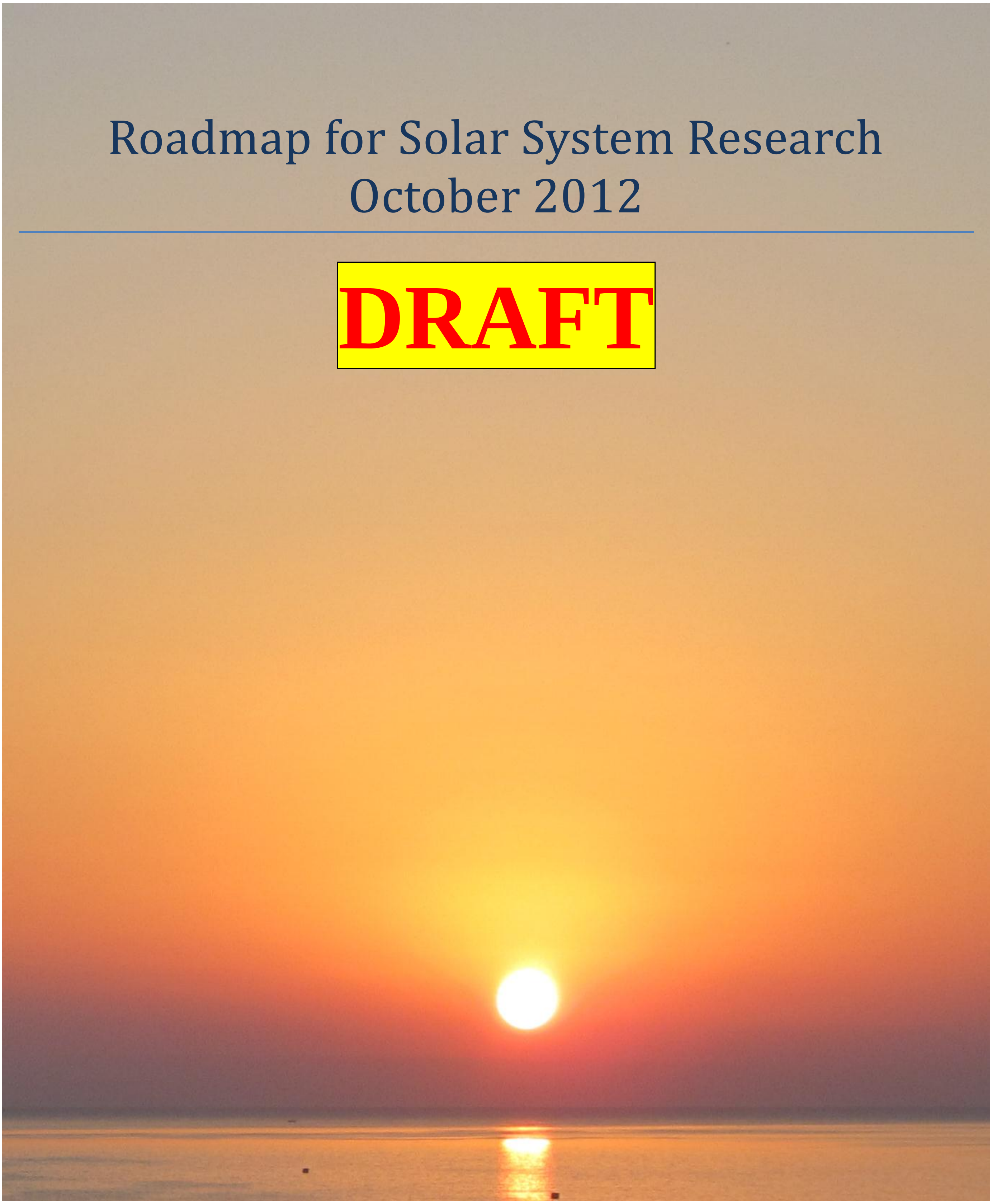

Prepared *by the Solar System Advisory Panel* on behalf of the UK Community of Solar and Planetary Scientists for the STFC Programmatic Review

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IMPORTANT NOTE:

This is a DRAFT version, and we are working to make sure that there is consistency in style and formatting throughout, especially in the way that we repeat the questions, or not, in the three themes.

Comments about style are welcome, but comments about content are essential! We are asking specifically for comments on what is missing and/or what is wrong. We will break up the text by adding a few images, so if anyone has a specific illustration that can be used, especially if it is of something that STFC funded, please send it to us.

Executive Summary (*to be completed*)

1. The Solar System Advisory Panel (SSAP) invited its community to a Town Meeting in London on 10th September 2012, at which the content and structure of the SSAP Roadmap (this document) was discussed. The SSAP drafted the Roadmap, which was circulated to the community in mid-October, then revised by the SSAP prior to submission to the PPAN review board in early November 2012.
2. The SSAP acknowledges, with gratitude, its predecessor body, the Near Universe Advisory Panel, whose extremely thorough report of November 2009 was used as a guide and a template for this Roadmap.
3. Three overarching themes were identified which encompass the outstanding scientific questions to be addressed over the next two decades. These themes are: (1) Solar Variability and Space Weather (**Section R2**); (2) Planets and Life (**Section R3**) and (3) Underpinning Processes (**Section R4**).
4. The Roadmap recognises specific strengths where the UK is particularly well-placed to make significant contributions to the questions, in terms of three complementary areas of expertise (theory, observation and experimentation).
5. 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. Facilities include a requirement for High Performance Computing (**Section R5**).

The SSAP has attempted to assign priorities to the projects and facilities required for its research programme, but recognises that such a process is fraught with difficulties. This Roadmap does not contain an absolute ranking of individual projects, but bands them into levels of High, Medium and Low importance. What **MUST** be recognised is that, because of the long lead-in times associated with space missions, the prioritisation is, of necessity, an issue of timeliness: a project that is of low importance now will become of increasing importance as the mission timeline is traversed towards science exploitation.

6. The community recognises that it is not an island isolated from other research communities, particularly the Astronomy and Particle Astrophysics communities, and that there is potential for overlap in the research aims of the communities. Where possible, this has been indicated in the text.
7. The community also recognises that 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 are involved in different aspects of the research. The SSAP hope that this Roadmap will help these bodies as they also define their research priorities.

Preparation of the Roadmap

Introduction

At the heart of the research undertaken by the communities represented by the SSAP is a drive to understand the origin and evolution of the Solar System, and the nature of the forces and processes that influence its dynamics. The remit of the Solar System Advisory Panel (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 charged 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 and interplanetary 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 are applicable to, and are able to direct the study of, planetary systems around other stars.

In order to focus the efforts of the community of solar and planetary scientists and the expertise they bring to the study of the Solar System, 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) **Underpinning 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 and theoretical modelling. The questions speak to and extend the 'Big Questions' that currently comprise STFC's Science Roadmap (http://www.stfc.ac.uk/Roadmap/index.aspx*)*. Complementing the science themes is a set of **Cross-cutting Issues**, areas of significant importance that are relevant for all three of the themes (indeed, they are relevant for all four of STFC's research communities).

Overlap with AAP and PAAP

Solar System research overlaps with astronomy in several areas, most particularly in the field of exoplanet research. Each community brings a different flavour to the research effort. 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 new solar systems contain objects for which there is no solar system analogue (eg super-Earths) and hence allow severe tests of our physics.

Solar System research overlaps with the field of Particle Astrophysics ………..

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 Issues, in order to draw attention to their importance.

Relationship with the UK Space Agency

Since the last roadmapping and prioritisation exercise carried out by the STFC, the UK Space Agency has been established. This 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. The selection of space missions, and the development of spaceflight instrumentation for those missions, are critically important issues for the solar and planetary communities, and so remaining a leading member of ESA is a top priority. Whilst consideration of the ESA subscription is not part of this prioritisation exercise, there are two reasons that we deem it essential to highlight the importance of ESA to our research goals. Firstly, the UK Space Agency calls upon the STFC (and other Research Councils) for information and advice when setting its own priorities. By ensuring that ESA features in STFC's roadmapping exercise, *to be continued*

Consultation Process

The SSAP acknowledges the thorough review of Solar System research and its priorities undertaken in 2009 by its predecessor, the Near Universe Advisory Panel (NUAP). However, because the remit of the SSAP is different from that of the NUAP, the goals and timeframes of the Roadmap produced by the NUAP now require modification and up-dating. Thus the SSAP engaged in consultation with the solar and planetary science community in order to develop this document. Consultation took place in several stages:

1. A notice announcing the STFC Prioritisation process, and preparation of the Solar System Roadmap that forms the community input to the process was circulated in late August. The notice also invited the community to a Town Meeting.
2. The Town Meeting was convened on Monday 10th September 2012 at the Royal Astronomical Society in London; approximately 80 members of the community attended. Following discussion at the Town Meeting, the idea of two major themes was developed, along with the science questions that underpin the themes. *[It was unfortunate that the date coincided with a meeting about the Solar Orbiter mission, such that part of the community was absent from the meeting. They, along with others who could not attend in person, provided written input to the SSAP]*.
3. The Principal Investigators of relevant (funded) projects were solicited for information through a questionnaire developed by STFC. Responses were received from XX investigators representing XX projects
4. An open call for information on potential projects was also made through an announcement on appropriate electronic mailing lists. Responses were received from XX investigators representing XX projects.
5. On the basis of discussion and submissions received, the two themes were expanded to three. A draft report was prepared by the SSAP, then circulated to the community in mid-October for comment and revision
6. The revised document, completed in early November, forms the basis of this Roadmap

Structure of the Roadmap

The Roadmap is broken down into five sections (R1-R5). 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 final 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.

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 can we predict/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 is the nature of the Sun-Earth connection, and what are the underlying processes that drive it?

- S3.1 How does the solar wind, including transients, evolve throughout the heliosphere, and can we predict/forecast conditions at Earth?
- S3.2 How does the Sun produce geoeffective events and can we forecast them?
- S3.3 How does the magnetosphere/ionosphere/thermosphere system emerge from its interaction with the solar wind?
- S3.4 What are the processes that cause enhancement/loss of radiation belts around planetary bodies?
- S3.5 What is the nature of the coupled solar wind-magnetosphere-ionosphere-thermosphere systems at the ice giant planets?

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 structures of the other planets and satellites within the Solar system?
- P1.4 How do size, location and composition of planets and satellites affect their evolution?
- P1.5 How did the planets get to where we find them?
- P1.6 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 or was there life elsewhere in the Solar system and what are the biomarkers?
- P2.2 Where do prebiotic molecules form and how do they get to where they form life?
- P2.3 What are the requirements and bounds of habitability?
- 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: Underpinning 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 created?
- U1.8 How do we know what we are seeing?
- U1.9 How do plasma interactions affect planetary evolution?

U2. How do planetary systems work?

- U2.1 How do fundamental plasma processes vary throughout the Solar System?
- U2.2 What fundamental processes exchange energy and material between different components of a planetary system?
- U2.3 What are the processes that have created and modified the crusts, interiors and atmospheres of solar system bodies?
- U2.4 How do we build an holistic picture of planetary magnetospheres?
- U2.5 How are Solar system planets archetypes for planets in other planetary systems?
- U2.6 How common are Earth-like planets in other planetary systems?
- U2.7 How stable are conditions in our Solar System?

Theme 4: Cross-cutting issues

These are listed in alphabetical order, not in terms of priority

C1. Data and Data Centres

C2. Grants and Fellowships

C3. High Performance Computing

Theme 1: Solar variability and its Impact on us

Introduction

The Sun is a fascinating and important object of astrophysical research for many reasons. The first and foremost reason is the vast number of amazing physical phenomena the Sun displays. These phenomena continue to surprise us, despite solar physics being a mature scientific discipline. Long term modelling efforts and repeated observations pay dividends, by evolving a subject from an initial, possibly wrong, superficial interpretation to a complete and detailed understanding of all the physical processes. For example, shortly after the invention of the telescope, sunspots were thought to be either the shadows of undiscovered planets or clouds in the solar atmosphere. Their true magnetic nature was only identified some 300 years later. Solar physics has made great progress over the last couple of decades in increasing our knowledge of both the solar interior and the solar atmosphere. With this increase in knowledge, it is abundantly clear that solar phenomena are more exciting, but also much more complex than we ever imagined – with present day resolution and coverage, we observe intrinsically three-dimensional, time-dependent and usually non-linear behaviour on all length and time scales. This poses enormous future challenges for both observation and theory, requiring the use of innovative techniques and methods. The UK has a proud history of major solar discoveries and developments and the skills required to meet these challenges.

The Sun, our star, is essential for our understanding of other stars. This includes all aspects of solar physics from the solar interior (e.g. energy and magnetic field generation and transport) to the solar atmosphere (e.g. coronal heating, flares) and the solar wind. Methods for the Sun, for example, magnetic field extrapolation and seismology, are now applied to other stars. In addition to other stars, many of the fundamental astrophysical processes we can observe in high spatial and temporal resolution on the Sun occur in other, more exotic, astrophysical and laboratory plasmas. The Sun provides a unique opportunity for understanding physical processes, such as magnetic field generation and evolution, particle acceleration, instabilities, magnetic reconnection, heating, plasma waves, magnetic turbulence and many more. The Sun, together with other solar system plasmas, can be regarded as the Rosetta stone of astro-plasma physics.

The Sun has a direct impact on the Earth and our life. Coronal mass ejections (CMEs) and solar flares can eject enormous amount of material and particles at a tremendous speed within a few seconds. Such rapid intense activity can significantly disrupt the magnetic environment of the Earth with possible disruptions to power grids, radio communications and satellite orbits. In addition, the amount of open flux affects the cosmic rays impacting the Earth's atmosphere. Predicting and forecasting such severe, impending events requires knowing how solar variability can create these phenomena and how they impact on the Earth?

Understanding the variability of the Sun requires a large coordinated effort in connecting together many different strands such as multi-wavelength observations, theory and high performance computing. The UK has about 20 solar research groups and holds a world-leading position within the international solar physics community in instrumentation, observational analysis, MHD theory and plasma physics. The key participation of UK solar physicists is actively sought in major new projects. The UK has held PI roles, for the last 30 years, on the majority of the major international collaborative solar space missions, as well as the highly regarded ground-based helioseismology network (BiSON). Many UK solar scientists have done pioneering theoretical work using MHD framework; work now acknowledged and used around the world to understand/explain various solar observations. Thus, we are well placed for maintaining a leading and productive role in this field over the coming years, with a strategic approach to mission and facility involvement, analysis techniques and theory and modelling.

S1. What are the causes, consequences and predictability of solar magnetic variability and the solar cycle?*need to ref subquestions within text*

The Sun's atmosphere and its behaviour is controlled by the 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 is varying on a wide range of time scales, from the sudden rapid release of energy and mass over a few seconds, through to the propagation of magnetic waves and oscillations throughout the solar atmosphere over minutes and to solar cycle over a decade or so. There are even variations over hundreds of years detected through proxies in geological samples. The main goal 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 particular processes that affect our 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. 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? 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: 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)? Are the small-scale magnetic fields in regions of quiet Sun generated purely by magnetoconvective processes, or do they owe their existence to a small-scale dynamo driven by turbulent convection? This theoretical underpinning of the origin of magnetic activity is constrained by our knowledge of the solar interior through helioseismology. The current experiments have been going for long enough for us now to begin to measure the first gravity modes (oscillations that provide information of the density and temperature near to the centre of the Sun). Continued longstanding ground based helioseismology experiments 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 and even smaller. What is the form of the field in the solar interior and what are the physical process involved? Is there a small-scale dynamo operating just below the photospheric surface? 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? The extreme diversity dynamic solar phenomena evolve on a wide range of timescales and lengthscales. For example: fast dynamical evolution occurs in flares, spicules, surges, heating, CMEs (once the plasma is destabilized); more moderate evolution during active region formation, active region outflows, coronal holes, polar plumes, coronal hole jets, 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. Although they have different properties, they all satisfy the same conservation laws of plasma physics. How does the Sun create such different scales? Once we understand their magnetic formation, we can then investigate their dynamical evolution in more detail.

S2. What are the structures, dynamics and energetics of the Sun? *need to ref subquestions within text*

The magnetic fields, which thread the solar surface, fill and structure the solar atmosphere. This interaction of the plasma and magnetic field produces a number of dynamic phenomena whose size and lifetime evolve over a wide range of length and time scales. Traditionally, the solar interior and the different levels of the solar atmosphere have been treated as separate regions due to the limitations of previous observations. However, the wealth of new multi-wavelength, through both space and ground-based instruments, observations are giving us a simultaneous view throughout the various atmospheric layers. The time is now right to understand how these layers are coupled together. The new high-cadence, high-resolution observations from the Hinode and SDO satellites have shown how incredibly dynamic the entire solar atmosphere is. Transient and explosive events, such as nanoflares to microflares, spiclues, CMEs and flares, occur throughout the solar atmosphere, at all scales. Flows are also prevalent. Key questions are: What is the nature of the coupling between the solar interior, surface and the atmosphere? How is mass, momentum and energy transported from the convection zone to the corona? How does the lower atmospheres regulate the mass and energy supply to the corona?

Magnetogram observations have shown that the distribution of the surface magnetic flux follows a power law over many decades, with many small-scale magnetic elements and fewer large-scale sunspots. Coronal active region loops appear to consist of many threads, with the elemental thread presently unresolved. Key theoretical questions include: Why are there solar structures on different length scales and time scales, and what process is responsible? How do these solar magnetic fields evolve dynamically? What is the magnetic nature and properties of the elemental thread and why? The large-scale coronal magnetic field is built up from these structures and its subsequent evolution will depend on the magnetic topology. How does this topology change over various time scales?

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. The transfer from the interior is either through direct transfer by the emergence of magnetic fields or through the propagation of waves/oscillations along magnetic structures. 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? How is this energy transported and distributed in closed and open magnetic field regions? 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? How do waves propagate in a highly stratified and structured magnetic environment? How is the plasma in open field regions accelerated to produce the solar wind? How do fields, flows and particles interact in the solar atmosphere? How does the global magnetic field store energy over periods of months to years? 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 of magnetic energy into other forms of energy, 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: 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. 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, 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, but 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. But testing theories of shock acceleration 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 earlier solar activity and flare accelerated particles. Due to the efficiency of energetic particles to emit 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.

It has always been assumed that the solar 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 require 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. 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 both observations and theoretical modelling with HPC that we will solve these major problems. Once the underlying physical processes are understood, we will be able to make predictions.

S3. What are the underlying processes that drive the Sun-Earth connection, and similar processes throughout the heliosphere?

The Sun-Earth system is readily accessible by both spacecraft and ground-based observations making it an ideal laboratory for studying universal plasma processes. Many of these processes are common throughout the solar system, although the local conditions at other planetary bodies may vary. An understanding of these processes has applications both to space weather monitoring and in providing insight into a wide variety of astrophysical processes throughout the universe.

S3.1 How does the solar wind, including transients, evolve throughout the heliosphere, and can we predict/forecast conditions at Earth?

The solar wind, carrying with it the solar magnetic field, and its interactions with bodies within the heliosphere can have a profound influence on their environments. It is thus critical that both the origins at the Sun, and the evolution of the wind and magnetic field, are fully understood in order that we can understand the variations that we see in situ and their subsequent impact on the Earth and other solar system bodies. Such understanding is essential to underpin further research into predicting the propagation of solar wind transients (CMEs and geoeffective high speed streams) 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. This is one of the fundamental drivers for the Solar Orbiter mission, in which the UK has already made considerable investment. Solar Orbiter will approach the Sun to 0.28 AU and will be unique in combining in situ observations with high resolution imaging and spectroscopic observations closer to the Sun than ever before both in and out of the ecliptic plane. 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 evolution of the ambient solar wind in the inner heliosphere can be used to model the propagation of CMEs through this environment and their interaction with it. Improved observational knowledge of solar wind evolution in the inner heliosphere will lead to subsequent improvements in the models.

With the advent of space borne heliospheric imagers such as the Solar Mass Ejection Imager onboard the Coriolis spacecraft and the STEREO Heliospheric Imagers, our ability to track solar wind transients (including coronal mass ejections, co-rotating interaction regions and isolated plasma blobs) 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 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 at an atomic level. For it to be useful to operators of ground or space-based technological 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 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.

Current operational forecasts use estimates of the initial speed and direction of a CME measured with coronagraph data and propagate these through a background solar wind derived from a statistical relationship between solar wind speed and observations of the solar magnetic flux. An improved physical understanding of the acceleration processes involved is necessary to improve the accuracy of such forecasts.

S3.2 What constitutes a geoeffective event and can such events be forecast?

Extraction of energy from the solar wind is a highly complex process. While advances have been made in the 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 geoeffectiveness of an event is strongly dependent on the direction of the heliospheric magnetic field in the locality of Earth, both in the sheath region upstream of the transient and embedded within the transient itself. If the direction of this field is opposite to the Earth's (a southward HMF or negative Bz), this maximises the efficiency with which the two fields can merge through 'magnetic reconnection', allowing energetic solar wind plasma to enter the Earth's magnetosphere and, as the solar wind continues to travel past Earth, the two interconnected fields stretch the Earth's field into a long magnetotail. The two fields eventually disconnect downstream in the solar wind and the distorted magnetic field snaps back towards Earth, accelerating plasma and generating auroral substorms. 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.

Despite its importance the only way to currently predict this quantity is via in-situ measurements at the ACE spacecraft, orbiting the L1 point approximately 0.01 AU upstream of the Earth in the solar wind. Such measurements provide advanced warning of the geoeffective nature of an event only about 40 minutes prior to its arrival at Earth. Developing techniques to measure the polarity of the HMF embedded in a transient well ahead of its arrival at Earth would be a major advance and would be of great strategic value to future space weather forecasting capabilities.

While there has been a considerable body of work investigating the relationship between the orientation of the magnetic field in the solar atmosphere at the source of the solar wind transient and the direction of the HMF within a transient at 1AU, there are considerable uncertainties in tracking these complex magnetic field structures all the way to Earth. Several techniques have been proposed to measure this quantity directly: 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; a single spacecraft orbiting much closer to the Sun than the current L1 point using a solar sail to balance the forces necessary to keep it up-stream of the Earth; use a ground-based radio telescope to measure the Faraday rotation of the signal from astronomical radio sources as it passes through the solar wind. Of these, the first has been proposed by scientists in the USA, the second is dependent on the proof of technology of the solar sail and the third, while feasible, would require a demonstration to prove the concept.

S3.3 How does the magnetosphere/ionosphere/thermosphere system emerge from its interaction with the solar wind?

One of the great challenges in solar-terrestrial relations is dealing with the vast range of scale sizes involved. The complex nature of the structure in solar wind transients is apparent from both spacecraft images and solar wind models. In both cases, it is important to note that the Earth lies within a single point in an image or model grid. 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 Earth-radii in extent into an area around the size of a continent. Under different levels of forcing from the solar wind different parts of this coupled magnetosphere-ionosphere-thermosphere 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. 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.

Particle acceleration processes throughout the solar system are extremely important to understand if the consequences are to be accurately predicted. The flux of particles precipitating into the Earth's atmosphere is a good example. 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. In addition to investigating particle acceleration processes as a means of understanding complex plasma physics, such knowledge is also important in accurately predicting 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.

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 and it is important to ensure that science at the boundaries of research council remits is enabled through consultation between research council strategies.

S3.4 What are the processes that cause enhancement/loss of radiation belts around planetary bodies?

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. 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. 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.

S3.5 What is the nature of the coupled solar wind-magnetosphere-ionosphere-thermosphere systems at the ice giant planets?

The magnetospheric configurations of Uranus and Neptune differ significantly from those of the gas giants due to 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. It is known, however, that the upper atmosphere of Uranus is dominated by seasonal effects despite the very weak insolation at these distances. All these aspects require significant future study.

The ability to detect and study exoplanets via their auroral radio emissions is a growing theoretical area in which the UK has a lead, however these radio emissions from Uranus are quite unique. Exoplanet observations show us that exoplanets with a mass similar to Uranus/Neptune are common, thus requiring a deeper understanding of the generation of these auroral radio emissions which rely critically on the nature of the coupling between the solar wind, magnetosphere, ionosphere and thermosphere.

Most of what we know about the above topics derives from the Voyager-2 fly-bys ~25 years ago, together with on-going ground-based observations of IR H_3^+ emission at Uranus. Observations of UV auroral emission from Uranus have only recently been obtained using the HST, while IR H_3^+ emission has yet to be detected from Neptune. Major progress requires future IR observations using the ELT and JWST. In addition, serious planning consideration needs now to be given to future ice giant orbiter space missions.

UK Strengths and Areas of Excellence relevant to Theme 1

The UK is internationally competitive in many areas, and especially in aspects of MHD and plasma theory, data analysis and instrumentation. As described above these areas are inter-linked.

1. Theory. The UK has several internationally recognized theory groups working on large-scale simulations, mathematic modelling and atomic theory

   a. Developments in large-scale simulations, through the DiRAC High Performance Computing facilities are essential to maintain our world leading research. HPC facilities are used in understanding all of the key questions in solar physics.

   b. The UK has led the way in understanding MHD wave theory in the solar atmosphere and the development of coronal seismology to use the observed wave motions to determine the local plasma properties.

   c. The UK has a long history in the detection and interpretation of global oscillations of the Sun. Helioseismology is a key tool in understanding the solar interior and recent developments has shown the existence of the tachocline at the base of the convection zone.

   d. The particle acceleration and transport problem is a key problem in solar flares. Several UK groups are internationally recognized experts in this area, as can be judged from the number of UK chapters in the forthcoming RHESSI volume.

   e. UK groups are internationally leading in the provision of atomic data for the interpretation of atomic spectra from spectrometers. CHIANTI is the preferred atomic physics package throughout the international solar community.

2. UK solar scientists have well-established expertise in the use and analysis of many disparate datasets, with excellent track-records in the use of UK-led and non-UK-led instrumentation. Many novel techniques developed for this purpose are widely used internationally.

   a. Helioseismology data from the BISON network provides a unique long-term dataset that is critical to making the breakthrough in understanding the solar dynamo. UK scientists also hold key science roles in the major existing international (SOHO, GONG, PICARD, Hinode) and forthcoming missions in helio and astroseismology (SDO, Solar Orbiter). We lead the international Solar FLAG efforts to search for g-modes.

   b. Spectroscopic observations of the solar atmosphere, combined with the essential atomic physics expertise to develop plasma diagnostic tools has been a key international strength in the UK for many years, underpinning research into most solar atmospheric phenomenon. UK scientists have successfully exploited spectroscopic and associated imaging data from recent and current missions and our spectroscopic strengths are highly sought after internationally.

   c. Emergence, evolution and eruption of magnetic fields and the tracking of the associated disturbances through the heliosphere to their impact at Earth. This includes the developing field of Heliospheric Imaging, in which the UK has played a leading role, with SMEI and STEREO; the UK STEREO HI instruments for the first time allow CMEs to be tracked from their solar origin to the Earth.

   d. Solar wind and interplanetary scintillations. The UK involvement in Ulysses and Cluster, together with supporting theory, has produced much ground-breaking work in our understanding of the solar wind and its interactions within the heliosphere. UK has a key role for the UK in the area of interplanetary scintillation within the LOFAR consortium. New results from Hinode from within the UK are for the first time providing concrete evidence of the origins of the solar wind in the low corona.

3. Solar space instrumentation is principally concentrated at RAL and MSSL, with the emphasis on spectroscopic imaging of the outer solar atmosphere and heliospheric imaging. These groups have led major international consortia for such instruments over the past three decades (e.g. recently SOHO, Hinode, STEREO) and have a world leading reputation in the associated science. UK also excels internationally in the provision of CCD and APS based camera systems and CCD detectors, and this is a key link to UK industry (e2v and Andor Technology). The recent ROSA instrument, developed by QUB, is being base-lined as one of the first generation instruments for the U.S. Advanced Technology Solar Telescope (ATST) and potentially for the European Solar Telescope (EST).

4. The UK magnetospheric and plasma science community has a long record in data analysis, theory and instrumentation

(magnetometry, plasma detectors and imaging) to study the magnetosphere of the Earth and Space Weather, and in exploring other planetary magnetospheres. Imperial College, MSSL, RAL, Sheffield, and Sussex have all provided instrumentation for magnetospheric studies on both European and NASA spacecraft. Aberystwyth, Leicester and RAL have a long history of utilising ground-based observatories to carry out magnetospheric studies. The UK has considerable international success in studying: radiation belt and auroral particle acceleration; energy storage and release mechanisms in planetary magnetotails; magnetic reconnection; auroral and magnetospheric processes at the giant planets; and fundamental magnetospheric plasma physics processes at magnetospheres across the solar system and beyond.

Theme 2: Planets and Life

Introduction

The origin of the Solar System and the question of "are we alone?" are some of the oldest and most profound questions in humanity. We are now at an epoch where significant progress is being made into understanding these aspects of our distant past and place in the Universe. We may be the first humans to find out whether there is life beyond Earth. The UK planetary science community is engaged in a variety of fundamental planetary science investigations targeted at understanding our Solar System and 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 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. 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. 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.

The UK community is considerably active in the search for life beyond Earth and is involved in research searching for the evidence for past or present life. Our understanding of the habitability of planetary environments is now moving beyond the pure consideration of the "Goldilocks" zone of habitability to include wider environments in the Solar System, such as the warm environments inside the icy moons of the giant planets, and is extending our understanding of the bounds of habitability. Research is ongoing into determining the biomarkers that are the signs of life, and how these signs degrade due to environmental effects.

The populations of exoplanets that have been discovered in our local group of stars in the last few decades have revealed a staggering variety of planetary systems very different to our own Solar System. The complete investigation of our own Solar System is essential in providing ground truth for understanding exoplanets. Terrestrial planets are also starting to be discovered in extrasolar systems. While it will be at least a decade before we have terrestrial planets in the habitable zones of their stars that are bright enough that we can confirm and characterise their atmospheres. Nonetheless, in the long term this method promises to show us a range of different classes of terrestrial planets (comparative planetology) from which we can learn about the evolution of our own planet.

Studies of other planets can inform us about some of the major dangers faced by our civilisation on Earth, such as magnetic field reversals, asteroid 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 will yield data about the nature of asteroids which may be of major importance in understanding the potential for major impacts on Earth. Furthermore, as we use up the resources of our own planet, we may ultimately need to explore and exploit the resources of other planets.

P1: How did the Solar System form and evolve?

This fundamental question reaches to the heart of research in planetary sciences. 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 the planets of our Solar system are archetypes for planets in other solar systems. To this end, we undertake studies of early solar system material, in the form of asteroids, comets, primitive meteorites, and inter-planetary dust-particles. Within this material, we can find pre-solar grains (derived from supernovae that exploded prior to the birth of our Solar System), refractory grains (the earliest solid particles formed in the solar system), chondrules (formed 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). Material left over from the formation of the

Solar System (comets, asteroids) are 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 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?

Following accretion of these particles into small planetesimals and then planets, the interiors, atmospheres and magnetospheres evolved following key sets of underpinning processes (U2). These processes lead to the observed structure of the other planets and natural satellites within the Solar System. 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 our Solar System is not common in our local group and we now generally accepted that the planets have undergone orbital migration through tidal interactions between planetesimals, planets and the protoplanetary disc. However, the question of how the planets arrived at where we find them today (P1.5) has not been comprehensively answered. These questions can be addressed via studies of meteorites derived from differentiated asteroids, lunar and martian samples (including future sample-return missions), and ancient planetary surfaces such as those of Mercury, Callisto and the Moon.

It is now becoming clear that Solar radiation is as fundamental as gravity in driving the physical and dynamical evolution of small asteroid bodies via the YORP and Yarkovsky effects (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) Exactly 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 is YORP and Yarkovsky is 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 these forces acting on them, and is YORP 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. We have little understanding of how solar radiation and solar plasmas have affected the formation and evolution of other solar system bodies, from comets to full-scale planets. Our knowledge of the physical and compositional properties of cometary nuclei and related populations like the Kuiper Belt is limited. Most detailed knowledge of the former comes from the limited number of spacecraft missions to these bodies.

P2: How widespread is life in the Universe?

“Is there life beyond Earth?” is one of the oldest questions of humanity. We may be the first humans to find an answer. The Solar System contains (or has contained) a great diversity of planetary environments, many of which contain some or all of the essential requirements for life as we understand it: presence of liquid water, an energy source, nutrients, and stable sheltered environments. Exploration of planets and satellites where such conditions exist (or have existed in the past) offers us the best possibility of detecting evidence of life elsewhere. The detection of extinct or extant life critically relies on the detection of appropriate biomarkers and a key question currently being explored (part of this being led in the UK) is what are the biomarkers and how are these biomarkers affected by environmental effects such as oxidising chemistry and radiation (P2.1).

A key point in the development of life is in the formation of prebiotic molecules and we have a crude understanding of the origin of these molecules. Research is ongoing into the fundamental chemical processes that lead to these molecules and 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, either on terrestrial planets or the icy moons of the giant planets. Ongoing research will lead to a more complete understanding of these processes and how life forms from such molecules (P2.2).

Our understanding of habitability is now moving beyond the pure consideration of the “Goldilocks” zone of habitability to including wider environments in the Solar System, such as the warm environments inside the icy moons of the giant planets, and is extending our understanding of the bounds of habitability (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 ongoing), 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 to investigate places within the Solar System in which there is or was liquid water and sheltered habitats (e.g. Mars, some icy moons of giant planets), but also areas where ice-water has been sequestered since early solar system times, such as the south pole of Moon, craters of Mercury, Main Belt Comets and other cometary populations, and the Kuiper belt.

The key science investigations required to answer this question 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 bio-essential 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. Beyond our Solar System it is important to determine the effect of stellar class on these processes.

In terms of solar 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. We are searching essentially for markers of rudimentary life-forms, both in the Solar System and elsewhere, but within the scope of this topic, we are also searching for the answer to the question: how many steps are required to evolve from inanimate dust to human cognition? 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?)

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 are 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.

The early Earth and its Solar System environment preclude the formation of Earth's oceans in situ and so it is generally accepted that Earth's oceans must have been transported to the Earth via cometary and/or 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 in comets was found to be incompatible with that of Earth's oceans. A new population of volatile-bearing bodies was recently uncovered in the Main Belt, that may very well have formed in-situ. The Main Belt Comets (MBC) now represent an opportunity to sample volatile material – readily accessible by spacecraft – that formed at its present location in the solar system. Such data would be hugely valuable for early Solar System formation models. 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? Only on-going theoretical modeling 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) are necessary to answer these key scientific questions in the evolution of Earth and the emergence of life on Earth.

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. 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.

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

Our increasing understanding of the environments and history of other planets within our solar system is revealing a great deal of information which can be used to shed light on the origin and evolution of our own planet, 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). 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.

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 the due to 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. The presence of heavy organics in the nitrogen-rich atmosphere of Saturn's largest moon Titan and their suspected 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 exploitation of planetary resources has recently become of international interest and UK expertise can play an important role in this effort (P3.4). 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. In the latter case 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.

UK Strengths and areas of excellence relevant to Theme 2

The UK has some of the best equipped analytical laboratories in the world for the analysis of extra-terrestrial material (e.g. involvement in Stardust and Genesis missions), short-lived radionuclides, noble gases, light elements, etc. UK expertise in isotope and analytical geochemistry is world-renowned. Continued investment in mass spectrometry and micro/nano geochemical analysis will be required to maintain our position at the forefront of cosmochemical research. UKCAN (Cosmochemical Analytical Network) is an example of how access to facilities is well-established between different laboratories nationwide.

UK scientists have been involved in recent discoveries with the Cassini mission (e.g. dynamic atmosphere at Enceladus heavy ions in Titan's atmosphere; ring system at Rhea), and have constructed the first global time-dependent models of the upper atmospheres of the gas giants and Titan. UK scientists are participating in research and modelling relating to data from Venus Express and Mars Express. They are also working on developing a range of geophysical instruments (penetrometers, microseismometers) which will enable us to investigate the interior of planets such as the Moon (via MoonLite) and Mars (via Aurora). The UK has world-leading technology and expertise in X-Ray spectrometers for mapping the chemical composition of planetary surfaces such as the Moon (Chandrayaan-1) and Mercury (BepiColombo). 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 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.

UK teams are also involved in developing and utilising instruments for analysis of the composition and dynamics of planetary atmospheres, including Mars Express, Mars Climate Sounder (on MRO), Venus Express and Cassini. They have played major roles in developing software for climate statistics and numerical models for the climate of Mars, Venus and Titan. Via participation in the Cassini and Mars/Venus Express missions, future participation in Juno, modelling and the use of HPC, and use of ground-based telescopes, the UK has become a world leader in the study of planetary atmospheres and their interactions with their parent planetary bodies and magnetospheric environments. This area of excellence will continue with ongoing support for exploitation of Cassini and Mars/Venus Express data, exploitation of Juno data, support for JUICE and EChO, and access to ground- and space-based observatories.

Astrobiological research is a major strength of UK scientific activity. Remote sensing of the surface of Mars has revealed evidence for the previous existence of liquid water and the present existence of water ice. In terms of attempting to detect life, UK teams have built miniaturised mass spectrometers, X/γ-Ray spectrometers, Gas Analysis Packages, environmental sensors, and IR microscopes. UK groups have also lead projects on characterising the nature of life in extreme environments on Earth, and characterised microorganisms in samples exposed to space conditions in orbit. The UK has played a lead role in understanding the decay of biomarkers via oxidising and radiolytic processes with critical implications for the search for extinct life on Mars and other Solar System bodies.

The UK is a world leader in the study of planetary magnetospheres and their interactions with moons, rings and their parent planets through participation in Mars and Venus Express, Cassini, Juno, JUICE, and related studies at Earth. Future support for missions and facilities that enable the study of planetary magnetospheres, such as Cassini, JUICE, Gemini and Uranus Pathfinder will ensure this continued key role.

The UK currently leads the world in ground-based transit surveys for exo-planets (e.g. WASP, SuperWASP, WFCAM Transit Survey) and is heavily involved in other methods of exo-planet detection (microlensing; ground-based imaging; radial velocity detection. Through the WASP and SuperWASP systems the UK has pioneered the low-cost discovery of exoplanets and the UK is playing key roles not just in the discovery of new exoplanetary systems, but now taking the important step of characterising these systems as planetary bodies through the EChO mission led by the UK. The UK has quickly developed a network of international competitive groups working in many areas of observational and theoretical exoplanet research. For large planets the SuperWASP project has been the most prolific exoplanet discovery machine and this expertise has led to the development of the Next Generation Transit Survey (NGTS) being constructed at Paranal in partnership with ESO. NGTS is capable of detection of large terrestrial planets in the habitable zone of low luminosity stars. In the area of radial velocity detection, UK researchers have been central in the AAO Planet Search and are collaborators in the HARPS-N follow-up of Kepler candidates. In microlensing surveys, UK researchers have produced software tools that allow efficient targeting and scheduling of potentially important objects. A number of groups are developing leading observational and theoretical studies of exoplanet atmospheres. In theoretical areas we have renowned experts in composition and dynamical evolution. The UK has also developed leading positions in asteroseismology and its application to planet host stars.

R4: Underpinning Processes

Underpinning these important science questions are a broad range of fundamental physical and chemical processes that are essential in answering these questions. These also represent important science questions in their own right and are important to answer in order to advance our understanding of Solar System and astrophysical processes, where solar system science can provide critical in situ measurements. The UK demonstrates considerable international leadership in moving towards answering these questions.

U1. What are the fundamental processes at work in the solar system?

U1.1 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 also offer important diagnostic information about the highly-structured plasma medium through which they propagate, giving enormous potential for solar, stellar and other astrophysical seismology. The current generation of high-precision solar system observations have revealed the importance of plasma structuring on wave propagation. 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 plasma inhomogeneities, which could evolve dynamically on timescales similar to the wave periods? 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 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, what state does an unstable magnetic field relax to? How do small-scale current sheet instabilities grow and contribute to large-scale magnetic reconnection events?

U1.3 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 will have 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 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 are plasma instabilities triggered, or damped, by turbulence? 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 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?

U1.6 Solar system plasmas exist under a wide 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. Largely due to the vast difference in length and time scale ratios (10^6 -10^{10} for typical solar system plasmas) this cross-scale coupling is not yet understood. Without understanding cross-scale coupling, theories of plasma heating, particle acceleration/transport and the interpretation of observations, e.g. of solar radio emission, will eventually remain incomplete. Another fundamental point is to understand 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 due to 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 The 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, planetary radiation belts, and energetic particle populations observed in planetary magnetospheres. Some of the key processes, for example 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 in, e.g., solar flares, 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 In order to capitalise on current and future solar missions, laboratory astrophysics should be an integral part of current and new investments, as recommended by ASTRONET. The UK has traditionally been leading atomic and molecular calculations with high performance parallel computing, to provide data to the wider astrophysical (and fusion) communities. Adequate investments in both staffing and HPC hardware must be made to maintain this area of research above a critical level that will guarantee the survival and continuity of this UK expertise. The UK has also been leading the 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 is featuring 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 the plasma dynamics. The UK has a strong expertise in solar spectroscopy, and is involved significantly in many 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. Adequate investments over the next few years should be made to maintain UK expertise in solar spectroscopy.

U1.9 Equipped with an understanding of space plasma physics it is important to apply this at a system level to understand how plasma interactions between flowing plasmas and planetary bodies (both airless and with thick atmospheres) so we can understand how these processes affect the evolution of planetary surfaces, atmospheres, and volatile budgets. Recent missions to the giant planets have demonstrated a critical role for dust in the atmospheres of moons, the ejection of volatiles from the interiors of icy moons and the resurfacing of icy moons, and the plasma physics of the interaction between icy moons and their parent magnetospheres. How important are these dust plasma effects in the wider context of planetary science? For example to what extent do dusty plasma processes participate in complex chemical processes leading to the formation of very heavy ions and pre-biotic chemistry?

U2. How do planetary systems work?

U2.1 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, for example 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 A fundamental question for plasma physics is how energy is transported, converted and released. In a Solar System context, a similar question concerns the exchange of energy and mass between the different components (interiors, surfaces, atmospheres, magnetospheres, rings, moons) of a planetary system. Key science questions include: How do different energy sources drive planetary atmospheres? How does sputtering and transport distribute mass between rings and moons? What processes occur in the interior of moons to bring volatiles to the surface and to eject them into space?

U2.3 To properly understand the formation and evolution of the Solar System, 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.

U2.4 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?

U2.5 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?

U2.6 A critical question with wide importance, both scientifically and societally, is to identify how common Earth-like planets are in other planetary systems

U2.7 Within our Solar System we find a variety of planetary science environments whose characteristics vary on a number of timescales. Key science questions include: How stable are the environmental characteristics such as radiation and meteoroid flux? What is the seasonal variability of planetary atmospheres, on what timescales do planetary systems change? On what timescales do habitable zones last what implications does this have for the development of life, particularly related to planetary bombardment?

UK Areas of Excellence relevant to Underpinning processes

The UK has excellence in all areas of these underpinning processes and has international leadership in many areas. *To be completed*

Theme 4: Cross-cutting requirements

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 fully exploited. Storing data is not just a matter of putting data files on some 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. Only then is it possible to use these data secure in the knowledge that their limitations are known. 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. Additional resources are required to preserve such archives which, by their nature are also less accessible for scientific research.

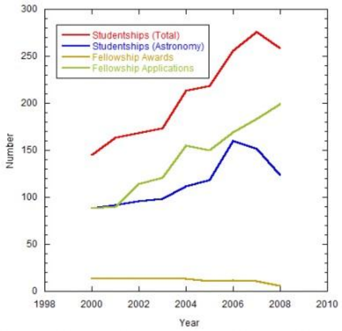
Many high-profile experiments (such as the search for the Higgs boson) while of fundamental importance, are not bound to a particular time and, if there was the political or scientific will, could be recreated long after the original experiment has ended. This is not the case with data gathered for environmental monitoring purposes. Many of the datasets that are being 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. For example, a very large sunspot group formed on February 11th 1917. It may seem unnecessarily obvious to state but this date will never occur again. We must preserve what information we have.

The solar system provides a wonderful opportunity to study some extreme astronomical environments at relatively close quarters. Unlike traditional laboratory experiments however, it is almost always impossible to influence the medium being studied and the range of environmental conditions or 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 does not currently have a data policy. While STFC missions (some now funded by the UKSA) archive their data through existing data centres such as the UK Solar System Data Centre (UKSSDC) at the Rutherford Appleton Laboratory, this process is funded through the post-launch support for each mission. Core funding for such data centres is minimal. While historical and active data sets are made available, there is no requirement for these data to be accessible after a mission has ended. 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.

C2. Grants, Fellowships and Studentships

The best analytical facilities in the world are useless if they have no staff to run them. 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. 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 (Figure X). Also shown is the steep increase in the number of applicants for Fellowships – showing that we are disappointing (failing?) a higher number of gifted researchers each year. *To be completed*



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

C3. High Performance Computing

(HPC) for solar system research and, indeed, for all STFC theoretical research. The increase in computing power means that problems that were only dreamt about, 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. MagnetoHydroDynamics (MHD) modelling requires the numerical solution of eight coupled, nonlinear, partial differential equations. These codes 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. However, additional physical processes, such as optically thick radiative transfer can be included and, by including the instrument response functions, it is now feasible to compare directly the outcome of theoretical simulations with high-resolution observations. Kinetic Theory requires the solution of the plasma distribution function, a function of 7 independent variables (space, velocity and time) and Particle-In-Cell methods are now bridging the gap between kinetic and MHD scales. It is essential that the UK remains competitive with overseas scientists. In addition to the HPC needs of simulations, data analysis also requires significant HPC resources. The present space missions generate around 1 Tb of data per day and accessing and processing this data is a major undertaking.

Hence, access the HPC facilities is essential to analyse, interpret and understand the observations.

In our quest to exploit, understand and interpret the data from our observational facilities, a full theoretical description is entirely dependent on HPC simulations. These become more sophisticated and computationally demanding as our observational facilities scrutinize the solar system in greater depth and detail. HPC facilities should be seen in exactly the same light as an observational facility. Both are essential in our goal to understand the solar system. The direct comparison between observations and simulations is much stronger now, since output from simulations can be processed, using the appropriate instrument response functions in a technique known as Forward Modelling. The UK has traditionally been, and continues to be, a recognized world leader in computational MHD. The first ever simulations of magneto-convection in the 1960s were undertaken in the UK. The UK has a tradition of writing and developing our own codes.

This tradition is a major benefit to UK PhD students. The code writers are supervising them and PhD students with good HPC skills are highly sought after in non-academic positions.

A few of the key science areas dependent on HPC facilities are: (i) dynamo modelling, magneto-convection, flux emergence and global coronal field evolution within S1; (ii) MHD wave propagation in inhomogeneous plasmas, MHD instabilities, magnetic reconnection, coronal heating, particle acceleration within S2 and S3; (iii) heliospheric and magnetospheric simulations, plasma wave generation and wave-particle interactions within S3; (iv) modelling impacts, ring and accretion disc dynamics, and orbital evolution in P1; (v) modelling planetary atmospheres in P1,P3; (vi) and across the full range of underpinning principles (U1-U3).

To remain competitive in the critical area of HPC expertise, STFC must develop a clear and appropriate funding strategy for HPC. The recent investment in DiRAC was an unexpected windfall from BIS and STFC must ensure this investment is used wisely. There are two main models for HPC provision, either place all the compute nodes all at one site or maintain several, smaller but still extremely powerful, machines at University campuses and invite the host University of enhance the machine by adding more nodes to it. In addition, there should be a coherent plan for hardware refresh, since hardware improvements are advancing at an impressive rate. With several machines spread around the UK, it is easier to upgrade one machine at a time than to upgrade just part of a large national facility. A sustainable strategy for HPC is an essential requirement for the UK to remain at the forefront of world science and this applies to all science and not just STFC science.

In comparison to ground based and space based instruments, the cost of maintaining HPC is minimal. However, in addition to the hardware, PDRAs are required to assist the academics. Continued training in HPC, through annual summer schools, will ensure that our computational methods remain up-to-date.

C4. Laboratory facilities.

Timeline of Solar System Research

Note: this table is incomplete please let us know if your favourite mission is missing

Theme	Question	Mission or Facility			
		Currently operational	**Near-term operational (2013 - 2016)**	**Medium-term operational (2016 - 2020)**	**Long-term operational (2020 - 2030)**
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; SDO; RHESSI; ROSA; HiC	Solar-rocket studies (2013-15)	Solar Orbiter (2017); KuaFu (2017); Solar-C (??); ATST (2017); EST; IRIS	SMEX (??) SPARK (??)
	What are the structures, dynamics and energetics of the Sun?	SOHO; STEREO; Hinode; SDO; RHESSI; LOFAR; ROSA; HiC	Solar-rocket studies (2013-15)	Solar Orbiter (2017); Solar-C (??); ATST (2017); EST; IRIS	SMEX (??); SPARK (??)
	What is the nature of the Sun-Earth connection, and what are the underlying processes that drive it?	SOHO; STEREO; Hinode; SDO; RHESSI; LOFAR; Cassini/Huygens; Cluster		Solar Orbiter (2017) CENTINEL Pathfinder (+5yrs from now) KuaFu (2017)	CENTINEL (+10yrs from now) Alfven (2025+) SMEX (??) Lunar Lander (2025+)
Planets and Life	How did the solar system form and evolve?	Cassini/Huygens; SuperWASP; Venus Express; UKIRT; ING; HARPS-NEF; UK CAN	NGTS (2013); Rosetta; JWST; GAIA	Bepi-Colombo; Sample Return Curation facility	Uranus Pathfinder Main Belt Comet mission; Lunar Lander (2025+); Marco-Polo-R; JUICE; ExoMars; E-ELT
	How widespread is life in the Universe?	Cassini/Huygens; Venus Express; UK CAN	Rosetta; JWST; GAIA	Sample Return Curation facility	Uranus Pathfinder Main Belt Comet mission; Lunar Lander (2025+); Marco-Polo-R; JUICE; ExoMars; E-ELT
	What do other planets tell us about the Earth?	Cassini/Huygens; Venus Express; UKIRT; ING; HARPS-NEF; UK CAN	Rosetta; JWST; GAIA	Bepi-Colombo; Sample Return Curation facility	Lunar Lander (2025+); JUICE; ExoMars; E-ELT
Underpinning Processes	What are the fundamental processes at work in the Solar System?			CENTINEL Pathfinder (+5yrs from now)	CENTINEL (+10yrs from now); Fresnel Lens Imager for Proba-3; Alfven (2025+)
	How do planetary systems work?				

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 and other funding sources). Any prioritisation process is painful, and has the potential to divide a community, rather than unite it. In recommending priorities within the Roadmap, the SSAP has taken cognisance of several parameters. Scientific excellence was, as ever, the main driver for the prioritisation, but following from that, the following indicators were considered: the international significance of the project; the extent of UK leadership; timeliness; …………The SSAP did not feel it appropriate to give a complete ranked list of all projects; rather, they were banded into High, Medium and Low priority **for the 2013 prioritisation process**. The emphasis is placed on the 2013 timeframe – it **must** be recognised that many projects have a very long lead-in time; this might gain them a Low priority for the current prioritisation, but **must not** result in them being denied appropriate resources.

High Priority Projects

Medium Priority Projects

Low Priority Projects

The above three sections will be completed and sent out separately following further discussion.