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Roadmap for Solar System Research

2022

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

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Executive Summary[1]

1. Solar System research is a fundamental part of the overall UK research endeavour and is internationally recognised as world leading in many aspects, including contributions to the development and operation of facilities, missions and instrumentation, as well as scientific output and public engagement.
2. Three overarching Solar System research themes encompass the key scientific questions to be addressed in the near to mid-term. These themes are: (1) Solar Variability and its Impact on Us, (2) Planets and Life and (3) Space Plasmas. We note that whilst the key questions are similar to previous Roadmaps (thus emphasising the foundational and fundamental nature of these problems), they have, of course, evolved in response to our growing understanding.
3. The Roadmap recognises specific strengths where the UK is particularly well-placed to make significant contributions, in terms of observation, experimentation, laboratory analysis, simulation and numerical modelling. Alongside each theme we describe specific space missions and facilities (national and international) that are required to help deliver the research goals.
4. Since the 2015 Roadmap, there have been a diverse range of notable successes in Solar System research that the UK has either led or played a prominent role in. These include the successful deployment of MIRI on the James Webb Space Telescope, the recovery of a pristine UK meteorite fall via a fireball network, and the launch of the MIXS-T X-ray telescope on BepiColombo mission to Mercury. First images from DKIST, with STFC-funded UK camera technology, showed the Sun's surface in unprecedented detail, whilst ESA's Solar Orbiter and NASA's Parker Solar probe are furthering our understanding of the Sun's atmosphere. The UK space science community continues to provide leading science across the three themes that are described in this Roadmap. Community inputs to the roadmap have highlighted that in the next few decades an exciting range of new ground-based and space mission opportunities will expand our knowledge of all three Solar System themes, from space weather to sample return and the search for life beyond Earth. Exoplanet research is now opening up new ways of understanding our own Solar System.
5. Solar System science is multi-disciplinary, with increasing links beyond STFC to Research Councils covering biology, chemistry, physics, earth sciences and computer science (AI), and, very importantly, with UKSA (mission related support, aerospace engineering, etc.).
6. There are several cross-cutting activities that are essential for successful delivery of the goals outlined in this Roadmap. These activities are also relevant to the research activities of the other communities funded by the STFC and are (in alphabetical order): Data centres and data archiving; Grants, Fellowships and Studentships; High Performance Computing and Laboratory Equipment and Infrastructure and Telescopes. As budgets have got tighter over the last decade, and as Brexit has changed the routes by which grant money can flow into UK science, it becomes even more important that these activities are not neglected but recognised as essential and integral parts of the research environment that require funding.
7. Solar System science is a broad ranging subject, and this Roadmap does not prioritise one Solar System body above others. The diverse nature of objects studied by the science community leads to equally diverse requirements in facilities and missions.
8. Astronomy in all its forms is a UK strength. The UK strength is across the breadth of the field, from planetary science to cosmology. There is a clear consensus on the key science questions to be addressed, and these require access to a wide range of facilities and capabilities, many of which address multiple key science questions. International partnerships (e.g. ESA, ESO, SKA and bilateral programmes) are extremely important in order for the UK to play leading roles in international science teams, including across Europe. A strong relationship with UKSA and ESA, and engagement with their plans, is also essential. The UK astronomy programme is naturally split across several STFC advisory panels (e.g. AAP, SSAP, PAAP), but there are many synergies, in terms of the need for access to exploitation funds, the support for theoretical studies, training & skills, computing resources, instrumentation and technology development, etc. The advisory panels are therefore not in competition but rather are synergistic, and where there are overlapping interests there is concordance over the science and technology aspirations.

Summary of Recommendations

Recommendation: SSAP recommends that STFC further strengthens its efforts and commitments to ensuring that the Solar System community reflects the diversity of the UK population and uses examples of best practice from the UK Solar System community to influence more widely, within UKRI and beyond.

Recommendation: SSAP recommends that STFC builds on the success of programmes such as e.g., SWIMMR to articulate the importance of UK Solar System Science within UKRI, and to continue to work with the UK Solar System Community to identify and secure long-term support outside of core Research Council budgets.

Recommendation: The 'dual-key' funding approach between the UK Space Agency (UKSA) and the research councils continues to present challenges in ensuring that the funding process is agile, transparent, and effective. SSAP recommends reviewing the relevant advisory and governance structures to make sure opportunities are fully visible to both sides to maximise mutual benefit. The UKSA Aurora space exploration programme offers one successful model which has integrated instrumentation development and science exploitation.

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[1] Front cover image credits: NIRCam image of Jupiter, JWST NASA/ESA/CSA/Schmidt

Recommendation: SSAP recommends that STFC continues to support UKSA in its investment in ESA's Science, Human and Robotic Exploration, and Space Safety Programmes, recognising the value that this investment brings to supporting and sustaining the UK Solar System community.

Recommendation: SSAP recommends that STFC plays a clear role in the development of UKSA's Bilateral Programmes to ensure alignment with well-established UK scientific goals and priorities. SSAP notes the strong UK Solar System Community support for such a programme, provided it does not come at the expense of existing international activity.

Recommendation: This Roadmap highlights UK community strengths and areas of leadership but given the fundamentally international nature of Solar System science, SSAP does not recommend it should be the (sole) basis for any prioritisation exercise by STFC. SSAP recommends that STFC take note of the synergies between this Roadmap and relevant international exercises, to both illustrate the excellence of UK science and to understand strategic opportunities for international impact.

SSAP offers the following recommendations regarding cross-cutting activities which underpin the delivery of UK Solar System science. These recommendations are not presented in order of priority.

Recommendation: To promote a culture of open-data and maximise the long-term return of UK investment in missions and instrumentation, it is paramount that STFC fully supports data storage and curation both for individual scientific projects and missions and facilities.

Recommendation: Increasing the exploitation funding line level (cash basis, not percentage of the programme) should be a top priority for STFC. Grants, fellowships and studentships have been chronically underfunded and are at a level where the community's international leadership position cannot be maintained. SSAP welcomes the recently announced uplift in the STFC grant line, but a further uplift will be required to return this to an internationally competitive level (particularly if association with Horizon Europe is not achieved).

Recommendation: HPC is now a core requirement across Solar System research and SSAP strongly urges STFC (and UKRI) to implement a long-term, sustainable HPC strategy. The investment in hardware must be accompanied by support for skills training for early-career researchers and STFC should recognise the long-term nature of code development and the requirement for support for highly skilled people on timescales beyond the 3-year funding cycle.

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

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

Note on Prioritisation

UK Solar System research is internationally known for its breadth of expertise and this Roadmap recognises specific strengths of the community and identifies key science questions as well as the space missions, facilities and other underpinning resources that are essential to deliver these science goals. This Roadmap does not prioritise particular missions or facilities and should not form the sole basis for such a prioritisation or for decisions on funding thresholds; SSAP does not have the information or mandate from the community to do this. If required, specific exercises to tension opportunities in SSAP science would be most appropriate and would need to be resourced sufficiently to allow comprehensive consultation with SSAP and the full SSAP community.

Maintaining the international leadership and breadth of the UK Solar System expertise requires exploiting current and planned space missions which involve ESA/UKSA investment, taking into account ESA's Voyage 2050 and Terra Novae (E3P) priorities. Support is also needed for the community to propose and engage with the new UKSA bilateral programmes which offer opportunities for collaboration with US, Japanese and other national programmes. Alongside space missions, there is a continued requirement to maintain and develop our interest in large, ground-based solar telescopes. Taking leading roles in future opportunities is only possible with ongoing support for technology development, and finally, support for advancing theory (including large-scale computational modelling) and lab-experimentation.

Introduction

At the heart of the research undertaken by the communities represented by the Solar System Advisory Panel (SSAP) is a drive to understand the origin and evolution of the Solar System, and the nature of the phenomena that influence its dynamics. The scientific remit of the SSAP, as noted in previous Roadmaps, covers the origin and evolution of the Solar System, and the nature of the phenomena that influence its dynamics.

Solar System science is an extremely active area of research in which the UK is world-leading in many crucial topics. Moreover, the UK provides significant scientific, technical, and programmatic leadership, and certainly 'punches above its weight' in exerting influence and guiding the direction of the field, as evidenced by high-profile roles in numerous space missions, scientific consortia and other activities, both within Europe and the European Space Agency (ESA) but also beyond.

This is a time of extraordinary opportunity for Solar System research. Missions have recently taken place, are active, or in advanced preparation to study a wide range of Solar System phenomena, from the Sun itself (via NASA's Parker Probe and ESA's Solar Orbiter), to the inner planets, comets and asteroids, and the outer Solar System. The long awaited deployment of JWST has also created new opportunities for Solar System research. ESA's BepiColombo has started its series of Mercury flybys with mapping orbit commencing in 2025. Venus will be the target of ESA's EnVision probe, now undergoing project definition and to be launched in the early 2030s. At Earth, the ESA/CAS Solar wind Magnetosphere Ionosphere Link Explorer (SMILE, launch 2024) will revolutionise our understanding of the terrestrial magnetosphere, joining long-running observations from ESA's Cluster and Swarm missions. Preparations are advancing for Mars Sample Return (with a return date in the early 2030s) and for a new generation of outer Solar System missions (ESA's Jupiter Icy Moons Explorer, to be launched in 2023, and NASAs Europa Clipper, to be launched in 2024). The Moon is about to be visited by a whole range of new missions, including an orbiting space station (the Gateway, which will launch carrying ESA's European Space Radiation Array space weather payload) and robotic and crewed landers as part of the Artemis programme. Asteroid sample return missions have recently provided samples (from asteroid Ryugu) to the international community for analysis (via the JAXA Hayabusa2 mission), and NASA's OSIRIS-REx will return more samples (from asteroid Bennu) in the near future (2023). ESA has its own asteroid mission: HERA, to be launched in 2024, to study the target of NASA's DART (asteroid redirect) mission, plus Comet Interceptor, designed to visit a long period comet on its first passage into the inner Solar System (to be launched later in the decade).

The UK has active involvement with a wide range of these activities, either directly via ESA, via bilateral partnerships or through winning open calls for participants to join analysis efforts (recognising our internationally leading reputation). The UK has extensive laboratory based infrastructure and intellectual resources dedicated to Solar System research. These are not only applied directly to space missions, but cover fundamental processes which are important to understanding the Solar System (e.g. space plasmas, astrobiology, etc.).

Our community of academics both help lead, and respond vigorously to the opportunities that arise, extending and enhancing the field in the UK, proposing instruments for missions, leading sample analysis efforts and taking on leading roles in missions and international projects. One example of our growing capacity is the national Fireball Network, which helped monitor the fall of the Winchcombe meteorite in 2021, and the nationwide effort that then sprang into action to recover and analyse the object. Over 20 institutions took part in this serendipitous research opportunity (even in the midst of the COVID crisis), showing the strength and depth of the community.

Another example of growing capacity is in space weather, where the UK has implemented internationally-leading activities via the SWIMMR (Space Weather Instrumentation, Measurement, Modelling and Risk) programme, delivered by UK Research and Innovation (UKRI) via both STFC and NERC. In this translation of basic scientific research to the Met Office for space weather operations, the Solar System science community is demonstrating significant ongoing impact.

In order to fulfil the request STFC made to the SSAP to produce a Roadmap of the key goals and requirements for Solar System research over the next 15 – 20 years, we have consulted with the community that the Panel represents. This has been delivered via a detailed questionnaire, the input of 55 white papers from the community, and multiple sessions at national meetings (National Astronomy Meeting; UK Solar Physics and Magnetosphere Ionosphere Solar Terrestrial community meetings; British Planetary Science Congress), held both online and in-person where possible. The Panel is indebted to the community for its engagement with, and support of, this process particularly given the impact of COVID-19. This has allowed the Panel to formulate a series of recommendations regarding our wider research programme. More specifically, we identify three overarching themes by which we organise key questions and areas of research:

- Theme 1: Solar variability and its impact on us.
- Theme 2: Planets and life
- Theme 3: Space plasma processes

The questions speak to and extend Challenge B ("*How do stars and planetary systems develop and how do they support the existence of life?")* of STFC's science challenges in frontier physics[2], and are discussed in detail in the Roadmap.

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[2] https://www.ukri.org/publications/stfc-science-challenges/stfc-science-challenges-in-frontier-physics/#section-challenge-b:-how-do-stars-and-planetary-systems-develop-and-how-do-they-support-the-existence-of-life?-

The scientific questions defined in this Roadmap are pursued through a combination of observations (reliant on both space- and ground-based instrumentation), laboratory analysis and experimentation, computational simulation and theoretical modelling. All these areas have seen very significant changes over the last decade, for example the rise of machine learning and artificial intelligence applied to data reduction, processing and analysis, and a drive to develop more efficient, miniaturised instrumentation. Furthermore, the need to promote sustainable activities in space is also increasingly paramount, so that as an environment it remains accessible for future generations. From consultation with the community, it is clear that there is a strong desire to ensure that future space activities are consistent with this goal. The ongoing success of the UK Solar System community is also supported by the strong commitment to open access publishing promoted by UKRI and STFC, and we note considerable community efforts in the commitment to open access data and code, for example by highly visible UK participation and leadership in various international projects such as SunPy (software for observational data in Python) which are in the vanguard of this effort. This is helping to ensure a cohesive and collaborative research community, both within the UK and internationally.

Science is performed by people, and so it is also within the remit of SSAP to consider questions concerning the vitality of the community itself. We sought input on this through the white paper and questionnaire responses, as well as discussions in community fora, and we highlight the extremely strong support of the whole UK Solar System community to provide opportunities for all, broadening our community so that it reflects the true diversity of the UK population. There is wide recognition that equality, diversity, and inclusion all have to move into the centre of our efforts. The UK Solar System community is engaged in many examples of meaningful, impactful science communication, engagement and outreach activities, but more can and must be done, with the support of STFC.

Recommendation: *SSAP recommends that STFC further strengthens its efforts and commitments to ensuring that the Solar System community reflects the true diversity of the UK population and uses examples of best practice from the UK Solar System community to influence more widely, within UKRI and beyond.*

To discuss these and other issues, and complementing the science themes set out above, we also include a set of Cross-cutting Activities, areas of significant importance for all three themes.

The Roadmap is organised as follows: in the remainder of the introduction, we discuss the wider context for UK Solar System research, to place the Roadmap in its proper context. This includes the structure of STFC itself, the introduction of UKRI since the last roadmap, the relationship with the UK Space Agency (UKSA) and UK Space Policy more generally, and the international context. We then present Science Themes, supported by Cross-cutting Activities.

The wider context

The landscape in which UK Solar System science is performed has altered dramatically in the last decade. Major changes domestically include the formation of UK Research and Innovation, the growth of the UK Space Agency, and the development of a unified UK space strategy with specific policy relating to severe space weather. Internationally, the seismic impact of Brexit and the ongoing aftershocks in readjusting the UK's relationship with Europe (including in late 2022 the still undetermined nature of the UK's relationship with Horizon Europe), remain challenging. Whilst ESA is separate from the EU, in many areas relating to Solar System science there are entwined interests (for example in Space Safety) and it is impossible to provide definitive statements about the ultimate impact of this uncertain relationship.

The UK landscape

Space is now of key importance to the UK, as reflected in the September 2021 publication of the first-ever National Space Strategy[3]. The UK's vision states in part 'Through cutting edge research, we will inspire the next generation and sustain the UK's competitive edge in space science and technology'. Five specific goals are outlined, one being 'Lead pioneering scientific discovery and inspire the nation'. Space weather, which here we define as the impact of the space environment on human activity and technology, both in space and on the ground, remains a very specific high priority within the overall UK space strategy, which we mention because of its reliance on the UK Solar System community. Severe space weather is included in the National Risk Register and is the subject of specific government policy (Severe Space Weather Preparedness Strategy, published October 2021). Domestically, space weather resilience is coordinated via the Met Office, and the Met Office Space Weather Operations Centre. This has benefited from the very strong science foundation provided by the UK Solar System community, and in turn the symbiotic relationship between basic research and operational application has further invigorated blue sky research into solar activity, the physics of the heliosphere, and the way in which magnetosphere-ionosphere coupling at Earth creates space weather phenomena. The roadmap presented here shows that Solar System research is indeed a jewel in the crown of UK space activity and the community is well placed to help deliver this vision.

Solar System science within STFC

Solar System research overlaps with astronomy in several areas, e.g., in the study of stellar activity, asteroseismology draws on results from helioseismology, and work on solar flares and prominences informs consideration of related stellar features. Similarly, the study of solar and planetary dynamos feeds into research on astrophysical dynamos, turbulence in disks, etc. The field of exoplanet research also demonstrates complementarity between the Solar System and Astronomy communities, with each community bringing a different flavour to the research effort. As we move from the detection to the characterisation of exoplanets, the skills and knowledge of the Solar System community will become central to our understanding of these alien worlds but, equally, the knowledge gained from exoplanet research is influencing our understanding of our own Solar System. We are starting to reach the stage of having sufficient confidence in the data to apply some of our most simple Solar System models to exoplanetary systems. This is fundamentally important as some of the newly-discovered planetary systems contain

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[3] https://www.gov.uk/government/publications/national-space-strategy/national-space-strategy

objects for which there is no Solar System analogue (e.g., super-Earths) and hence allow severe tests of our physics. Solar System research also overlaps with the field of Particle Astrophysics, particularly in the study of neutrinos, cosmic rays, interstellar dust, wave-particle interactions, shocks, and other particle acceleration processes. As noted in the previous section, there are several issues which are common to the research communities represented by the different Advisory Panels (data archiving, grants, fellowships and studentships, high performance computing and laboratory instrumentation). In this report, we have brought these areas together under the heading of Cross-cutting Activities, in order to draw attention to their importance.

Solar System science within UK Research and Innovation and its relationship with other Research Councils

The formation of UK Research and Innovation in 2018, bringing together all the Research Councils, Research England, and Innovate UK into one entity, has been highly significant. UKRI has a mandate to deliver collaborative research, downstream impact, economic impact and solutions to major societal problems. This means that whilst Solar System research is still largely the provenance of STFC, there is an increasing interest and drive to develop cross-research council projects which deliver real-world impact to societal challenges. Often these new projects sit outside of Research Council core funding; for example the UKRI Strategic Priorities-funded SWIMMR programme mentioned above.

The community represented by SSAP performs a range of cross-disciplinary research that is supported in various areas by STFC, NERC, EPSRC (and UKSA). For example:

- Fundamental plasma physics: astrophysical/Solar System plasma physics is funded by STFC, laboratory physics is funded by EPSRC/STFC.
- Solar-Terrestrial Physics and Planetary Science: supported by STFC/NERC and STFC/UKSA, where mission related activities (mission science planning, instrument development) are supported by UKSA, science exploitation mainly by STFC, with ground-based studies supported by NERC.

The formation of UKRI evidently has the potential to avoid historical problems in research which sit at the interface between different Research Councils. SSAP recognises the difficulties in bridging these gaps, especially in a constrained funding environment, but in our view some formal mechanism is required. Existing arrangements for cross-research council research do not appear to be as effective as one might expect, leading to potential loss in opportunities for the UK and the UK research community.

The SWIMMR project is an example where STFC, working with NERC and fully in the context of UKRI, has been able to bridge historic responsibility gaps (i.e. the division of space- and ground-based solar terrestrial physics between STFC and NERC, which is artificial in the context of space weather) in order to make a step change in capability and impact. However, SWIMMR was funded via the Strategic Priorities Fund, and so there is a potential lack of continuity of support, which in turn could mean the long-term impact of SWIMMR being highly reduced.

Recommendation: *SSAP recommends that STFC builds on the success of programmes such as e.g., SWIMMR to articulate the importance of UK Solar System Science within UKRI, and to continue to work with the UK Solar System Community to identify and secure long-term support outside of core Research Council budgets.*

Solar System science and the UK Space Agency

Although the overall UK emphasis on space is very welcome and strongly supported by the UK Solar System community, challenges remain concerning the way in which activities are organised and administered. The community continues to note the risks arising from a perceived disconnect between the UKRI, and STFC specifically, and the UK Space Agency. UKSA delivers the UK civil space programme, is the UK interface to the European Space Agency, and directly funds instrumentation for space science missions (TRL 4+). It is not part of UKRI, and it does not have a mandate for scientific discovery per se. It is important that the UK Space Agency strategy is consistent with the science requirements of the missions and instrumentation, as determined by STFC (and other Research Councils, e.g., NERC), to reap the full benefits of UK participation in space-based projects in terms of science definition, data exploitation and interpretation, training of PhD students and PDRAs, and outreach opportunities.

The tension between UKSA and UKRI/STFC is felt by the Solar System community, despite the best efforts of leadership on both sides to provide a process that is as transparent as possible. Known as the dual-key approach, SSAP recommends that this system is independently reviewed to determine if it is still fit for purpose. The Solar System community is concerned that the dual-key approach is significantly affecting the ability of the UK to deliver world-class science. Typically, STFC supports fundamental instrument technology development, and UKSA supports more mature instrument development but the border between these is not always well defined. It is important to resolve this in such an internationally-competitive environment with implications for space exploration, human spaceflight, and Earth observation. In parallel with these issues, there is no mechanism within the grant systems of UKSA or STFC to support mission science planning, particularly the type that is required to support instrument development and establish science leadership during a space mission flight hardware programme, as such activities fall outside the remit of UKSA and are not supported by the STFC grants scheme. It is important that the UK community has access to a fully joined-up funding framework to gain maximum benefit and return on development, design and building of mission instrumentation, and involvement in both ESA and bilateral missions. This includes modelling, simulations and comparative studies to prepare for future missions as well as to exploit data from current and past missions. However, in contrast, the UKSA Aurora programme which has focused on Mars exploration and more recently lunar exploration concepts, does offer one model to resolve some of these issues. Aurora has funded ECR fellowships and science exploitation grants as well as instrument-related development.

Recommendation: *The 'dual-key' funding approach between the UK Space Agency (UKSA) and the research councils continues to present challenges in ensuring that the funding process is agile, transparent, and effective. SSAP recommends reviewing the relevant advisory and governance structures to make sure opportunities are fully visible to both sides to maximise mutual benefit. The UKSA Aurora space exploration programme offers one successful model which has integrated instrumentation development and science exploitation.*

The European Space Agency

Since the previous Roadmap was published, the UK has left the EU, and is now navigating the various consequences of this decision. It should be recognised that ESA is distinct from the EU, and the UK remains a full and active ESA member. Membership of ESA is considered central to the UK Space Strategy which notes ESA 'will remain a close multilateral partnership for the UK for civil science, exploration, climate monitoring, and technical collaboration'. Whilst the subscription to ESA falls within the UKSA remit, we nevertheless want to highlight the importance of ESA to our research goals. The selection of space missions, and the development of spaceflight instrumentation for those missions, are critically important issues for the Solar System science communities, and so remaining a leading member of ESA is a top priority, strongly endorsed by the UK Solar System community. The UK Space Agency relies upon STFC (and other Research Councils) for information and advice when setting its own priorities. By ensuring that ESA (and other space agencies') mission-related research is cognisant of STFC's road-mapping exercise, the UK Space Agency also has a firm scientific basis for its recommendations. We note that UK Space Agency-supported missions include technical demonstrations that provide pathways to meet future science requirements in addition to mature science missions.

Also since the last Roadmap, ESA has heavily expanded its Space Safety office, and the UK is a strong supporter of this optional programme. UKSA has successfully leveraged the science excellence of the Solar System community to play a leading role in this activity, generating international impact. For example, the UK plays a leading role in the development of Vigil (L5 Space Weather monitoring mission) and the Distributed Space Weather Sensor System (D3S), the operation of the Expert Service Centres, and modelling capabilities for space weather forecasting. Space Safety also covers important research relating to Near Earth Objects, for example via the Hera mission.

Solar System science is also strongly relevant for Human and Robotic Exploration, at the Moon and Mars. Since the production of the previous Roadmap, the ELIPS, Aurora, and ISS programmes have been combined by ESA into the Terra Nova (E3P) European Exploration Envelope programme. Again, UK strengths in this area mean that participation in this optional programme is beneficial for the community, because it allows the UK to play a leading role on the international stage, magnifying the science return and generating impact.

Recommendation: *SSAP recommends that STFC continues to support UKSA in its investment in ESA's Science, Human and Robotic Exploration, and Space Safety Programmes, recognising the value that this investment brings to supporting and sustaining the UK Solar System community.*

Opportunities for Bilateral Programmes

Brexit has brought a renewed focus on understanding the international opportunities for space science, and this has led to new bilateral activities that will have a tangible impact on the UK Solar System community. The agreement with NASA to provide instrumentation for the upcoming Interstellar Mapping and Acceleration (IMAP) mission is an example of this. More generally, agreements such as the UK-Australia space bridge provide new pathways to promote novel international collaboration.

We note that the proposed new UKSA bilateral programme for space science and exploration is particularly relevant to the SSAP's Roadmap. The programme will be competitive and science-driven and the first call for proposals has been announced at the time of writing (late 2022). The Space Science community welcomes the opportunity for new bilaterals, and recognises that investment in such activity brings the UK up to parity with similar economies such as France and Germany. Nevertheless, the community cautions that this should not come at the expense of existing activity. In the general aspiration to grow the space economy, an increased level of activity can only be achieved by an increased level of investment. As with other space science activities, it will follow the Dual Key approach, and the panel notes that there is a need to ensure the selection process is as clear as possible, particularly regarding scientific remit and level of community support and involvement, since this new approach isn't linked to the normal and relatively well understood processes associated with our ESA subscription for instance.

Recommendation*: SSAP recommends that STFC plays a clear role in the development of UKSA's Bilateral Programmes to ensure alignment with well-established UK scientific goals and priorities. SSAP notes the strong UK Solar System Community support for such a programme, provided it does not come at the expense of existing international activity.*

Other Roadmap Exercises

The scientific questions defined in this Roadmap are also questions of international importance, as they echo priorities that have been recognised in road-mapping exercises undertaken by several international bodies.

- ESA's Voyage2050 prioritisation exercise published in 2021 highlighted exploration of the icy moons and determining their habitability as one of their main priorities for future large missions, in addition to temperate exoplanets.
- This can complement NASA decadal priorities in planetary science which also highlight exploration of the Gas and Ice

Giant Moons. However, the NASA decadal highest priority for Solar System exploration is completing Mars Sample Return.

- The NASA Heliophysics decadal survey (2024-2033) is in its early stages at the time of writing, but there is already clear community support for missions to explore fundamental space plasma processes and constellation missions, to name but two themes identified in this Roadmap.
- ASTRONET is designed to provide a common science vision for European astronomy, and to enable comprehensive long-term planning. As a core-team member, STFC plays an important role representing the UK Solar System Community in this activity which is distinct from e.g. ESA. Astronet is currently (2022) preparing its next science vision and infrastructure roadmap, which contains a significant emphasis on Solar System science.

In conclusion, the UK scientific interests and priorities are highly aligned with the international context, and the UK is well placed to benefit from international roadmap priorities, by contributing instrumentation and science leadership to international projects, and leveraging data from those projects to enable and achieve long-term science goals.

Recommendation*: This Roadmap highlights UK community strengths and areas of leadership but given the fundamentally international nature of Solar System science, SSAP does not recommend this Roadmap should be the (sole) basis for any prioritisation exercise by STFC. SSAP recommends that STFC take note of the synergies between this Roadmap and relevant international exercises, to both illustrate the excellence of UK science and to understand strategic opportunities for international impact.*

Roadmap for Solar System Research Sections and Associated Key Questions

Theme 1: Solar Variability and its Impact on Us

Theme 2: Planets and Life

Theme 1: Solar Variability and Impact on Us

Figure 1.1 The Aurora Borealis over northern Canada, photographed by Tim Peake on the International Space Station, 20 January 2016 (ESA/NASA/Tim Peake).

1.1 Introduction

The Sun is an intrinsically fascinating and important object for astrophysical and plasma research. From a wider astrophysical perspective, the study of the Sun is essential for understanding other systems. Many of the fundamental processes, which occur in astrophysical and laboratory plasmas, are observed in situ or remotely in high resolution on the Sun and in planetary magnetospheres, providing a unique opportunity for understanding magnetic field generation and evolution, particle acceleration, instabilities, reconnection, heating, plasma waves and turbulence. The UK has a proud history of major solar and solar-terrestrial discoveries and has the technical expertise to continue and build on this track record.

Through a combination of extensive, long-term observations and high-resolution, focused missions, we are now acutely aware that the Sun exhibits greater variability and more complexity than previously imagined. The quality of current observations allows multi-wavelength studies of three-dimensional, time-dependent and non-linear behaviour over a wide range of length and time scales. This poses enormous challenges for both analysis and theory, requiring the development of innovative methods of observation and modelling. This includes all aspects of solar physics from the solar interior (e.g., generation and transport of energy and magnetic field), the solar atmosphere (e.g., coronal heating, flares), and the solar wind. Methods developed for solar physics, such as magnetic field extrapolation and seismology, are now routinely applied to other stars.

As our closest star, the variability of the Sun can have profound consequences for the Earth and the modern technological systems on which society relies, for example for communication but equally for daily and long-term monitoring of our planet's climate. The impact of the Sun on our technology has become known as 'space weather', and the UK government has listed severe space weather as a high priority natural disaster[4]. In 2014, the Met Office established a Space Weather Operations Centre that is leading space weather forecasting in Europe. Space weather features prominently in the UK government's National Space Strategy[5] and the government has produced a UK Severe Space Weather Strategy[6] that commits to improving our scientific understanding of space weather; improving forecasting capabilities; and investing in space-based infrastructure for observing and monitoring.

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https://www.gov.uk/government/publications/national-risk-register-2020

https://www.gov.uk/government/publications/national-space-strategy/national-space-strategy

https://www.gov.uk/government/publications/uk-severe-space-weather-preparedness-strategy

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

Solar wind variability, resulting from solar variability, and its evolution throughout the heliosphere plays a significant role in driving dynamics in planetary magnetospheres which are important in understanding the evolution of planetary surfaces and atmospheres and will play a crucial role in the viability of future human exploration. The mechanisms by which the Sun, solar wind and CMEs influence the other planetary bodies in the Solar System vary, from the entirely solar wind-driven magnetosphere of Mercury to the largely internally-driven magnetosphere of Jupiter. The induced magnetospheres of Mars and Venus provide a degree of shielding of the atmosphere to loss processes via their interaction with the solar wind. The fact that Venus has a thicker atmosphere than Mars, yet is subjected to a larger degree of solar wind forcing reveals the complexities in understanding how the Sun and solar wind influences these systems.

To maintain a comprehensive suite of observations, enabling a study of the complete Sun-Earth or Sun-planetary system in the required detail, STFC must liaise closely with space agencies, research councils and industry to ensure that the science they fund meshes seamlessly with other national and international programmes such that all required measurements are made, from the solar interior and solar atmosphere through to the space environments of the planets and down to the terrestrial bedrock.

Although the UK has a strong and active community in solar, solar-terrestrial and solar-planetary research, there are now substantial concerns about the impact of more than a decade of flat cash funding, which has substantially affected support for PhD students and PDRAs. Early career researchers are crucial to ensure the long-term viability of the community, continuity of expertise and innovation of thought, without which the world-leading position of the UK cannot be maintained.

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

1.1.1 UK Expertise relevant to Theme 1

The UK holds a world-leading position within the international solar-terrestrial community in instrumentation, observational data analysis, magnetohydrodynamics (MHD) and kinetic theory, plasma physics and planetary plasma science.

A sample of UK highlights and expertise for Theme 1 are listed below.

- UK research groups have a long heritage in solar wind, heliospheric, and magnetosphere/ionosphere/thermosphere physics through world leading contributions to, among others, the Ulysses, STEREO, Cluster, THEMIS, and MMS missions, and include expertise in exploiting in situ space plasma data as well as remotely sensed solar observations, and the associated theory and modelling.
- The UK has several hardware groups developing instrumentation for space- and ground-based projects, resulting in the UK taking PI roles on instruments that contribute to the success of several international space missions and ground-based facilities. Participation of UK physicists is actively sought in major new projects. For example, the UK has major roles in four of the instruments on-board Solar Orbiter, launched in 2020, and a leading role in the SMILE (*Solar wind, Magnetosphere, Ionosphere Link Explorer*) mission. In ground-based instrumentation, UK expertise in optical sensors has delivered cameras for the U.S. Daniel K. Inouye Solar Telescope (DKIST), which had first light in 2020.
- Our pioneering theoretical work in MHD and kinetic theory is valued worldwide, including advances in large-scale simulations through, for example, the DiRAC High Performance Computing facility.
- The UK has internationally recognised expertise in both solar interior and atmospheric seismology.
- UK groups are internationally leading in the provision of atomic/molecular data for the interpretation of atomic/molecular spectra from spectrometers and CHIANTI is the preferred atomic physics package throughout the international solar community.
- Provision of open-source software, e.g. Sunpy (adopted internationally as the standard for the analysis of observational data in Python), large-scale simulations codes (e.g. Lare3D which is a fully 3D MHD code).
- The UK has a broad spectrum of capabilities, ranging from global MHD modelling to particle-in-cell plasma kinetic simulations for application to the solar wind and Earth's magnetosphere.
- The UK has developed considerable expertise in simulations of wave-particle interactions and their application to radiation belt production/loss, important for the forecasting of space weather.
- Through the use of ground- and space-based observatories, the UK has built an international reputation for the remote study of giant planet magnetospheres and ionospheres through the analysis of auroral images and spectra and their theoretical interpretation.
- The UK currently hosts state-of-the-art models of the coupled magnetosphere-ionosphere-thermosphere jovian and saturnian systems and these can be further developed to understand physical processes including magnetic braking, auroral emissions, and the transport of energy and angular momentum.

1.2 - S1: What are the causes, consequences and predictability of solar magnetic variability and the solar cycle?

The Sun varies on a wide range of time scales, from the sudden rapid release of energy and mass over a few seconds, to the propagation of MHD waves and oscillations throughout the solar atmosphere over minutes, and to solar cycles over a decade and longer. Variations over hundreds of years can be detected through proxies in tree rings and polar ice sheets. The main goal of S1 is to identify and unravel all the physical processes responsible for such a wide range of solar variations. In S3 we address the additional possibility of predicting or forecasting the specific processes that generate space weather.

Key questions
S1.1 What is the form of the magnetic field in the solar interior and what are the physical processes involved in its generation?
S1.2 Why does the solar cycle vary in duration and strength?
S1.3 What is the structure and rotation profile in the solar interior?
S1.4 What is the nature of the coupling between the solar interior, surface and the atmosphere?
S1.5 How is mass, momentum and energy transported from the convection zone to the corona and solar wind?
S1.6 How are the many different coronal magnetic structures formed?

1.2.1 The Solar Interior and Magnetic Field generation

Fluctuations in the Sun's outer regions and its behaviour are controlled by its magnetic field, which owes its existence to dynamo action which is now believed to be a combination of a deep-seated, interior dynamo and a small-scale surface dynamo. What is the form of the field in the solar interior and what are the physical processes involved? 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. A previous extended solar cycle minimum was unexpected and at odds with all cycle predictions. Why does the solar cycle vary in duration and strength?

The theoretical underpinning of the origin of magnetic activity is constrained by our knowledge of the solar interior through helioseismology. Continued long-standing, ground-based helioseismology experiments (BiSON) together with the space-based instruments on Solar Orbiter, Hinode, and SDO, guarantee new results in our understanding of the Sun's interior.

1.2.2 Magnetic field through all layers in the Solar Atmosphere

It is now widely accepted that the different levels of the solar outer regions form an intrinsically coupled system, with the magnetic field mediating the coupling. The wealth of modern multi-wavelength observations, from both space and ground-based instruments, has enabled a simultaneous view throughout the various atmospheric layers. Progress has been made on understanding this coupling, but a recent revelation is the pivotal role of the chromosphere as a regulator of mass and energy transfer in this system. Even with advances in high-resolution observations and radiative numerical models, the small-scale chromospheric structure and dynamics remain challenging to observe and model. Pertinent issues are the ability to interpret (and model) the non-local radiation and non-equilibrium nature of the chromospheric plasma. Further, the plasma in the photosphere and chromosphere is partially ionised, requiring the development of multi-fluid approaches. Given the immediate science operations of DKIST, and the high-resolution (~100 km), high-cadence (<1s) photospheric and coronal observations from Solar Orbiter the time is right now to study how the chromosphere regulates the coupling of these layers. Detailed studies of the coupling will be possible in the near to medium future with exciting new missions, such as MUSE and Solar-C EUVST, which will cover temperatures ranging from 10kK to 10MK at high temporal and spatial resolutions. 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 and solar wind? How does the lower atmosphere regulate this transport?

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 and above.

Magnetic fields emerge on all spatial scales, ranging from large active regions to small internetwork bipoles. Are the small-scale magnetic fields in the quiet Sun a result of magnetoconvective processing of fields rising from the main dynamo at the tachocline or do they owe their existence mainly to a local small-scale dynamo driven by near-surface convective motions? How are the many different coronal magnetic structures, such as active region loops, prominences and coronal holes, formed? In sunspots, how does the complex interlocking comb structure of penumbrae form and why is this stable? What is the link between magnetoconvection and the small-scale features in sunspot umbrae (umbral dots)?

How does the Sun create such different scales? Once we understand their magnetically-controlled formation, magnetic characteristics and drivers, we can then investigate their dynamical evolution in more detail. Significantly, we need to know the 3D vector components of the coronal magnetic field, as this is a crucial missing ingredient in our ability to understand the dynamics of the corona. The weak nature of the coronal field means that measurements with standard spectropolarimetric techniques are challenging and it is an area of current active development.

1.2.3 Key missions/facilities and requirements for S1:

- BiSON, SoHO, Hinode, HMI/SDO, and Solar Orbiter provide global and local helioseismology measurements as well as vector magnetograph measurements to accurately measure the emerging flux.
- Hinode, SOHO, STEREO, SDO, IRIS, DKIST, and Solar Orbiter (and in the future PUNCH, MUSE and Solar C EUVST) are key to

understanding physical processes in emerging and developing magnetic fields across all spatial scales.

- The Solar Orbiter mission, with its unique orbit, will provide a view of the poles to enable helioseismic measurements of that unexplored region – this will probe the fundamental behaviour of the magnetic cycle in the Sun.
- DKIST (and the future EST) will resolve, with unprecedented sensitivity, individual magnetic flux concentrations, observing their emergence, structure and dynamics, measuring their field strengths and direction. In addition, DKIST's multi-wavelength capability will provide high-cadence observations of waves and oscillations from the photosphere/chromosphere/corona at high spatial and temporal resolutions.
- The construction design for the European Solar Telescope is nearing completion and an interim legal figure (Canarian Foundation) has been established in order to complete the steps necessary to apply for the first-stage ERIC application. The UK continues to play a central role in the design and development of the post-focus instrumentation, data centre and adaptive optics for EST, with the latter leveraging the UK's significant investment in the ELT. Continued support for EST through membership of the Foundation would ensure the UK would retain the option to capitalise on previous investments through potential membership of the ERIC.
- SDO, DKIST, Hinode and UCoMP (*Upgraded Coronal Multi-channel Polarimeter*) are able to provide indirect measurements of the magnetic field. They exploit the plethora of MHD waves observed throughout the solar atmosphere and magnetic induced transitions, with recent initial successes measuring local and global coronal magnetic fields.
- New instrumentation is required to achieve the goal of global vector magnetic field measurements. A potential option is integral field spectropolarimetry. However, this technology is still in its infancy and the development of large-field Integral Field Units (IFUs) requires investment, along with investment in sensor technology, e.g., InGas technology for the near infrared with mercury cadmium telluride (MCT) for the far infrared. Ultimately requires the development of a constellation of space-based polarimeters with multiple vantage points but a number of alternative methods have recently been revealed and should be developed.

1.3 - S2: What are the structures, dynamics and energetics of the Sun?

The extreme diversity of dynamic solar phenomena means that they evolve on a wide range of timescales. For example: fast dynamical evolution occurs in flares, spicules, surges, coronal hole jets, CMEs (once the magnetic field is destabilised); more moderate evolution takes place during active region formation, active region outflows, coronal holes, polar plumes, magnetic carpet and small scale emergence; slow evolution of the global coronal field's structure and its open flux, quiescent and active-region prominences (until they erupt). How does the structure, evolution and predictability of coronal magnetic fields relate to dynamic phenomena? The magnetic fields, which thread the solar surface and structure the solar atmosphere are of fundamental importance. The interaction of plasma and magnetic fields produces a wide range of dynamic phenomena. Transient and explosive events, such as microflares, spicules, CMEs and flares, occur throughout the solar atmosphere, at all scales. Flows are prevalent, and waves and oscillations are omnipresent.

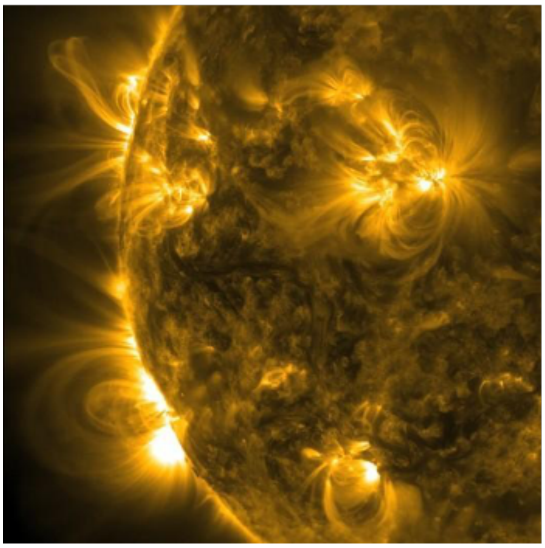

Fig 1.2. Loops above active regions of the Sun, viewed by the EUV imager of the SDO in Oct. 2012 (NASA/GSFC).

Understanding these complex and dynamic features requires direct incorporation of observational data into theoretical models to reproduce and understand the physics behind them. It is only through the synergy of improvements in observations, theory and simulation with High Performance Computing (HPC) that we will be able to answer these key questions. Once the underlying physical processes are understood, we will be able to make predictions.

Key questions

S2.1 Why are there solar structures on different length scales and time scales?
S2.2 What role do small- and large-scale flows at the level of the photosphere play in the build-up of energy?
S2.3 What triggers solar eruptions, and can we predict them?
S2.4 How is magnetic energy transferred into other forms of energy?

S2.5 How are shocks formed and propagated through the heliosphere?
S2.6 How do non-equilibrium processes affect the plasma modelling and diagnostics?

1.3.1 Building Blocks of Solar Magnetism

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

1.3.2 Energy Transfer

An underlying process involved in all solar atmospheric phenomena is the transfer of magnetic energy not only from its source in the interior but also into thermal energy, kinetic energy and the acceleration of particles. Transfer from the interior is either directly by the emergence of magnetic fields or through the propagation of waves/oscillations along magnetic structures. 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. 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?

To transfer 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 in coronal and chromospheric heating: reconnection and waves? 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 on the scale of the reconnection region, but the flare site has a much larger scale, encompassing active region structures. There are also problems of interpretation, since particle propagation and emission effects mediate the observational signatures, needing a multi-wavelength approach to disentangle their properties. CMEs are associated with solar energetic particle events measured by spacecraft at 1 AU, which fill a substantial portion of the heliosphere contributing to the radiation environment in the Solar System. Shocks are known to be efficient acceleration sites for energetic particles, and those formed ahead of CMEs are a natural explanation for solar energetic particle events. Testing theories of not only the shock acceleration processes, but also propagation and time evolution effects, requires modelling of the inner heliosphere. It is also necessary to know the initial state of the energetic particle populations, and this can depend on previous activity events and flare accelerated particles. Because of the efficiency of energetic particles emitting in radio, optical, ultraviolet and X-ray wavelengths, they serve as the unique signatures of the physical processes and, without them, our understanding of the solar atmosphere would be rather limited.

1.3.3 Modelling the non-LTE corona

It has traditionally been assumed that the solar coronal plasma is in local thermodynamic and ionisation equilibrium. However, from the recent highly dynamic observations, it has become clear that we need to take a different, more challenging approach to modelling the atomic processes and solar plasma, with a rapidly developing, worldwide interest in developing models of non-equilibrium and non-thermal effects. 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?

1.3.4 Key missions/facilities and requirements for S2:

- The Hinode and SDO missions provide high-resolution data on the flows and magnitude of the magnetic field that drives activity at all scales. The UK-led spectrometer EIS continues to provide critical information on plasma parameters such as flows as the magnetic field varies.
- IRIS provides high-resolution spectroscopic data, complemented by context images of the solar Transition Region, a key region to understand the mass and energy flow in the solar atmosphere.
- RHESSI continues to provide outstanding data on high-energy solar events, sites for particle acceleration, and in the future, Proba3 (Fresnel Lens) will image the hottest flare plasma, at sub-arcsecond spatial scales that approach fundamental structural coronal scales. SPARK is designed to target the whole range of particle acceleration, from suprathermal electrons to relativistic ions, through the combination of imaging and spectroscopy.
- STEREO provides a heliospheric imaging capability, led from the UK, which is unique in the study of CMEs from onset to Earth impact, feeding into studies of coronal structure and evolution as well as issues such as SEP production.

- DKIST observations of solar flares provide exceptional imaging of the fine structure of chromospheric filaments and allow us to relate those with post-flare eruptions and CMEs. DKIST can determine the importance of waves as fundamental carriers of energy through the solar atmosphere.
- LOFAR, together with other ground- and space-based instruments that observe the Sun in radio, optical, EUV, and X-ray wavelengths, will studystudies dynamical aspects of solar activity, such as solar flares.
- Solar Orbiter (and Parker Solar Probe) is now providing 'encounter' type science by providing high-resolution imaging and spectroscopy during the unique orbit as well as combining in-situ and remote-sensing observations.
- The Solar-C mission focuses on analysing energy flow spectroscopically all the way through the solar atmosphere. This is not achievable with current instrumentation and will make huge steps forward in understanding fundamental processes
- The energy released in solar flares is stored in stressed magnetic fields. DKIST, and later EST, will provide accurate magnetic field measurements in the photosphere, chromosphere and corona and determine the pre- and post-CME magnetic field configuration. The magnetic fields of prominences and eruptive filaments will also be measured to coronal heights.

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

In the last decade, there has been a significant leap forward in our understanding of the way in which Sun-planet connections work, driven by a new generation of space missions focussing on different aspects of this problem, and complemented by computer simulations of ever-increasing size and complexity.

Key questions
S3.1 How does the solar wind (including transient structure) evolve through the heliosphere, and how can we make earlier accurate predictions of the conditions at Earth?
S3.2 By what physical mechanisms are geoeffective events produced, and how can we better forecast them?
S3.3 Is there a unified theory of solar wind-magnetosphere-ionosphere-atmosphere plasma interactions?
S3.4 What are the processes and mechanisms in planetary magnetospheres that create, transport and remove energetic particles?

1.4.1 - S3.1 How does the solar wind (including transient structure) evolve through the heliosphere, and how can we predict earlier, and more accurately, the conditions at Earth?

In the inner heliosphere (defined here as distances up to and including 1 AU from the Sun), an unprecedented flotilla of spacecraft is redefining our understanding of this region of space. In particular, Parker Solar Probe (PSP) and Solar Orbiter are of key importance, with strong UK participation and leadership in both missions. How the solar wind is formed is now beginning to be revealed through the combination of PSP and Orbiter, and this will be a central to progress in heliophysics over the next decade. Bepi-Colombo in its transit to Mercury adds a third observation point. At distances of 1 AU from the Sun, multiple satellites at the Sun-Earth L1 point observe the solar wind, and STEREO provides a synoptic view across the Sun-Earth line. Beyond the planets, perhaps the final piece of the picture is to understand the edge of the heliosphere, and the point at which the influence of the Solar System fades and interstellar space begins. In the last decade, data from Voyager and IBEX has provided tantalising new information and perhaps posed more questions than answers. The IMAP mission, which will remotely sense the outer heliosphere, will build on the results of IBEX, whilst at the same time measuring the solar wind at L1. These observations are complemented by a growing simulation capability covering a variety of approaches which are both physics-based and data-driven. Together this has enabled considerable progress in developing our understanding of many science questions, whilst at the same time opening up new questions requiring the next generation of instrumentation and simulations to solve them.

Basic questions still remain concerning the three-dimensional structure of the heliosphere. With the exception of in situ measurements from Ulysses, our viewpoint of the Sun remains largely fixed to the ecliptic plane. Solar Orbiter is planned to undergo latitude raising to 30°, and while it will image the polar regions for the first time, it will not necessarily provide a complete and comprehensive view. Remote sensing together with in situ measurement is crucial to understand polar fields, flow and circulation, and knowledge of the way in which high-latitude magnetic fields connect to the wider heliosphere is needed to confirm basic aspects of solar models. Furthermore, for studying solar wind transients, a view from out of the ecliptic is logically necessary to complement longitudinally-separated observations and thus fully triangulate ICMEs.

The solar wind is also fundamentally turbulent, and whilst being a laboratory for studying turbulence in its own right, this is thought to control key aspects of solar wind thermalisation. How is turbulence driven and dissipated through the Solar System? Where and how is energy injected into the turbulent cascade, and how does this energy ultimately heat the solar wind? How does turbulence change through the heliosphere and what impact does this have on the solar wind?

Although Solar Energetic Particles (SEPs) are understood at a basic level, we do not yet understand in sufficient detail the acceleration and transport processes that control observed fluxes and energy profiles. There is still much debate about relevant mechanisms, the environments and locations in which they occur; understanding this is necessary to improve predictive capability which is highly relevant for space weather. Complexity in the transport of SEPs through the heliosphere compounds this problem and addressing this requires both computer simulations and new observational capability. Forward modelling of non-thermal electron physics, coupled to large scale MHD evolution is particularly relevant for understanding the acceleration of particles by flares, the creation of type III radio bursts, and the subsequent observation of electron beams in situ. These questions also connect to the prediction of space weather conditions at Earth associated with flares and solar energetic particles.

Finally, more accurate and earlier prediction of conditions at L1 is directly related to the basic challenge of space weather forecasting. Most specifically, the grand challenges in this area are to ultimately be able to predict the emission of CMEs and solar flares, and to predict the conditions of the solar wind at Earth, up to one day ahead. The way in which ambient conditions affect the evolution and propagation of CMEs is critical, as there is a growing realisation that the most severe space weather events are in fact associated with multiple interacting CMEs, or a series of CMEs where the first 'clears the path' creating a slipstream effect for a second to arrive at Earth still moving with extreme speed. A second major question is to understand how the geoeffectiveness of CMEs changes during their transit from the Sun to the Earth, and indeed to be able to predict ahead of time what that geoeffectiveness is going to be. Development of solar wind forecast capability is intimately related to the applied question of producing better space weather forecasts, since the dynamics of Earth's magnetosphere is fundamentally controlled by the solar wind. It is widely recognised that this forecast capability can be both physics-based or data-driven using AI and machine learning, and the UK is very active in this area.

1.4.2 Key missions/facilities and requirements for S3.1:

- Solar Orbiter and Parker Solar Probe are central to progress in heliospheric physics in the next decade. They will be joined by the NASA IMAP mission, exploring the outer heliosphere as well as the solar wind at L1, and UK participation in this mission is therefore extremely timely and will unlock considerable opportunities for the Solar System community. The NASA HelioSwarm mission will address basic questions about the nature of space plasmas using a constellation of nine spacecraft, and again UK participation is crucial to ensure that the community has access to, and a leadership role in, this mission which is the natural successor to the 4- and 5-satellite Cluster, MMS, and THEMIS missions.
- Although envisaged as a spaceweather oriented mission, Vigil, launching to L5, will provide key contextual data for science investigations by imaging the solar disk, tracking CMEs moving along the Sun-Earth line, and measuring the solar wind in situ to understand the environment into which the CME is propagating.
- The NASA Punch mission, consisting of a coronagraph and three heliospheric imagers will provide high-cadence observations of the extended corona.
- Looking towards future mission development, SULIS (Solar cUbesats for Linked Imaging Spectropolarimetry) is a UK-led mission consisting of a pair of formation flying CubeSats. The sunward satellite acts as the occulter for a coronagraph carried on the anti-sunward satellite, and the long baseline defined by the CubeSat separation enables a significant step forward in imaging capability. A Solar Polar Orbiter is also considered of considerable community interest, with specific manifestation in the Solaris proposal to NASA, currently in phase A. The UK has provided input to Solaris, which only contains remote sensing payload, and is therefore well placed to contribute to the development of this and other concepts.
- It is also widely recognised in the UK community that an Interstellar Probe is a necessary follow-on to Voyager, and thanks to its scientific leadership and instrumentation capability, the UK is well placed to drive the development of this mission in the next decade.
- Aside from space mission development, access to sufficient HPC facilities is crucial. The UK has invested heavily in developing simulation codes which are internationally leading, and highly relevant for the applied problem of space weather forecasting. Large computing resources (i.e. internationally competitive) are needed for the next generation of multi-scale simulations.

1.4.3 - S3.2 By what physical mechanisms are geoeffective events produced, and how can we better forecast them?

At Earth, our understanding of the coupling between the solar wind and the Earth's magnetosphere has been revolutionised by Magnetospheric Multiscale's high resolution observations of reconnection, and the combination of MMS, THEMIS, Cluster, Geotail, Swarm, and other magnetospheric spacecraft means that the quality and quantity of data now available for research in this area is better than ever before, and the UK community is particularly vibrant in this area, providing considerable scientific and project leadership. Notwithstanding operational issues in the NERC/STFC divide relating to responsibility for solar terrestrial physics, the UK community is successfully bridging the gap between ground- and space-based observations. By combining space-based measurements from the aforementioned missions with ground-based magnetometer, radar, and other remote-sensing systems, and with comprehensive simulation capabilities, the UK community is certainly world-leading and particularly vibrant, as evidenced by the strong support for regular national meetings convened by the RAS Magnetosphere, Ionosphere and Solar Terrestrial (MIST) group in this area.

The plethora of observations (both ground and space based) has revealed that despite 50+ years of exploration there are still basic questions about the operation of the Earth's magnetosphere that are still not understood. For example, there is now clear evidence for asymmetry in the hemispheric response of the magnetosphere to solar wind driving.

Whilst in situ measurements are increasingly precise, the lack of global context and knowledge of the 3-d structure frustrates progress. Questions relating to energy transport, the role of changing boundary conditions and the precise drivers of magnetospheric substorms, and steady magnetospheric convection remain unresolved. Other basic questions relate to the modes of energy conversion, partition and storage, and how this energy can be injected into particle acceleration causing rapid transport.

There also is a growing understanding that the magnetosphere's behaviour cannot necessarily be understood simply by studying the component parts alone because the complexity of non-linear coupling and feedback mechanisms leads to emergent system behaviour of the magnetosphere itself. Local processes have global consequences across spatial and temporal scales covering several orders of magnitude, but are often driven by the global boundary conditions in a highly interconnected way. We do not yet fully understand how system scale interactions constrain, or alter, fundamental plasma processes (for example how magnetotail reconnection is constrained by the size of the magnetotail itself). Similarly, we do not completely understand how small-scale dynamics may impact the large-scale system, which matters because of, for example, the discovery of reconnection within magnetospheric turbulence which has the potential to change the way in which energy is transported through the system. Answering these questions requires observational capability which goes beyond existing missions, to ‘constellation class’ missions of more than four spacecraft which can access multiple temporal and spatial scales simultaneously.

We conclude that whilst there has been considerable progress, future breakthroughs are frustrated by a lack of global knowledge, and a need to reduce the sparsity of in situ measurements. This drives the development of key missions and facilities as described below, all of which are benefiting from significant UK leadership as a consequence of the extremely strong science base supported by STFC.

1.4.4 Key missions/facilities and requirements for S3.2

- The ESA/CAS Solar wind, Magnetosphere, Ionosphere Link Explorer (SMILE) mission will simultaneously image the outer boundaries of the magnetosphere in soft X-ray and the auroral oval in UV to provide the first global view of the dynamics of Earth’s magnetosphere. These remote sensing measurements will be complemented by in situ measurements of the magnetic field and the solar wind. SMILE will transform our understanding of the Earth’s magnetosphere/ionosphere and solar wind coupling (as well as key space weather pathways) because it will provide a global view connecting solar wind impact and energy input on the dayside with processes leading to energy release on the night-side and in the ionosphere. The UK Solar System community will be in the vanguard of this effort because of its international leadership of the SMILE project, provision of key instrumentation (particularly the Soft X-ray Imager), curation of the data facility maximising access and use, and associated wider strengths in magnetospheric physics and computer modelling. Consequently, the UK community will be in an excellent position to direct SMILE operations, lead the scientific exploitation of the mission, and make substantial, definitive contributions to answering this science question.

- Within the magnetosphere, the planned remote sensing measurements provided by SMILE must be complemented by in situ measurements. Long-standing missions such as Geotail, Cluster, THEMIS, and indeed MMS continue to provide data, but it is clear that whilst these missions have enabled considerable progress, a new generation of mission is needed to explore the questions which we are now confronted with. In particular, local magnetospheric dynamics are fundamentally multi-scale, both in the plasma sense and the magnetospheric sense, and so multi-scale measurements from constellations of more than four spacecraft are needed to truly understand the observed dynamics and their evolution in both space and time. The Plasma Observatory mission, selected for phase-0 study as part of the ESA M7 opportunity and holding considerable UK Solar System community support, and the NASA-selected HelioSwarm mission, in which the UK has very strong scientific and hardware involvement, are emblematic of the next observational frontier in this area. Thanks to its outstanding track record, the UK is thus strategically placed to lead the next generation of scientific discovery.

- This extends to measurement points outside the magnetosphere, specifically measurements of the inflowing solar wind. There is a considerable flotilla of spacecraft in the vicinity of the Sun-Earth L1 Lagrange point providing this data, to be joined by IMAP and the Space Weather Follow-On (SWFO) mission in the coming years. Supporting the continued acquisition of L1 solar wind data is crucial because without this data, it is impossible to satisfactorily decipher magnetospheric dynamics.

- Another piece of the observational puzzle is ground based measurement. SuperDARN, EISCAT-3D, SuperMAG and auroral cameras, together with other facilities, will all provide synoptic views of the magnetospheric dynamics, and important ground truth for certain types of space weather impacts. Here, we emphasise it is crucial to ensure close cooperation between NERC and STFC. The Panel hopes this cooperation will be facilitated, not hindered by the evolving UKRI structure, because whilst this should be a cost-effective way to achieve significant science progress, administrative friction has the potential to also stall these efforts. This is not only a scientific issue, because the primary pathway of space weather socio-economic impact is through widespread and potentially long-duration loss of power caused by ground geo-electric fields driven by geomagnetic activity. Understanding, forecasting, and mitigating this risk requires a deep understanding of the entire “sun to mud” chain, and the UK has a uniquely well developed science/operations ecosystem to address this, in the context of space weather more generally.

- Demonstrating the innovative approach within the UK Solar System community, further ideas are being developed that offer intriguing ways to study this science question. So-called active space experiments have been attempted (e.g. with AMPTE in the 1980s), and there is growing interest in using e.g. electron beam technology to directly trace along field lines and establish the connectivity between different regions. A second opportunity to be explored is the use of sub-orbital rockets and balloon-borne experiments. These are used to great effect by other communities to enable low-cost access to space for a wide variety of Solar System science investigations, and for providing hands-on training to students in science and engineering, as well as principal-investigator skills for early-career individuals. Moreover, they measure important regions of space in situ that cannot easily be accessed by satellites. The development of UK launch capability gives the UK Solar System community the potential for direct access to key regions of polar geospace, and so there is a unique opportunity to leverage this new capability in service of STFC science goals. An important question is how such a sub-orbital rocket and balloon programme should be managed between STFC and UKSA, and the Panel recommends that this be investigated as a matter of urgency given the timely nature of the opportunity.

- It is important to underline that the relationship between remote and in situ measurements of the magnetosphere is symbiotic. The remote sensing measurements (space- and ground-based) provide global context for the in situ measurements, but the in situ measurements provide ultimate ground truth for local plasma behaviour. The Solar System community stands on the cusp of having all types of measurements in the key regions of geospace for the first time, and this is in no small part to the fact that the UK is world-leading in this area.

- Finally, numerical modelling provides complementary insight, and this is another area where the UK is extremely active and strong. The Panel recommends it is crucial to invest in HPC support so that existing strengths are not lost. Specifically, this should include participation in ExCALIBUR, as many Solar System simulations are suited to tightly-coupled parallel architectures, provision of long-term data storage solutions, and consideration of how STFC can work with its sister councils, particularly EPSRC, in recognition of the deep synergies that exist between laboratory and space plasma investigations.

- Magnetosphere Ionosphere Thermosphere coupling at Earth via a multipoint constellation approach e.g. the NASA GDC mission and the Chinese CAS AME mission concept is also considered an important priority for the community.

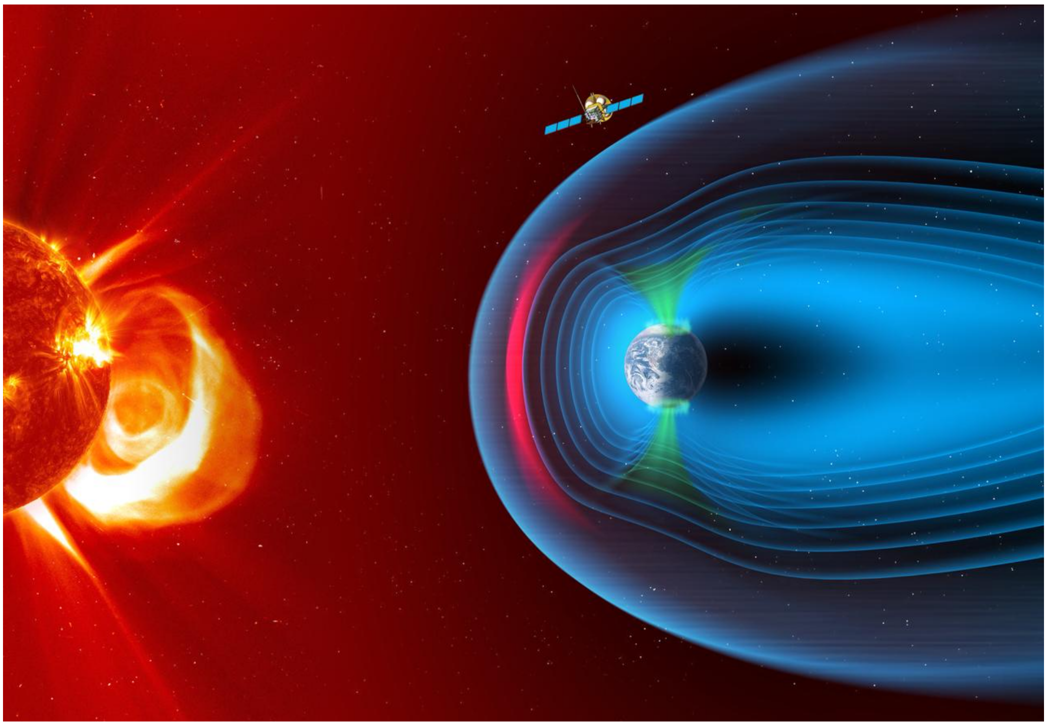

Fig. 1.3. Artist impression of SMILE observing the dayside magnetopause (pink), cusps (green) and the auroral oval (ESA).

1.4.5 - S3.3 Is there a unified theory of solar wind-magnetosphere-ionosphere-atmosphere plasma interactions?

The UK Solar System community is highly visible, playing a significant role in the exploration of essentially all Solar System bodies. It is therefore now poised to lead efforts in developing a unified theory of solar wind-magnetosphere-ionosphere-atmosphere plasma interactions. The Solar System presents a diverse set of planetary magnetic fields produced by dynamo action in their interiors (see also SM1.9), 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 therefore essential for understanding changes in the Earth's dynamo and magnetic field over a variety of timescales.

The Earth's magnetosphere is the most studied in the Solar System but because of the limited range of controlling parameters (such as field strength, solar wind properties, plasma sources) the range of physical processes that can be investigated is necessarily limited. The study of planetary magnetospheres throughout the Solar System is important to generalise our understanding of planetary magnetospheres and understand more extreme dynamics in the Earth's magnetosphere. The geomagnetic reversals of the Earth's magnetosphere are 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 remain the only opportunity to study such configurations in situ where we can test terrestrial palaeomagnetospheric models.

Studies of planetary atmospheres shed light on the evolution of Earth's atmosphere. How do planetary environments respond to differing energy input in terms of climate, atmospheric chemistry, meteorology, cloud formation and atmospheric circulation? The presence of heavy organics in the nitrogen-rich atmosphere of Saturn's largest moon Titan and their possible evolution into "tholins" has prompted the discussion of Titan as a prototype for the atmosphere of the early Earth. Future studies of Titan's atmosphere and the driving of both the atmosphere and atmospheric chemistry by solar insolation and the deposition of energy via charged particle precipitation is important in understanding the potential role these processes played in the atmosphere of Earth and the "seeding" of the primordial soup by the precipitation of tholins.

Within 1 au, the UK has a leading role in the exploration of Mercury with BepiColombo, which is set to transform our understanding of this planet in the next decade. In preparation, the UK has shown strong science leadership for example in the exploitation of data from MESSENGER, and in a theme which we will return to, in part this is because of the exceptional ability of the UK community to cross-fertilise ideas between different communities in a meaningful way. Key questions about Mercury's magnetosphere include: What is the relationship between Mercury's atmosphere, interior and the upstream solar wind conditions? Why does Mercury's magnetosphere respond so strongly to solar wind forcing and what is the nature of its internal current systems?

At Venus, the UK has important scientific leadership within the upcoming EnVISION mission, whose data will stimulate new work on planetary atmospheres, ionospheres and thermospheres that will impact the wider community. Beyond 1 au, our understanding of the solar wind coupling at Mars is similarly being transformed by the growing number of satellites in orbit, particularly MAVEN and Mars Express. Driven by a clear goal to understand the history of water on Mars, and the possibility of conditions conducive to life, this has benefited from the strong links between different parts of the UK community, where knowledge of the underlying processes at other planets has been successfully transferred. The UK is thus well placed to lead comparative studies of Mars and Venus, and develop a more unified understanding of the atmospheres of the terrestrial planets including Earth.

At the outer planets, the successful conclusion of the Cassini mission at Saturn led to considerable steps forward in our understanding of large, rapidly-rotating magnetospheres with internal plasma sources. At Jupiter, the JUNO mission has similarly revolutionised our understanding of magnetosphere-ionosphere coupling in this class of planetary system. Both missions benefit from strong UK scientific leadership, meaning that the UK community is extremely well placed for the upcoming JUICE mission to Jupiter and Ganymede. However, we still do not adequately understand the highly symmetrical nature of Saturn's magnetic field, nor the nature of the planetary period oscillations. To progress towards a unified understanding, the UK has the science base to lead studies comparing moon-magnetosphere interactions at the giant planets with the Moon, Mars, Venus, comets and other small bodies.

Deeper into the Solar System, a Uranus mission is now a high priority for the US community. This is highly relevant for the UK community, as exploration of the ice-giants would enable science closure to be reached on several important questions, as well as to understand how the solar wind interacts with complex magnetospheres, ultimately providing contact to the diversity of behaviour that might be expected with exoplanets. Investigation of the ice giants extends well beyond their magnetosphere/ionosphere/thermosphere dynamics, but they present a considerable challenge to our understanding in how such complex planetary fields are generated, and how they interact with the solar wind to create tilted, dynamic and highly asymmetric magnetospheres, with daily and seasonal variation. Our knowledge of the magnetospheres of Uranus and Neptune are limited to the Voyager 2 flybys, supported by more recent modelling activity and remote sensing. The ice giants thus represent the last frontier of true discovery.

1.4.6 Key missions/facilities and requirements for S3.3:

- In situ measurement of planetary magnetic fields and plasma environments is crucial for answering the above questions. The UK has leadership in a considerable number of ongoing and planned planetary space missions that are central to providing the necessary data. These include BepiColombo EnVISION, Mars Express, JUICE, Europa Clipper, Uranus Pathfinder, etc.
- The archive of data collected by planetary missions continues to grow, with many important discoveries still to be made. Emphasis should be placed on open data principles, to maximise the return on investment in previous missions such as Venus Express, Cassini, etc.
- Remote observations provide a highly important complement to in situ measurements. Data from JWST, UKIRT, ING and E-ELT are expected to provide crucial information to interpret the global structure of planetary processes.
- In the more distant future, the ability to place solar wind monitors upstream of a giant planet magnetosphere will be important to properly characterise the response of a giant planet magnetosphere to the solar wind.
- Computer simulations of planetary plasma environments and interactions are necessary to place experimental data in context, and provide predictions for observations, including optimizing the design of detectors. Planetary magnetospheres are potentially more complex than seen at Earth, because of a more diverse plasma population based around internal plasma sources, and because key processes may occur at non-MHD scales (e.g. at Mercury and Ganymede). There is, therefore, a need to develop the next generation of simulation codes to provide full insight into novel spacecraft datasets.
- The basic desirability of an ice-giant mission is underlined by the growing coordinated international interest in launching such a mission while it is technically feasible, relying on planetary alignments which suit launch at the end of this decade. Although identified as a top priority in the NASA Decadal survey, it is likely that an ice-giant mission will be one of international cooperation. The UK Solar System community has provided strong, consistent leadership meaning it is well placed to contribute both scientifically and technically to an ice-giant mission.

1.4.7 - S3.4 What are the processes and mechanisms in Solar System magnetospheres that create, transport and lose energetic particles?

Understanding how Solar System magnetospheres create, transport and ultimately lose energetic particle populations is not only important for basic exploration of space plasma physics, but highly relevant for understanding the risks posed by space weather, and also understanding the impact this may have on the habitability of Solar System objects in general. Tackling the basic questions of how energetic particles behave in space is also directly relevant for space weather, because the radiation around the Earth causes damage to satellites and can disrupt aviation.

The most prominent, and arguably best studied system is the Earth's radiation belts, where in the past decade data from the Van Allen Probes, complemented by many other observations, have dramatically improved our understanding of the way in which energetic particles are contained within Earth's magnetosphere. The Earth's radiation belts are the primary repository of energetic particles, and radiation belt physics is a specific area in which the UK Solar System community is extremely active. The radiation belt response to both internal dynamics (including cross-scale coupling) and external driving remains a question of high significance which has been probed with existing space observations and simulations, but is still not definitively understood. The precise mechanisms for particle-wave energy transfer and the role of instabilities as they become non-linear and fully developed still elude a full description. As noted above, the radiation belts are the driver for significant space weather hazards, and developing the next generation of physics-based models for forecasting will rely on scientific advances in this area.

Allied to this, measurements of energetic particles at the Earth's bow shock, and in the magnetotail, are starting to create a connected picture establishing where seed-populations are formed that can be further energised by other processes. Similarly, measurements of outer magnetospheric dynamics and solar wind drivers have shown how rapid energetic particle loss can also occur. As with other areas, the importance of modelling cannot be overstated so as to place in situ measurements in their global context and to truly understand the large-scale transport dynamics. Also related to S3.2, the behaviour and dynamics of electrons is an area that has been unlocked by Magnetospheric Multiscale, but primarily in the context of reconnection. All this points the way to a new landscape of science questions, which centre around the general problem of electron-scale physics, transport, and energisation. Specifically, how are particles energised in different regions of the magnetosphere and how do these processes work in concert to provide the seed populations for further energisation? This requires a new generation of instrumentation which is capable of measuring space plasmas in a variety of environments in sufficient detail.

Observations at other Solar System bodies, particularly Jupiter and Saturn, provide an important counterpoint, by allowing comparisons between solar-wind driven and rotationally driven magnetospheres. Specifically, understanding how and why the properties of radiation belts at different globally magnetised planets vary will provide a deeper understanding of trapped energetic particles more generally. There is increasing interest in the environment of Ganymede, driven by preparation for the JUICE mission, and this connects to Mars, where in both cases the role of energetic particles in understanding habitability is key.

1.4.8 Key missions/facilities and requirements for S3.4:

- For radiation belt physics, recent progress has benefited from fusing modelling and data in a highly integrated way. Data from satellite missions is crucial for understanding both the dynamic behaviour of the radiation belts, and also for uncovering basic physics, such as diffusion coefficients, that is needed for radiation belt models. Future progress will rely on a diverse range of modelling approaches, both data-driven (using machine learning and discoverable AI) and physics-based (covering a range of approaches such as diffusive, particle in cell and global MHD/test particle). Efficient progress further requires integration of different models to cover gaps in physical understanding and therefore generate a more coherent understanding of radiation belt dynamics. Many of the comments in S3.2 relating to computational work also apply here.

- Observations from multiple vantage points are also required. Whilst there is a wealth of archive data, new missions targeting multi-point coverage in the inner magnetosphere are required to introduce local time variation into radiation belt models.

- For the general problem of electron dynamics and energisation, new instrumentation and missions to measure space plasmas at very fine spatial and temporal resolution. The importance of this is underlined by the strong UK support for the Debye mission proposal, and similar ideas. The science goals of these missions drive instrument performance to, and perhaps beyond, the limits of existing technology, and so the Panel notes that there is a continuing role for STFC to support low-TRL instrument development, in order to both de-risk and demonstrate the feasibility of new payloads that are ultimately required to answer the science questions we have discussed here.

- A multi-point mission to address the sources of energetic particles at different regions within the magnetosphere.

Theme 2: Planets and Life

Fig. 2.1. The shadow of Ganymede cast on Jupiter imaged by NASA's Juno spacecraft in February 2022 (NASA/JPL-Caltech/Southwest Research Institute/Malin Space Science Systems).

2.1 Introduction

The origin of the Solar System and the possibility of life beyond the Earth are questions that have always occupied the minds of scientists; they are also questions that are of great interest to wider society and continue to inspire future astronomers and planetary scientists. In general, the surfaces of other planetary bodies offer a longer and sometimes "cleaner" record than that of the Earth in terms of the processes that have operated throughout the history of the Solar System. The early crustal history revealed on other bodies records not only external processes (e.g. impact cratering, solar wind scavenging) but also internal processes (e.g. relicts of primary crust) that are not available or accessible in the terrestrial record. Studies of planetary atmospheres shed light on the evolution of Earth's atmosphere. How do planetary environments respond to differing energy input in terms of climate, atmospheric chemistry, meteorology, cloud formation and atmospheric circulation? For instance, the presence of heavy organics in the nitrogen-rich atmosphere of Saturn's largest moon Titan and their possible evolution into "tholins" has prompted the discussion of Titan as a prototype for the atmosphere of the early Earth. 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.

Since the 2015 Roadmap, significant progress has been made into understanding our distant past and our place in the Universe. As highlighted in 2015, the UK community is engaged in a variety of fundamental planetary science investigations targeted at understanding the Solar System; knowledge gained from these studies also has direct application to the understanding of the formation of exoplanetary systems. Although we break down the main scientific questions into individual topics below, they are intimately linked with significant overlaps to Themes 1 and 3. In Section 2.1 we give a brief overview of a variety of areas where the UK is particularly active. In Sections 2.2, 2.3 and 2.4 we show how these topics are linked to the three sub-themes relating to this section. In Section 2.5 we then list relevant UK expertise, and in 2.6 the relevant space missions/activities.

2.1.1 Analysis of Extra-terrestrial Materials on Earth

Laboratory analysis of extraterrestrial samples is crucial to understanding the materials, processes, and timescales during the earliest stages of Solar System formation. Sample return missions, such as JAXA's Hayabusa2 mission to the C-type asteroid Ryugu, deliver pristine samples from known bodies in the Solar System. Grains from Ryugu – including those being analysed in the UK – are providing a more complete understanding of water-rock reactions and the structure and composition of primitive building blocks in the Solar System. UK scientists are also set to play a leading role in the analysis of samples returned from asteroid Bennu (Figure 2.2) by NASA's OSIRIS-REx spacecraft in 2023, while JAXA aims to launch its MMX mission to collect samples from the martian moon Phobos in 2024.

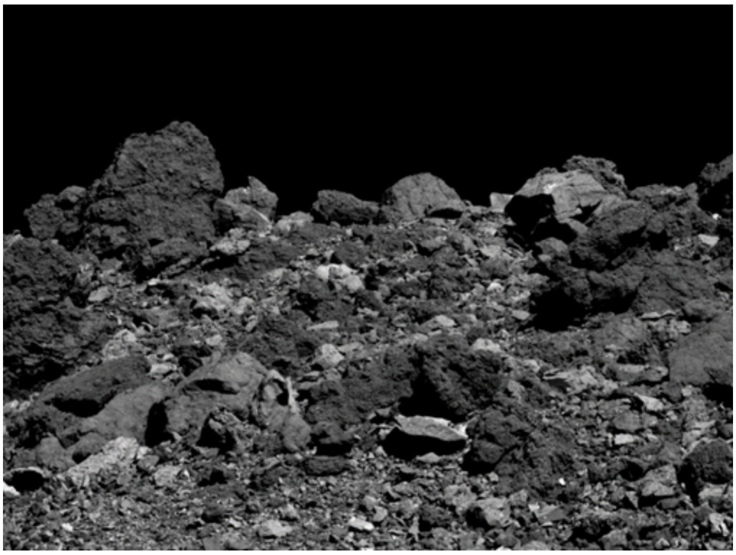

Figure 2.2. The surface of the carbonaceous asteroid Bennu imaged by NASA's OSIRIS-REx mission (NASA Goddard/University of Arizona). Samples from asteroid Bennu from 2023, and currently Ryugu (JAXA Hayabusa2 mission), are allowing the first analysis of materials from known B and C class asteroids.

Meteorites are another important source of extraterrestrial materials and sample a wide range of asteroid types, the Moon, and Mars. Over 560 lunar and 340 Martian meteorites (including paired samples) have now been identified, giving planetary scientists a unique way to study the mineralogical and geochemical evolution of these planetary bodies. Furthermore, the diversity of recognised martian meteorite types in particular is increasing as more have been found in the North West African desert and other regions. Martian meteorites record basalt lava flows, primitive cumulates, and regolith breccias. The nakhlite cumulate contains a unique record of water-rock reactions recorded in saponite-serpentine and carbonate veins.

The recovery rate of meteorite falls and our ability to precisely constrain their origins in the Solar System are improving due to the expansion of meteor and fireball camera networks. In the UK, this was demonstrated in 2021 by the successful recovery of the Winchcombe meteorite (Figure 2.3); the preceding fireball was tracked by the UK's camera networks, which enabled a pre-atmospheric orbit to be calculated and collection of the first meteorites only ~12 hours after landing. The Winchcombe meteorite is a rare carbonaceous chondrite, the first of this type to be recovered in the UK. Detailed studies show that it contains solid materials dating back to the start of the Solar System and pristine water-bearing minerals and complex organic molecules. Further support for the camera networks, plus potential field trips to Antarctica, will offer new meteorite samples to the UK planetary materials community.

Figure 2.3. Left - A fragment of the pristine Winchcombe carbonaceous chondrite meteorite. The fragment is ~2 cm across and has a small patch of brown/red fusion crust (Trustees of the Natural History Museum, London). Right – Footage of the fireball enabled the pre-atmospheric orbit and strewn field of the Winchcombe meteorite to be calculated (Richard Fleet / UK Meteor Network).

Ongoing Mars Science Laboratory and Mars2020 rover (Figure 2.4) and orbiter missions have greatly increased our understanding of the evolution of that planet, with its igneous, sedimentological, atmospheric and cryosphere evolution being revealed in unprecedented detail. Questions such as the STFC Science Challenge "*How widespread is life in the Universe?*" cannot be addressed without knowledge of the geological and environmental contexts of a planetary body, set within a chronological framework. Preparation for Mars Sample Return is the next major step in addressing the search for life beyond Earth, and UK scientists and engineers are involved in leading the science investigations, planning and technology development of Mars2020, sample collection on Mars and ground-based parts of MSR.

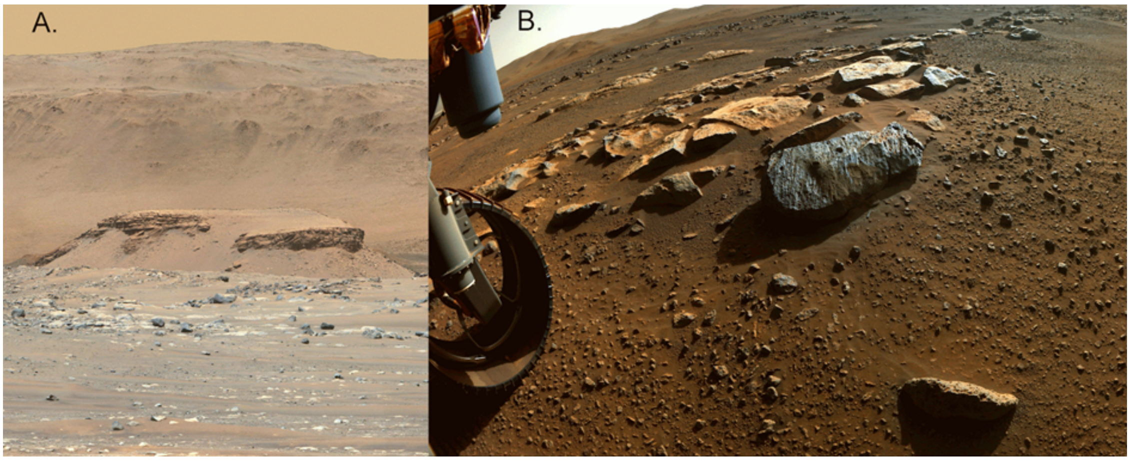

Figure 2.4. A) Lake-floor deltaic deposits imaged by the Mars2020 Perseverance rover on the surface of Mars in Jezero Crater (NASA/JPL-Caltech/MSSS). These deposits are a target for eventual return to Earth as part of Mars Sample Return. B) Rochette igneous sample with drill holes - some of the first samples to be prepared for eventual return to Earth in 2032.

2.1.2 Inner Planets and the Moon

Mercury's particular importance in studying the evolution of the Solar System is that it may represent a planetary embryo which accreted from a constrained reservoir of planetesimals with reduced mineral assemblages analogous to enstatite chondrites or achondrites. Mercury has a unique record of volatile redistribution, high Mg/Si regions and related impact structures, and may preserve traces of a reduced graphite-rich early crust.

Venus in contrast is the only other Earth-sized planet which we can study in detail beyond our own and it offers a contrast between stagnant lid and plate tectonic evolution. However, fundamental questions remain about how volcanically active Venus is and its tectonic history. The role and losses of water in its crustal-atmosphere evolution are also in contrast to that of the Earth's.

Mars remains one of the most active areas of planetary research, encompassing as it does remote sensing from orbiters, meteorite studies, landers and the prospect of sample return and ultimately human missions. Driven by a combination of science concerned with the search for ancient life, through robotic, and eventually human exploration, we have learnt more about Mars than any other extraterrestrial body. The fluviodeltaic and lacustrine environments of Jezero and Gale craters studied by the Perseverance and Curiosity rovers have illustrated how Earth-like some of its ancient environments were. The increasing number and diversity of martian meteorites and range of new analytical equipment that they can be analysed with offers another unique route to understanding the differentiation of the Mars crust and mantle and interaction with near surface water. Igneous samples identified at Gale and Jezero give a complementary, new view of Mars igneous differentiation.

The Moon provides a unique record of essentially pristine impact craters of all sizes (from micron- sized pits up to 1000-km impact basins) (Figure 2.5). Sample collection from and in-situ geophysical studies of pristine lunar craters of a range of sizes would greatly aid in our understanding of the impact cratering process. The Moon is an extremely large satellite in comparison to the size of its host planet, such that the Earth-Moon system is unique within the Solar System. Material ejected from the early Earth by impacts may still be present on the Moon, and may yield information about the early history of the Earth during its first 500 Myr. Likewise, debris and isotopic signatures found on the Moon from asteroid and cometary collisions in the past will tell us about the sources of impactors through time, helping to provide constraints for dynamical models of Solar System evolution and ascertain the causes of impact spikes in the inner Solar System.

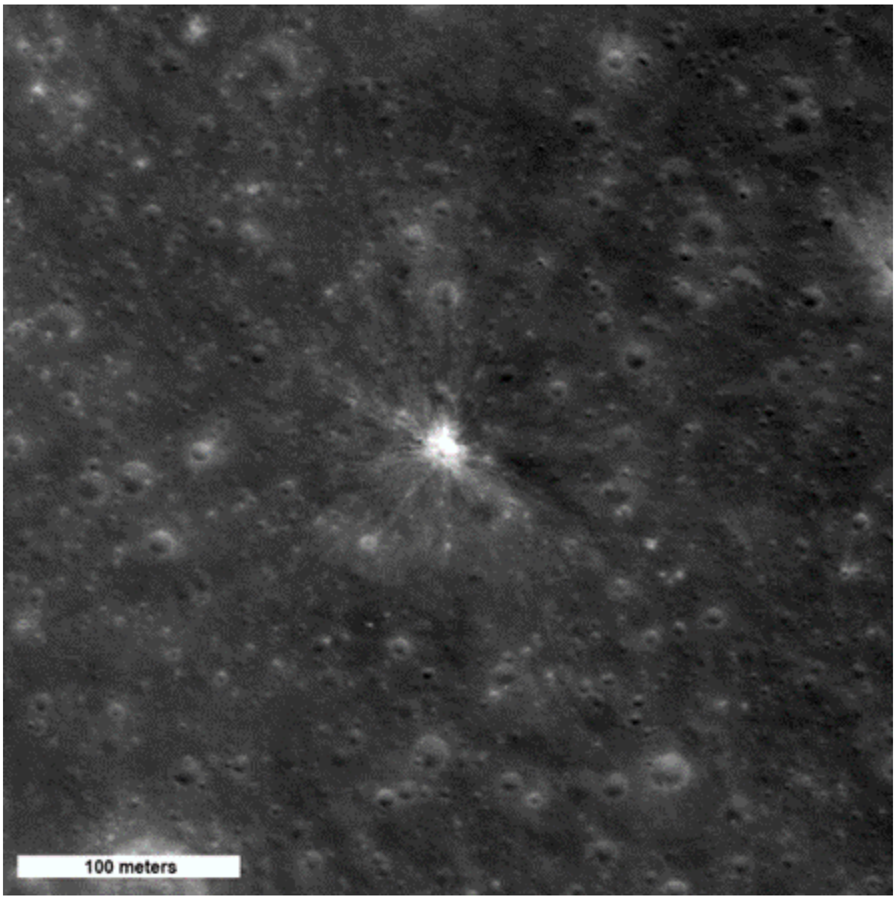

Figure 2.5. A recent impact crater on the surface of the Moon imaged by the Lunar Reconnaissance Orbiter (LROC) (NASA/GSFC/Arizona State University).

As well as the NASA Artemis human spaceflight programme to the Moon, China has also declared its intention of sending astronauts there. Both programmes have prioritised landing sites near the lunar south pole, where water ice may be accessible. In addition, NASA and China have a range of robotic lunar missions planned, which include landers and rovers, and will deploy scientific instrument packages onto the lunar surface. In-situ resource utilisation tests are also a vital part of these missions, preparing the way for a potential future long-term human presence on the surface including construction of structures. The UK has interests both in lunar science and the engineering related to in situ resource utilisation. Lunar science questions highlighted in submissions to the SSAP Roadmap include: was there an impact bombardment cataclysm in the inner Solar System ca. 4 billion years ago?; How much water ice is there at the poles, in what form, and how is it distributed and what is the source(s) of life-enabling volatiles (H, C, N) within inner Solar System planetary bodies?

2.1.3 Outer Solar System Planets and Icy Worlds

The large planets in the outer Solar System still present major challenges to our understanding of how planets form and evolve. Ongoing and planned missions to Jupiter and Saturn, will reveal more about these bodies and their satellites. Furthermore, Uranus and Neptune still await detailed study by orbiting spacecraft. Studies of these bodies and their moons by a wide variety of instruments, characterising their composition, structure and behaviour over a wide range of scales, is thus a major goal of planetary science, both in the coming decade and for years thereafter.

Consistent with the ongoing STFC challenge "*How widespread is life in the Universe?*", UK scientists are also involved in plans to investigate the surfaces and warm environments inside the icy moons of the giant planets (Figure 2.6, 2.8). ESA's Voyage2050 prioritisation exercise in 2021 highlighted exploring their habitability potential as one of their main priorities for future large missions. JUICE - JUpiter ICy moons Explorer - is the first large-class mission resulting from ESA's Cosmic Vision 2015-2025 programme. Due for launch in 2023, it will spend at least three years from around 2030 making detailed observations of Jupiter and its largest icy moons, Ganymede, Callisto and Europa including with J-Mag, the UK-led magnetometer.

Opportunities, either directly with NASA, or via ESA collaboration, for exploration of Uranus are also expected with a Uranus Orbiter and Probe (UOP). This was given the highest-priority new Flagship mission status for initiation in the period 2023-2032, following the NASA Planetary Decadal Review publication in 2022. The second highest priority in the NASA review for a new Flagship mission is an Enceladus Orbilander. Either mission could provide UK scientists and prospective instrument teams with opportunities that coincide with UK expertise built up during the Cassini, Huygens, JUNO and JUICE missions' development and operations. In addition, UK groups are increasingly contributing to the understanding of diverse chemical complexity which is possible on icy bodies and icy ocean worlds. This is essential laboratory-based research needed to help design instrumentation and strategies for future missions, as well as to understand the evolution of matter on these bodies in general to provide a context in which future mission data can be placed.

Figure 2.6. The surface of Jupiter's icy moon Europa imaged by NASA's Juno mission in September 2022 (NASA/JPL-Caltech/Southwest Research Institute).

2.1.4 Comets and Solar System Dust

Comets are largely icy bodies that accreted beyond the orbit of the giant planets and sample primitive reservoirs of the protoplanetary disk which can be investigated to understand the formation and evolution of planetary systems. UK leadership in comet science is set to continue through the Comet Interceptor mission. Scheduled to launch in 2029, Comet Interceptor will characterise the surface composition, shape, and structure of a pristine long-period comet, or potentially an interstellar object, in which there is significant interest following the discovery of the bodies 'Oumuamua and Borisov. Comets are also a major source of Solar System dust, along with smaller contributions from asteroids and the interstellar medium. Study of this dust provides insights into the composition of the parent bodies or reservoirs of the dust. Micrometeorites (typically <1 mm in size) represent the main part of the flux of extraterrestrial matter at the surface on the Earth, exceeding that from larger impactors into the atmosphere. Today several UK groups are active in collection of terrestrial micrometeorites and their analysis, including samples from Antarctica and urban samples collected from rooftops in the UK. Other groups are involved in the laboratory analysis of returned dust samples collected in space (e.g., NASA's Stardust mission returned both cometary and interstellar dust), or are active in designing new detectors to measure the dust flux in-situ in space.

Cis-lunar space will come increasingly into the ambit of interest in the next decade, with the Lunar Gateway and landers, offering ideal platforms for mounting dust detectors, some of which (e.g., from the Gateway) can be retrieved after long exposures, permitting detailed mineralogical analysis here on Earth. Mission proposals for detectors devoted to such a purpose continue to be made, including on any new interstellar probes as well as within the Solar System. Icy ocean worlds with naturally erupting plumes (e.g., Enceladus at Saturn, Triton at Neptune and possible Europa at Jupiter) all offer the possibility of collecting small particles close to their point of origin, thus exploring the interiors of these bodies without landing. Since these dust samples are usually collected in space via high-speed impacts, the use of hypervelocity impact facilities is vital in developing the relevant detector systems and understanding any alteration to the samples during collection.

2.1.5 Orbital Debris, Planetary Defence

In addition to dust of cosmic origin, there is a growing population of debris in regions visited by space vehicles. This debris is a particular hazard near the Earth. It comprises all objects placed into space by humanity, and the material they shed or produce over their lifetime in space. Some objects may even explode due to mission failures, detonation of unspent propellant, collisions with other objects, etc. There has even been deliberate destruction of spacecraft in weapons testing activities. All these disruptive events produce large quantities of small debris at the cm and mm scale or below. The relative speed in orbit means that impacts by objects of even 100 microns to 1 mm scale can cause serious surface damage on, or penetrate into the interior of an impacted body. Given the increased number of rocket launches and the ever-growing numbers of satellites, the flux of potential impactors is growing rapidly. Thus, the regions in Earth orbit favoured by satellites are now particularly at risk from the hazard posed by the debris related to human activities in space. The UK community, our National Space Strategy and ESA are now accordingly placing an increased emphasis on Space Situational Awareness. This includes measuring the total dust flux in Earth orbit (both from the ground for larger objects, and in-situ for the mm scale and below), determining the fraction of the flux due to debris, and developing mitigation strategies to reduce the rate of growth of the debris population. This problem is a serious risk to long term secure access to space and the utilisation of Earth orbit. The issue crosses the boundaries between planetary science and aerospace engineering, but represents a vital interest to all users of the space environment. The UK is involved with HERA, ESA's contribution to NASA's Planetary Defence, asteroid redirect mission (DART) which involved impacting the moon of asteroid Didymos in Sept. 2022. HERA (to be launched 2024) will visit the Didymos system to do a detailed post-impact survey of the results.

2.1.6 Exoplanets

It is important to evaluate how similar the planets in the Solar System are to those orbiting around other stars and the past decade has seen a major increase in both the number and diversity of exoplanet discoveries. There are now >5000 confirmed exoplanets (and 1000's more candidates) ranging from hot Jupiter-sized bodies to rocky super-Earths and multiple planet systems. Telescopes including NASA's Kepler and TESS, ESA's CHEOPS, and the UK-led SuperWASP have constrained fundamental properties (e.g., size, mass, and density) that provide key insights into the composition and interior structure of exoplanets. The launch and successful deployment of the JWST continues a transition to detailed characterisation of chemical signatures and the potential detection of moons that will transform our understanding of exoplanet formation and evolution. In particular, the UK has scientific leadership of the MIRI instrument on the JWST, which will be used to directly image larger exoplanets and determine the composition of exoplanet atmospheres, including those harbouring possible biosignatures. Further breakthroughs are expected to come from missions such as ESA's PLATO in 2026 followed by the UK-led ARIEL, which aims to investigate the compositions, structures and seasonal of exoplanet atmospheres. Comparative planetology is fundamental to unravelling the local history of specific planetary bodies, and in turn interpreting wider factors in protoplanetary disks, such as the location and migration of snowlines, variations in water-to-rock ratios, and the availability of radiogenic heat sources. Future missions to Solar System bodies combined with improved observations of disks around newly formed stars and further characterisation of exoplanets are expected to lead to significant breakthroughs in this area.

2.2 - P1: How did the Solar System form and evolve?

Our knowledge of the origin of all planetary systems requires systematic and detailed study of the Solar System, which contains the only presently known abode of life, and investigations of exoplanetary systems whose architecture is very different from that of our own. We need to understand in what ways Solar System planets are archetypes for bodies in other planetary systems. Therefore, we study early Solar System material, e.g., asteroids, comets, primitive meteorites (see Section 2.3), and interplanetary dust particles. Planets formed from the accretion of early Solar System material in the forms of dust and pebbles, ices, and gases in varying abundances related to their location in the protoplanetary disk. Physical properties such as the initial composition, mass, and orbit, strongly influenced the geological evolution of the planets, resulting in diverse interior structures, crustal mechanics, and atmospheric environments. The migration of Jupiter and Saturn likely scattered volatile-rich planetesimals from the outer Solar System into the terrestrial planet forming region, while late-stage giant impacts further shaped planetary systems. Continued efforts to combine analyses of extraterrestrial samples with exploration of planetary surfaces, high resolution astronomical observations, and computer modelling will be key to deciphering exactly where and when the first planetesimals formed in the Solar System, the role of planet migration, and the complex processes that modified planetary bodies.

Material remaining from the formation of the Solar System (comets, asteroids, Trans-Neptunian Objects) is also affected by changes in the evolution of the Sun, and may have had a major role in distributing material throughout the Solar System. Outstanding problems in understanding the early history of the Solar System include: (1) *What was the primordial state of the solar nebula?* (2) *How did the evolving*

Sun affect the evolving planets? (3) *What were the processes and timescales for accretion of the planets?* (5) *How and when did planets migrate?* These questions can be addressed via studies of materials from primitive and differentiated asteroids (Figure 2.7), lunar and martian samples (including future sample-return missions), as well as observation of ancient planetary surfaces such as those of Mercury, Callisto and the Moon. (P1.1 and P1.2)

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

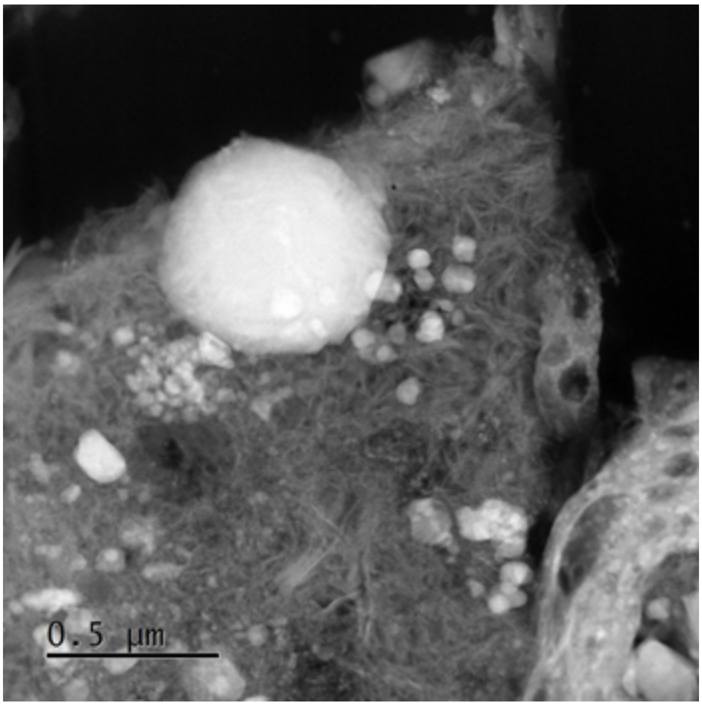

Figure 2.7. Over 5 g of water- and organic-rich material have been returned from the regolith of C-type asteroid Ryugu by the Hayabusa2 mission in 2020 (JAXA). HAADF image taken at ePSIC/U.Leicester of Ryugu material from Hayabusa2.

The evolution of a planetary surface is recorded in the surface observed today, from internal dynamics to surface and atmospheric processes. The diversity of planetary evolution within our Solar System is best demonstrated by the results of geological remote sensing, in-situ robotic studies and in the future by human assisted exploration. A greater understanding of the evolution of Mars has been made possible by access to high resolution, stereo images and topographic data coming from orbiters including Trace Gas Orbiter and Mars Reconnaissance Orbiter, and analysis of this, and data on the Martian interior from the Insight mission is ongoing. In-situ studies of planetary surfaces are also important in our understanding of their evolution, although so far, only the Moon and Mars (and, briefly, Titan, with the Huygens lander and comet 67P by the Rosetta lander) have benefitted from the deployment of instrumentation capable of providing appropriate information. Although we are able to study planetary and asteroidal bodies by remote methods, and also through analysis of meteorites, measurement of material returned from specific locations is vital. These locations include Mars (Mars Sample Return) or its moons (e.g., JAXA's MMX), as well as from specific asteroids (e.g., via Hayabusa2, OSIRIS-REx), and from new sites on the Moon (e.g., Chang'e 5 and from 2029 the EL3 Large Logistics Lander). Such work remains a key goal of planetary science research that is essential for understanding fundamental questions about Solar System evolution and planetary habitability. (P1.3, 1.4)

Hypervelocity impacts are ubiquitous throughout the Solar System: craters are seen on every solid surface and occur at all size scales. The InSight lander has detected impacts on the surface of Mars, providing constraints on the modern-day impact flux of the Solar System. Impacts are a major evolutionary driver of surfaces throughout the Solar System and understanding the physical processes that occur in the high pressure and high temperature regime that occurs during an impact are necessary to understand the compositional makeup of planetary surfaces. For example, light gas gun experiments are currently: testing hypotheses concerning the shock history of Ryugu samples, determining impact plume driven chemistry and developing sample collection techniques for future missions to plumes at icy satellites, etc. However, there are limitations to the physical size of a gun, so hypervelocity impacts on planetary scales have to be simulated using hydrocodes. By coupling the results from the experimental work into modelling insights are gained into planetary scale impact events: the formation of moons and the disruption of small bodies in the DART and HERA missions. (P1.3, P1.4, P1.5)

2.3 - P2: Earth's Place in the Solar System

As already stated, impacts can provide key insights into the origin and evolution of a body, including its surface and internal structures. The Earth is no different. The role of an impact in the Moon forming event and the role of impacts in changing the Earth on regional and planetary scales, e.g. via mass extinctions, still need further refinement. One critical aspect to be investigated is the record of airbursts in the Earth's atmosphere as well as large impacts upon the Earth (P2.1). These are increasingly seen as hazards which need to be understood. Yet our knowledge of impact processes is based on a combination of theoretical modelling, small-scale laboratory impact experiments, and field studies of generally poorly-preserved terrestrial impact craters (P2.2). In general, the surfaces of other planetary bodies offer a longer and sometimes cleaner record than that of the Earth in terms of the processes such as impacts that have operated throughout the history of the Solar System (P1.3 and P2.1). Indeed, the early crustal history revealed on other bodies records not only external processes (e.g., impact cratering, solar wind scavenging) but also internal processes (e.g., possible plate tectonics, volcanic activity) that are not available or accessible in the terrestrial record.

From within meteorites, we can isolate pre-solar grains (derived from stellar sources that existed prior to the birth of the Solar System), refractory grains (the earliest solid particles formed in the Solar System), chondrules (produced during high temperature flash heating events when the Sun was very young), and fragments of planetesimals that were formed and destroyed in the early history of the Solar System. Laboratory analysis of these components allows us to derive very precise timescales for the evolution of the solar nebula and the subsequent evolution of pre-planetary bodies. As well as lunar and Martian meteorites, as indicated by the recent studies of the Winchcombe meteorite, it is also possible to relate meteorites to specific regions of the asteroid belt and thus to probe the composition and evolution of asteroids. Micrometeorites provide the greatest contribution to the flux of extra-terrestrial material arriving at the Earth, and thus its study allows for a better understanding of the inventory of matter in the Solar System and its contribution to the geochemical budget of Earth. (P2.3)

Studies of planetary atmospheres on other bodies shed light on the evolution of Earth's atmosphere. For example, How do planetary environments respond to differing energy input in terms of climate, atmospheric chemistry, meteorology, cloud formation and atmospheric circulation? The presence of heavy organics in the nitrogen-rich atmosphere of Saturn's largest moon Titan and their possible evolution into "tholins" has prompted the discussion of Titan as a prototype for the atmosphere of the early Earth. Future studies of Titan's atmosphere and the driving of both the atmosphere and atmospheric chemistry by solar insolation and the deposition of energy via charged particle precipitation is important in understanding the potential role these processes played in the atmosphere of Earth and the "seeding" of the primordial soup by the precipitation of tholins. The atmospheres of other planets (e.g., Venus, Mars) can also give us insight into non-anthropogenic climate change that is occurring on Earth. How the atmospheres of these planets evolved into their present state, and the role of any solar wind or planetary magnetosphere interactions in this process are significant issues. (P2.3)

2.4 - P3: How widespread is life in the Solar System?

The Solar System exhibits a great diversity of planetary environments, many of which contain some or all of the essential requirements for life as we understand it: liquid water, an energy source, nutrients, and stable sheltered environments. Guided by the diversity of life on Earth and the conditions that sustain it, we can explore many of the planets and satellites within the Solar System where similar conditions exist (or have existed in the past). Setting aside the direct observation of active lifeforms, the detection of extinct or extant life relies on the detection of appropriate biomarkers, and key questions include what these biomarkers are, and how they are influenced by different environmental effects such as oxidising chemistry and radiation (P3.1). Crucial to the development of life is the formation of prebiotic molecules; the chemical processes that produced these molecules, and the environments where they formed (interstellar space, asteroids, comets) are not completely understood. Indeed, how life begins and in what environmental conditions, are not understood. For example, it is not just enough to say a habitable zone is defined by the conditions necessary for liquid water. The interaction of the overall environment (radiation, pressure, energy inputs etc.) and the liquid water is crucial in defining a genuine habitable zone (e.g. are sub-surface oceans on icy satellites habitable?). Future research will lead to a more complete understanding of these processes, how life forms from simple prebiotic molecules and in what environments this may occur (P3.2, P3.3).

Our understanding of habitability includes the warm environments inside the icy moons of the giant planets. This is of clear relevance for our understanding of exoplanetary systems and the search for extinct or extant life beyond Earth. Further, we need not only to investigate places within the Solar System in which there is or was liquid water (e.g., Mars, icy satellites), but also areas where ice-water has been sequestered since early Solar System times, such as the poles of Moon, craters of Mercury, Main Belt Comets and other cometary populations, and the Kuiper Belt. (P3.3)

The search for life beyond Earth has historically concentrated on studies of Mars, which meets (or met) all of the essential requirements for life. It also offers a chance to investigate the abiotic-prebiotic-biotic transition that is not possible on Earth. The stratigraphic record of Mars provides a rich record of the history of the planet, revealing time-periods and processes vital to understanding the formation and evolution of early life. Exploration of Mars includes the main objectives: (1) to characterise past and present habitability and search for evidence of life; (2) to characterise ancient and recent climates and climate processes; (3) to characterise the nature and evolution of surface and interior processes. Investigations of analogues and simulations are complementary to mission exploitation. The key science investigations required to address the issue of habitability involve understanding the geological, geochemical, photochemical and radiochemical processes that control atmospheric, surface, and shallow crustal chemistry, particularly where it bears on the provision of chemical energy and the availability (abundance, mobilisation, and recycling) of bio-essential elements and molecules. It is crucial to ascertain the nature and abundance of possible chemical energy sources that can drive organic and biological chemistry. It is also important to understand the role of global and local magnetic fields in providing environments that can protect (pre-) biotic molecules and life-forms themselves. The multi-scale nature of the problem is thus evident. (P3.2, P3.3)

These questions and investigations are particularly pertinent in the study of icy moons surrounding the giant planets. The presence of heat inside the volumes of icy planetary bodies provides the necessary energy to drive organic chemistry leading to life. The presence of oxidants is an essential component to the question of habitability and observational and laboratory studies characterising the radiolytic processes in planetary ices are essential in understanding the generation of oxidants on the surfaces of the icy moons that orbit the giant planets. A strongly linked question is the role of tectonic and volcanic/cryovolcanic processes in cycling the surfaces of terrestrial and icy bodies, thus transporting surface oxidants into interior oceans. These same oxidants and radiolytic processes are also important in degrading the signatures of extant life. (P3.2, P3.3)

It is possible that at least part of Earth's oceans were derived from water delivered to Earth by cometary and asteroidal impacts. Identifying the source population for this water is a key scientific investigation with important UK leadership (P3.4). The key measurable is comparing the D/H ratio of cometary and asteroidal populations. Until recently, the D/H ratio of comets was thought to be incompatible with that of Earth's oceans. However, comets and volatile-bearing bodies in the Asteroid Belt which may have formed in-situ, represent an opportunity to sample volatile material – readily accessible by spacecraft – that formed at its present location in the Solar System. Further, the poles of the Moon provide an accessible archive of hydrated asteroids and comets delivered in the past to the Earth-Moon system. Such data would be hugely valuable for early Solar System formation models and furthermore, isotope measurements could help establish a source for Earth's water. Other key questions include: (1) How could such bodies have remained in situ throughout the lifetime of the Solar System? (2) How widespread are the Main Belt Comets? (3) What drives their activity, and how important are inter-asteroid collisions in exposing volatile material? (4) How are volatile budgets modified during planetary collision processes? Further remote and in-situ studies of comets and asteroids, and also analysis of ice at the poles of the Moon, are necessary to answer these key scientific questions in the evolution of Earth and the emergence of life on Earth. (P3.4)

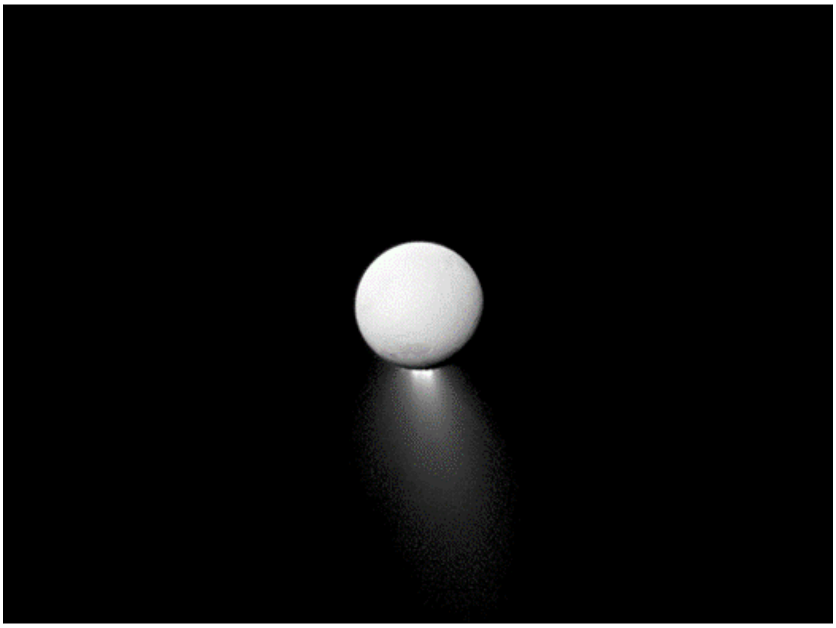

Figure 2.8. A plume of gas and icy particles spouting from the surface of Saturn's geologically active moon Enceladus (NASA/JPL-Caltech/Space Science Institute).

Identifying other locations in the Solar System with liquid water is an essential step in understanding the wider volatile inventory of the Solar System. Not all the Jovian and Saturnian icy satellites are yet sufficiently characterised to be able to determine if they have internal oceans. The Uranian and Neptunian satellites need similar characterisation. Indeed, 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. On a body such as Mars, where water once flowed freely, we need to understand what fraction of the volatile inventory has been lost to the solar wind and heliosphere, and what fraction has been stored in the crust of Mars. Both modelling of climate change and water-loss processes, and a better understanding of these processes in terms of the environmental history of the planet are required. Understanding the interior, atmospheric, surface and magnetospheric structures of planets and moons within the Solar System is crucial to providing constraints on the volatile budget. We need to understand why the giant planets (and their numerous moons) are so different from each other, in order to constrain models of planet formation. Finally, we have little understanding of how solar radiation and solar plasmas have affected the formation and evolution of Solar System bodies, from small bodies such as comets and asteroids, to full-scale planets. Measurements of the composition of asteroids, comets, small bodies and the giant planets (particularly the ice giants) is required to fully understand the wider inventory of volatiles such as ammonia and methane. This requires in situ and sounding measurements of the giant planets, remote and in-situ observations of small bodies, and sample-return missions to various small bodies. (P3.4)

Beyond the Solar System it is important to determine the effect of stellar class on processes relating to life. In terms of planetary systems elsewhere in the Galaxy, we do not yet understand how habitability relates to star-type. 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?) (P1.6, P3.3)

2.5 UK Expertise relevant for Theme 2

The UK has around 30 research groups active in planetary science research, totalling approximately 200 researchers. Despite a period of overall 'flat cash' UKRI funding in the UK since publication of the 2015 Roadmap, it continues to be recognised as a leading exponent of the laboratory-based analysis of extraterrestrial materials, as well as remote sensing of planetary atmospheres, surfaces and magnetospheres, small body dynamics and exoplanet detection. The field of astrobiology is an important sub-discipline within planetary sciences; the UK was amongst the first to recognise the subject as a cognate area and continues to be a major international driver of the subject, with significant investment flowing to that discipline within the UK, and several institutions hosting dedicated multi-disciplinary centres in the field and development of new technology for return of Mars samples to terrestrial laboratories.

- The UK has some of the best equipped laboratories in the world for the analysis of extra-terrestrial material, and UK expertise in this field located within universities, research institutes and centralised facilities is world-renowned.
- The Diamond Light Source 3rd generation synchrotron and the ePSIC electron microscopy facility, both located at Harwell, have maintained relatively high levels of investment in new equipment, beamlines and staffing. This enables UK researchers and visitors to the UK to make world-leading analyses of material from sample return missions and newly discovered meteorites. A major upgrade to Diamond is expected around 2025. A potential future STFC Curatorial Facility for planetary materials would benefit from existing facilities at Harwell and act as a central hub for UK and ESA studies of samples returned from space.
- Preparation for the now suspended ExoMars2022 mission, together with Mars Sample Return, Mars Science Laboratory and the CaSSIS and HiRISE imagery have stimulated the development of expertise and a successful research theme and expertise in the UK. This has been fostered by the UKSA Aurora science programme, which links instrument teams e.g., PanCam, CaSSIS, Raman RLS with operations and science exploitation, avoiding potential problems with a UKSA-STFC Dual Key approach.
- UK scientists and engineers are uniquely placed to play an important role in the lunar science and exploration renaissance; we are leaders in both tackling fundamental lunar science questions relating to the origin and evolution of the Moon, and lunar volatiles (10% of the principal investigators holding NASA Apollo samples are UK-based) and developing future lunar mission hardware (e.g., the ProSPA chemical laboratory and Lunar Thermal Mapper on Lunar Trailblazer). There is also a broad UK interest in radio-astronomy experiments from the lunar farside.
- The UK continues its strong legacy of planetary remote sensing and observation, with UK scientists participating in research and modelling of data from Venus, Mars, comets, the Moon, Mercury and Jupiter. In particular, UK scientists are leading instruments on several on-going or planned missions, including the MIXS-T X-ray telescope on BepiColombo to determine the composition of the Mercury surface at a few km resolution, the Lunar Thermal Mapper on NASA's Lunar Trailblazer, MIRMIS and the fluxgate magnetometer on Comet Interceptor, plus a science leadership role on EnVision.
- There is strong potential for a long term, UK-led Antarctic meteorite collecting programme, involving the British Antarctic Territory and collaboration with the British Antarctic Survey as an essential logistical element and collaboration across the research councils. Several successful recovery trips have already been made, and continued support would increase the number of meteorites available to UK researchers and enhance the chances of finding rare or new meteorite types.
- The UK currently has six active meteor and fireball camera networks, which collaborate as the UK Fireball Alliance (UKFAll). The networks are both academic and citizen-science led and consist of >150 cameras covering approximately 50% of the UK sky. Footage from the UKFAll led to the successful recovery of the Winchcombe meteorite in 2021, and increased coverage in the next 5 - 10 years will likely see the recovery of further UK meteorite falls. With a centralised computing facility and research infrastructure, the camera networks also have the potential to generate large open access datasets that can be exploited to investigate other astronomical phenomena, contribute to planetary defence, and monitor satellites and space debris.
- The UK is a leading international centre for hypervelocity impact studies. There is significant strength in computational hydrocode studies of impact events (which can be applied at all scales), and there are three operational impact hypervelocity facilities studying planetary science providing impacts at speeds in the range 1 - 7 km s^{-1} and samples shocked to the 10s – 100s of GPa scale.
- LARES is a consortium - 21 institutions and ~80 researchers - of UK planetary materials laboratories. This covers a wide range of mineralogical, isotopic, geochemical capabilities convened to investigate the formation of planets, moons, and minor bodies in the Solar System. To achieve this, it aims to build on existing expertise and facilities to develop a UK-wide integrated network of specialists and state-of-the-art laboratory instrumentation for the preparation, analysis, and curation of extraterrestrial samples. Such samples might include those from asteroids (e.g., Ryugu, Bennu), Mars and Phobos, the Moon, new UK meteorite falls, and meteorites from hot and cold deserts.
- Astrobiology is a major forte of UK scientific activity. In terms of attempting to detect life, UK teams have built miniaturised mass spectrometers, X-Ray and IR spectrometers and environmental sensors. UK groups have also led projects on characterising the nature of life in extreme environments on Earth, and characterised microorganisms in samples exposed to space conditions in orbit.
- The UK is world-leading in the detection and characterisation of exoplanets using both ground- (e.g., SuperWASP) and space-based facilities (e.g., MIRI on the JWST, ARIEL) and hosts several internationally recognised research groups that specialise in observational

and theoretical studies of exoplanet interiors and atmospheres, and understanding their potential role as habitable environments. This is continuing with JWST-MIRI, PLATO and Ariel, with major UK involvements for instrumentation (e.g., MIRI) and science.

2.6 Key missions and requirements for Theme 2

- Unique samples which contain components dating from the earliest stages of Solar System formation are now available to UK researchers from the JAXA Hayabusa2 mission, and in the next 1 – 10 years, NASA's OSIRIS-REx (in 2023) mission to asteroid Bennu and JAXA's MMX mission to Phobos (P1.1, P1.2). The direct return of samples from a primitive asteroid, such as by the Hayabusa2 and OSIRIS-REx missions, is also allowing detailed study of an intermediate stage in the transition from prebiotic to biotic molecules, as well as how the organic molecules are bound with inorganic species (P3.2).
- A necessary requirement for any sample return mission, whether from an asteroid, a comet, the Moon or Mars, is an appropriate Sample Curation Facility to undertake curation and storage of the material, and to house the instrumentation essential for preliminary examination of the returned samples (P3.1).
- Determining the environment of formation of prebiotic molecules, the reaction chemistries they follow, and the products of the reactions requires laboratory infrastructure for simulation and analysis of appropriate molecular species, as well as HPC to model reaction pathways (P3.2).
- A new era of lunar exploration research in the UK is expected to be driven by the NASA-led Artemis programme and Lunar Gateway with its aim of renewed human exploration of the Moon. In total at least 17 more robotic missions to the Moon are planned by 2030 (with many more commercial missions in the pipeline). The Large Logistics Lander EL3 - with the planned capacity to land 1500 kg payloads to the surface of the Moon by 2029 - is the Planned ESA-led contribution to Artemis. The UK's strengths in communications technology can also be developed with ESA's Lunar Pathfinder with its aim of creating a network of communications and data relay satellites. Both missions have UK involvement and are part of the international impetus towards future human bases on the Moon. The ProSPA chemical laboratory developed in the UK builds on heritage in miniaturised mass spectrometers and is a possible payload for future landing missions. New in situ resource utilisation technology will be needed for lunar and martian exploration. The NASA SIMPLEx programme mission (Small Innovative Missions for Planetary Exploration) called Lunar Trailblazer, carries the Lunar Thermal Mapper which was also developed in the UK. Lunar Trailblazer targets the notable discovery that the surface of the Moon bears water ice in places (P1.3).
- Detailed maps of the surface of different planetary bodies are required in order to understand their impact histories, compositions, and potential future resource utilisation. The latter includes H_2O trapped in the near surface lunar environment (P1.3, P1.5, P2.1, P3.4).
- Mars Sample Return is a high priority in the UK and internationally. The 2022 NASA Decadal Survey recently described MSR as its highest priority in planetary science and, together with ESA's commitment to MSR, this is likely to drive forward UK contributions to both flight and ground-based parts of MSR. The current UK priorities include Mars2020 participation, and MSR sample analysis campaign planning activities, the Double Walled Isolator technology for Basic Characterisation of samples in containment, and the possibility of an UK-ESA Curation Facility for MSR and other extraterrestrial samples (P1.3).
- Over the next few years Mars2020, Mars Science Laboratory, Trace Gas Orbiter, Mars Reconnaissance Orbiter, and InSight will continue to provide opportunities to understand Mars crustal differentiation and water-rock reactions, the switch from the ancient 'warm and wet' to today's cold and dry environments, and current atmospheric processes, compounds and structure. Mars Reconnaissance Orbiter continues to provide the highest resolution imagery available of Mars at 30 cm per pixel with the HiRISE camera, and CaSSIS on TGO gives a unique colour view of the martian surface. These datasets allow geological and geomorphological mapping second only in detail to that conducted on the Earth (P1.3, P2.4, P3.4).
- A notable set-back to the planetary community's planned Mars research is a suspension of the ExoMars mission due to the Russian invasion of Ukraine. At the time of writing, it is unclear what alternative, such as a launch later in the decade, may be possible. However, the planetary community is clear that the major investment in building the science community's expertise and developing instruments on the rover (PanCam and Raman in particular) should be preserved. This can be achieved either through a later launch of ExoMars without Russian involvement, with new bilateral, ESA/NASA mission opportunities or, if necessary, using the instruments on different mission opportunities such as lunar surface exploration (P1.3).
- The Mars Ice Mapper (MIM) mission due to be launched in 2026 will be the first synthetic aperture radar mission at Mars, will have important implications for astrobiology, and synergies with the radar mapping on the EnVision Venus mission. The MIM orbiter will map shallow subsurface ice to characterise accessibility for initial ice core sample return and eventual in-situ resource utilisation (ISRU) by human missions (2040s onwards). Support for UK science participation in MIM will allow researchers to influence mission science and build UK expertise ready to contribute to preparations for human exploration (P1.3, P3.4).
- ESA's EnVision is scheduled to launch around 2031 and will address how the surface and interior of Venus evolved and how Venus' atmosphere and climate have been controlled by geological processes. EnVision will allow high resolution radar mapping - with the UK potentially playing a key role in radar processing - and be complementary to the NASA orbiters VERITAS (recently delayed) and DAVINCI+, which is set to investigate Venus in 2029 (P1.3, P2.4).
- Mercury will be a world of increasing study as data flows in from BepiColombo, especially after reaching mapping orbit in 2025. The UK is leading the Mercury Imaging X-ray Spectrometer MIXS instrument on BepiColombo. Its telescope channel MIXS-T in particular will allow unrivalled surface compositional detail at the scale of km's, forming the basis for a deeper understanding of planetary differentiation. MIXS will also be used to analyse the auroral signatures at Mercury, and thus play a major role in understanding the

solar wind-magnetosphere-surface dynamics of Mercury (P1.3, P2.4).

- A Uranus probe has recently been highlighted by the NASA Decadal review as high priority. This opens an opportunity for UK and ESA instrumentation and science involvement in a new stage of Gas and Ice Giant exploration, giving more comprehensive comparisons between the planets. The science case for this is based on the bulk elemental and isotopic composition of the giant planet atmosphere, and what this reveals about the formation, migration, and evolution of the planet. Secondly, a Uranus entry probe will investigate the environmental processes shaping conditions within and below the clouds, at depths hidden from remote sensing. The ESA Voyage 2050 programme may give an opportunity for an M-class equivalent contribution to the NASA-led Uranus mission. Consortia of UK instruments (based on those involved in Cassini and JUICE) are currently forming with the aim to provide instruments on the orbiter and an entry probe, either through ESA or some future bilateral arrangement (P1.4, P3.4).

- In the post Cassini mission era, and since the last SSAP Roadmap, a significant element of the UK's outer Solar System science has focused on NASA's JUNO mission - which is now expected to last until 2025 - to Jupiter. The UK has scientific roles in both the Magnetospheres and Atmospheres investigations, including analysing data from JIRAM, JunoCam, MWR, and the particles and fields instruments. Groups around the UK are involved in the supporting ground-based programme, and in numerical modelling of the Jovian interior and atmosphere (P1.4).

- JUICE - JUpiter ICy moons Explorer - is the first large-class mission in ESA's Cosmic Vision 2015-2025 programme. Planned for launch in 2023 and entering Jovian space in 2031, it will spend at least three years making detailed observations of the giant gaseous planet Jupiter and three of its largest moons, Ganymede, Callisto and Europa, including entering orbit around Ganymede. The J-MAG - a magnetometer instrument for JUICE, is UK led (P1.4, P3.3, P3.4).

- The NASA Europa Clipper, planned launch 2024, with operations at Jupiter from 2030, including an emphasis on studies of Europa, is part of a major focus on giant planets in the coming years. The proposed NASA Enceladus Orbilander for the 2030s, highlighted in NASA's decadal survey, continues this, and may offer opportunities for UK science at a bilateral level (P1.4, P3.3, P3.4). As missions to the outer Solar System continue, it is important to fully characterise the interiors of the icy satellites of all the outer planets to determine the volumes of internal water and the conditions under which it is held (P3.4).

- Comet Interceptor is an ESA F-class mission selected as part of the Cosmic Vision Programme. Launching in 2029, it will make a flyby of an as-yet undiscovered pristine comet (or potentially interstellar object) that samples materials leftover from the start of the Solar System. The UK is providing the MIRMIS imager and fluxgate magnetometer, along with mission-wide leadership of the science team (P1.5). Ground-based studies of comets and other bodies will benefit from CUBES; a UV optimised spectrograph for the Very Large Telescope (VLT-ESO) expected to see first-light in 2028.

- The analysis of meteorites, including those from a UK-led Antarctic recovery programme, micrometeorites, interplanetary dust particles and previous sample return missions (e.g., Stardust, Hayabusa) will continue to be a key part of the UK planetary science community's priorities. In addition to the established sources of these samples, the February 2021 fall and rapid recovery of the Winchcombe carbonaceous chondrite demonstrated the potential for dedicated meteor and fireball camera networks to provide new and pristine meteorites for our active UK planetary materials community (P1.5, P2.3).

- Sample return and new meteorite opportunities require access to world-class analytical facilities and laboratories within the UK. The Diamond synchrotron's beamlines and ePSIC microscopy suite at Harwell enable the analysis of the small sample sizes associated with sample return missions and rare meteorites. The Diamond II facility with upgraded beamlines and optics (in around 2025) will help maintain this as a world leading facility. State-of-the-art instrumentation, embedded within UK universities and research centres is also required to maintain the UK's ability for leading planetary materials research (P1.3, P1.5, P2.3).

- The impact record of the Solar System can best be established by detailed, high resolution mapping of planetary surfaces from orbit and chronological studies of planetary materials (meteorites and returned asteroid, lunar and martian samples). This requires the current and future missions listed earlier, and investment in analytical laboratory equipment for sample analysis studies (P2.1).

- Cross council e.g., EPSRC, NERC, STFC collaboration could help facilitate the instrumentation needed and provide valuable new interdisciplinary research themes between engineering, materials, environmental and planetary science. The LARES consortium of UK universities and research centres is another potential avenue for renewing some instrumentation - mineralogical, geochemical, isotopic - used in planetary materials research (P1.3, P1.5, P2.3).

- The MIRI instrument on the JWST has UK science and engineering leadership. Following the recent successful deployment of the JWST, this mid IR instrument is allowing characterization of the atmospheres of transiting exoplanets, giving key comparisons to MIRI observations of the Solar System's giant planets (P1.6).

Theme 3: Space Plasma Processes

3.1 Introduction

Space plasma physics processes are of foundational importance to understanding the nature and behaviour of many phenomena observed in the Solar System, and also have application to astrophysical plasma environments. The first sub-question (SP1) focuses on what could be regarded as 'micro-physical' processes, and reflects the considerable progress in the past decade and the exquisite measurements that have been returned by many recent space missions meaning that we now cannot ignore the plasma distribution function. The next four sub-questions (SP2, SP3, SP4, SP5) focus on what are generally considered to be the three major 'macro-scale' plasma phenomena that have wide and enduring relevance for our Solar System: turbulence, reconnection and shocks. Sub-questions SP6 and SP7 connect all the previous questions. SP6 reflects the progress made in the past decade towards understanding space plasmas as systems that are fundamentally coupled across significant spatial and temporal scales, with large-scale emergent behaviour. SP7 focuses on the specific problem of particle acceleration, which can arise through a plethora of mechanisms, many aspects of which are still not understood. Whilst evidently important for a wide variety of Solar System phenomena, this question also connects to astrophysics more generally. SP8 solidifies this connection by asking, how completely can we understand and interpret the sources of electromagnetic emission? Finally, given the fundamental importance of magnetic fields to Solar System phenomena, SP9 returns to the basic question of how magnetic fields are created and sustained.

The UK has internationally-leading expertise in all these science questions. This capability is noted in the section discussing Theme 1, and so we refer the reader to that part of the roadmap rather than repeating that information here. Similarly, the missions/facilities and requirements to address these questions are largely covered in Theme 1, and so we do not repeat them here in the interests of brevity.

Key questions
SP1 How is the behaviour of space plasma influenced and controlled by the shape of its distribution function?
SP2 How do waves behave in inhomogeneous plasmas?
SP3 What is the correct, self-consistent model that describes space plasma turbulence?
SP4 How, and on what space/timescales, does magnetic reconnection convert energy and change space plasma magnetic field topology?
SP5 How, and on what space/timescales, do collisionless shocks mediate space plasma flows and repartition energy?
SP6 How does cross-scale coupling lead to emergent behaviour that cannot be explained by individual plasma processes?
SP7 How do space plasma processes efficiently accelerate different particle species?
SP8 How completely can we understand and interpret the sources of electromagnetic emission?
SP9 How are magnetic fields created and sustained?

3.2 - SP: What are the fundamental space plasma processes at work in the Solar System?

SP1 How is the behaviour of space plasma influenced and controlled by the shape of its distribution function?

With space missions such as Parker Solar Probe and Magnetospheric Multiscale, space plasma physics has now firmly entered the 'kinetic' age. The quality and detail of the data returned by these and other missions means that to understand and address the cutting edge questions about how space plasmas work, it is necessary to apply kinetic theory that addresses the evolution of the distribution function. This is intimately related to understanding how waves are generated, and where, how and why instabilities develop in different regions of both real and parameter space. These questions cut across all of the Theme 1 questions.

SP2 How do waves behave in inhomogeneous plasmas?

Waves, and wave-particle interactions play an important role in transporting and converting energy in a wide variety of Solar System contexts, from waves in the interior, photosphere, chromosphere, and corona of the Sun, to the solar wind, to planetary radiation belts. They offer important diagnostic information as they propagate through the highly-structured plasma medium, now seen in the current generation of high-precision Solar System observations, giving enormous potential for solar, stellar and other astrophysical seismology. The key scientific questions to answer are: What are the mechanisms for, and efficiency of, wave generation and guiding? How does wave scattering, conversion, dispersion and dissipation occur in dynamically evolving plasma inhomogeneities? What is the role of waves in the 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?

SP3 What is the correct, self-consistent model that describes space plasma turbulence?

In the past decade substantial progress has been made elucidating the properties of space plasma turbulence, in particular using data of increasing resolution to explore the transition from fluid-like behaviour to scales where the ion, and indeed electron, gyration cannot be ignored. Whilst theories have been developed to explain different aspects of turbulence, a complete and self-consistent model remains a 'grand challenge'. Turbulence can be studied throughout the Solar System, most notably in the solar wind, but also in planetary magnetospheres in a variety of contexts. This offers a wide range of parameter space to study the turbulence problem.

SP4 How, and on what space/timescales, does magnetic reconnection convert energy and change space plasma magnetic field topology?

The general understanding of magnetic reconnection has been transformed by new observations, particularly from Magnetospheric Multiscale, as well as advances in computer simulations. This has, for example, revealed the structure of the diffusion region down to the electron scale, but also presents un-ignorable evidence relating to the 3-dimensional nature of reconnection and the general complexity of plasma distribution functions created by reconnection. This progress has therefore unlocked the next level of enquiry, aimed at understanding where, when, and how energy is converted from being stored in the magnetic field to jets, heating, and accelerated particles, and unifying models and understanding based on in-situ data (typically in planetary magnetospheres) and remote sensing (i.e. the solar corona). The discovery of electron-only reconnection on small scales in the turbulent magnetosheath has underlined the fact that reconnection acts on a variety of scales.

SP5 How, and on what space/timescales, do collisionless shocks mediate space plasma flows and repartition energy?

Shock waves are ubiquitous in the Solar System because of the super-magnetosonic flow of the solar wind. Planetary bow shocks span several orders of magnitude of Mach number, and comparative studies have improved our understanding of the general properties of shocks. More detailed measurements of the Earth's bow shock have further revealed the full complexity of behaviour, but with a new generation of computer modelling, the relationship between different parts of the shock, and its dependence on the magnetic field geometry and plasma beta has become clearer. Nevertheless, the way in which the quasi-parallel shock works (where the magnetic field is aligned to the inflow) remains poorly understood. Recent discoveries of so-called magnetosheath jets, where the shock periodically fails to locally process the inflowing plasma, are calling into question basic understanding of how shocks work.

SP6 How does cross-scale coupling lead to emergent behaviour that cannot be explained by individual plasma processes?

As mentioned elsewhere, there has been considerable progress in understanding different individual plasma processes, with space missions that have often been targeted to a particular region, plasma scale, or phenomenon. In making this progress, the fact that different phenomena are coupled – across regions, spatial and temporal scales has become unignorable. For example, data now clearly shows that shocks generate turbulence in the downstream flow, and that within this turbulence, reconnection is acting to repartition the downstream energy. In the Earth's magnetotail, magnetic reconnection can generate turbulent jets, inside which further reconnection is seeded. This so-called emergent behaviour is hard to decouple from the constituent processes. Up to now, the imaginative use of fortuitous conjunctions between different space missions has enabled some insight, but there is a general recognition that further progress depends on multi-point, multi-scale plasma measurements.

SP7 How do space plasma processes efficiently accelerate different particle species?

Energetic particles are an important component of space plasmas which challenge our understanding of how non-thermal particle populations arise, in particular the processes that can boost particles to extremely high energies. It is likely that a variety of processes, acting in concert, enable this, but there is a lack of understanding of how, when and where acceleration happens in different Solar System environments. Energetic particles are also the source of electromagnetic emission that can be used to remotely observe space, solar and astrophysical phenomena, and so understanding how this works across the domains we can access in the Solar System will shed light on other objects beyond.

SP8 How completely can we understand and interpret the sources of electromagnetic emission?

In recent years it has become ever-more clear that space, solar and astrophysical observations provide a richness of spectroscopic data which has in fact outpaced efforts in the laboratory to benchmark expected spectra. Spectroscopy remains one of the fundamental tools to diagnose and understand processes on the Sun, and so this is a necessary part of understanding remotely sensed Solar System regions. In a related point, the growth of other mechanisms (e.g. solar wind charge exchange leading to soft-X-ray emission from the magnetosphere), reinforced by outer planets remote sensing (e.g. auroral emission across the electromagnetic spectrum), means that in the coming years there should be renewed efforts to maximise our understanding of this overarching question.

SP9 How are magnetic fields created and sustained?

The formation of magnetic fields in the Solar System is central to understanding its physical behaviour. From the Sun to Ganymede, there is a wide variety of magnetised objects, all of which generate magnetic fields via internal convection and dynamo action. There is no overarching understanding of how such magnetic fields are created and sustained. Insight into the basic question as to why some solar cycles are stronger than others is expected from Solar Orbiter, which as it moves to higher latitudes, will provide the first remote sensing information about the dynamics of the solar polar regions. In planetary dynamos, the final results of the Cassini mission, showing negligible dipole tilt even in the grand finale data, stand firm as a grand challenge to our basic understanding of how planetary magnetic fields arise. Future exploration of the ice giants, where the rotation and dipole axes are highly non-aligned, will further challenge our understanding, and JUICE and BepiColombo will similarly challenge our understanding by investigating the small, but vastly different, magnetospheres of Ganymede and Mercury, respectively. Finally at Mars, the evidence that this planet had a dynamo which ceased action remains a puzzle with implications for understanding its habitability.

Cross-cutting Activities

As mentioned in the Introduction, the delivery of the above science themes is underpinned by a variety of cross-cutting activities. These are areas of significant importance for all Solar System research, and we are grateful to the UK Solar System community for their input on these matters. They relate to fundamental, long-term issues concerning infrastructure, facilities and funding models, and so SSAP offers Recommendations against each activity with the aim of maximising the return on investment in UK Solar System research. These activities are listed alphabetically and hence the order in no way indicates ranking in terms of priority.

C1. Data Centres and Data Archiving

The STFC's scientific data policy requires all STFC-funded activities, facilities and grant proposals to have a data management plan. It states that data should normally be managed and made publicly available through an institutional repository. It is, therefore, important that STFC supports data archiving facilities to an adequate level in accordance with its own data management policy and that STFC and AGP recognise that long-term data storage requirements extend beyond the three-year consolidated grant lifetime.

Having gathered data from the many missions, facilities and models, it is of great importance that these data are made freely available to the community in order that they can be exploited fully. Storing data also involves gathering and storing all information that explains where the data come from, how the measurements were made and what processing has been carried out on them. Historical data sequences are of tremendous value in understanding the context of modern observations.

While STFC/UKSA missions archive their data through existing and proposed data centres, this process is funded (ad-hoc) through the post-launch support for each mission and core funding for such data centres is minimal. Given the ever-increasing rate of data collection, the issue of sustainable data preservation is one that needs to be addressed sooner rather than later.

Recommendation: *To promote a culture of open-data, and maximise the long-term return of UK investment in missions and instrumentation, it is paramount that STFC fully supports data storage and curation both for individual scientific projects and missions and facil*ities.

C2. Grants, Fellowships and Studentships

In response to our Community Survey, only 39% of respondents were satisfied with the current balance of support provided by STFC for different aspects of Solar System research (i.e. the balance of funding between development, operations and exploitation). Exploitation (particularly the need for increased funding for PDRAs) remains the community's key priority, including the grants line and Fellowship and Studentships programmes. The community strongly feels that after more than a decade of flat-cash funding, there simply is not enough money. The short-term nature of PDRA funding (2-3 years) and a perceived expectation to move institutions as an ECR, results in lack of job security and stability, and may disadvantage some groups within the community. Further points included: tension between short-term grant funding cycles and long-term mission-related support, and for technical and software engineering posts, and unsustainably low levels of PI funding, with a number of responses indicating that some universities are now requiring significant funding of PI time for PI's to be considered 'research active'.

Fellowships and Studentships are the main pathways for bringing young people into research, technology and academia. The Fellowship programme is an important way of recognising and training future leaders in the field, who will continue to drive research forward, to the benefit of the UK and its ability to compete effectively at international levels. They also form the next generation of academics. Studentships introduce young people to the research community, and equip them with a variety of high-level skills in communication, programming, data analysis, and presentation, that have application far beyond what might be a relatively-narrow research topic. The skills acquired through studying for a PhD are of great benefit to the UK as a whole, not just for those who remain in STFC-funded research.

Recommendation: *Increasing the exploitation funding line level (cash basis, not percentage of the programme) should be a top priority for STFC. Grants, fellowships and studentships have been chronically underfunded and are at a level where the community's international leadership position cannot be maintained. SSAP welcomes the recently announced uplift in the STFC grant line but a further uplift will be required to return this to an internationally competitive level (particularly if association with Horizon Europe is not achieved).*

C3. High Performance Computing

High Performance Computing (HPC) is essential across Solar System research and, indeed, for all STFC-funded theoretical research. Almost all the scientific questions defined in the preceding sections are dependent on HPC facilities. In addition to the HPC needs of simulations, access to appropriate HPC facilities is essential for the successful analysis and interpretation of observational data. Furthermore, space missions generate large data volumes and accessing and processing these data is a major undertaking. HPC facilities should be seen as an analogy to an observational facility, and both are essential for our goal to understand the Solar System.

Although the community welcomed the DiRAC-3 upgrade in 2021, the reality is that the update was long overdue and that international competitors have benefited from more rapid investment. A long-term and sustainable strategy for HPC is an essential requirement if the UK is to regain its leadership position in high performance computing.

HPC expertise across the UK SSAP community is internationally recognised but to maintain this position, investment in training of PDRAs and PhD students is required, as well as a funding model which allows long-term support for development of computational models. Training in HPC skills is a major benefit to students, both those who wish to stay in the field, and those who enter other fields, since students with good HPC skills are highly sought after in non-academic positions. Although the UK community has a strong tradition of writing and developing its own codes, international competitors are 'professionalising' code development through engaging software engineers. It is important to recognise the long-term nature of code-development which requires funding on longer timescales than a 3-year funding cycle. Grants panels must recognise that publication rates will often drop during periods of code development.

Recommendation: *HPC is now a core requirement across Solar System research and SSAP strongly urges STFC (and UKRI) to implement a long-term, sustainable HPC strategy. The investment in hardware must be accompanied by support for skills training for early-career researchers and STFC should recognise the long-term nature of code development and the requirement for support for highly skilled people on timescales beyond the 3-year funding cycle.*

C4. Laboratory Infrastructure

Laboratory experimentation is a key part of Solar System science exploration. The benefits of laboratory experiments include the ability to modify methods and techniques as appropriate, the capacity for repeat measurements to gain high accuracy and precision, the opportunity to gain extra information by applying complementary techniques and enabling inter- comparison between different materials and laboratories. There is also the added benefit of being able to archive samples for analysis in the future, when new techniques become available.

The SSAP recognises the important role that national and international laboratory facilities, such as the Diamond Light Source and ePSIC, have for its research. These facilities continue to benefit from investment in new international leading beamlines and microscopy facilities. The UK also has a long history of supporting laboratory infrastructure at the university level, enabling the UK to take part in high profile sample analysis programmes, such as analysis of material returned from the asteroid Ryugu by the Hayabusa2 mission, and to respond rapidly to a new, pristine meteorite fall in Winchcombe in 2021. In addition to instrumentation for sample analysis, the UK houses laboratories for undertaking simulation studies. The UK has a suite of world-leading impact facilities, split over several institutions (e.g.two-stage light gas guns (LGG) firing projectiles in horizontal flight, and capable of impact velocities of over 7.5 km s^{-1}, and thermal-vacuum facilities used for instrument testing and basic science).

It is important that the UK maintains its high profile in international consortia, and the expertise that the UK scientists have in laboratory instrumentation bears fruit in two ways. Firstly, of course, is their ability to analyse samples in ground-based laboratories and the complementary development of instrumentation for space missions. In conjunction with analysis of returned samples, is a requirement to curate them, a process which encompasses preliminary examination, material selection and distribution as well as storage of material for future generations. Through the UK Space Agency and STFC, UK-based laboratory experimentalists have expressed a desire to provide the UK with a sample curation facility. Selection and curation of analogue materials by this facility will also aid development of future in situ experiment packages and sample return mission designs.

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

C5. Telescopes

SSAP recognises that a detailed consideration of telescope operations and the relative prioritisation of instrumentation is beyond its remit, and is part of the remit of the Astronomy Advisory Panel. However, it is important to note that Solar System science requires telescope observations of Solar System bodies, across the complete wavelength range; such observations are essential in meeting almost all of the science goals described in Themes 1 and 2. These facilities present many opportunities to complement results from space missions and related projects. Particular examples where telescope instrumentation is essential to achieve the required results include higher- spectral resolution data than available from space missions and long baselines of observations. Reference is made to individual telescopes at various places in the discussion of specific science questions.

It is essential that STFC continues funding for both ground- and space-based telescope facilities at an adequate level to support the science programme laid out in this report (and of course also the goals laid out in the Astronomy Advisory Panel Roadmap). It must also be noted that even after instruments cease operation, there are still opportunities to exploit data generated by those instruments, requiring support from the appropriate funding lines. Investment in the development of new telescopes, instrumentation, and data reduction and processing techniques are key in the advancement of UK Solar System science, and we welcome the opportunities that the UK will gain through participation in the SKA, E-ELT and EST projects.

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

Space Missions supporting Solar System Research

This table lists active space-based missions and those in development where the UK space science community has a significant science or instrumentation involvement. It is based on UKSA and STFC data. For reasons of brevity, it does not include those missions where curated data is still being analysed but which no longer have active operations relevant to the space science community.

Mission	**Planet**	**Launch**	**Partners**	**Theme**
BepiColombo	Mercury	2018	ESA, JAXA	Themes 1, 2
Veritas	Venus	2027	NASA	Theme 2
DAVINCI	Venus	2030-31	NASA	Theme 2
EnVision	Venus	2031+	ESA	Theme 2
Mars Express	Mars	2003	ESA	Theme 2
Mars Reconnaissance Orbiter	Mars	2005	NASA	Theme 2
Mars Science Laboratory	Mars	2011	NASA	Theme 2
Maven	Mars	2013	NASA	Themes 1, 2
Trace Gas Orbiter	Mars	2016	ESA	Theme 2
InSight	Mars	2018	NASA	Theme 2
Mars Sample Return MSR	Mars	2020	NASA, ESA	Theme 2
Mars2020	Mars	2020	NASA	Theme 2
Martian Moons Explorer MMX	Mars	2024	JAXA, NASA, ESA	Theme 2
Rosalind Franklin ExoMars	Mars	2028	ESA, NASA	Theme 2
Mars Ice Mapper	Mars	2031	Canada, JAXA	Theme 2
Juno	Jupiter	2011	NASA	Themes 1, 2
Europa Clipper	Europa	2024	NASA	Themes 1, 2
JUICE	Jupiter, Ganymede, Callisto, Europa	2023	ESA	Themes 1, 2
Dragonfly	Titan	2026	NASA	Theme 2
Cluster	Earth magnetosphere	2000	ESA	Theme 1
THEMIS	Earth magnetosphere	2007	NASA	Theme 1
SWARM	Earth magnetic field	2013	ESA	Theme 1
Arase	Earth radiation belts	2016	JAXA/ISAS	Theme 1
SMILE	Earth magnetosphere	2025	ESA, CNSA	Theme 1
Chang'e 5	The Moon	2020	CNSA	Theme 2
Lunar Trailblazer	The Moon	2023	NASA	Theme 2
Astrobotic Peregrine Lander	The Moon	2024	ESA/NASA	Theme 2
ERSA	Lunar Gateway	no earlier 2024	ESA/NASA	Theme 1
LUMEX	The Moon	no earlier 2025	JAXA/ISRO/ESA	Theme 2
Artemis	The Moon	2026?	NASA, ESA	Theme 2
Commercial Lunar Payload Services	The Moon	2028	NASA, commercial partners	Theme 1, 2
Lunar Trailblazer Orbiter	The Moon	2023	NASA	Theme 2
Wind	Solar wind	1994	NASA	Theme 1
SOHO	The Sun	1995	JAXA, NASA, ESA	Theme 1
ACE	Solar wind	1997	NASA	Theme 1
STEREO	The Sun	2006	NASA	Theme 1
Hinode	The Sun	2006	JAXA	Theme 1
IRIS	The Sun	2013	NASA	Theme 1
DSCOVR	Solar wind	2015	NASA	Theme 1
Parker Solar Probe	The Sun	2018	NASA	Theme 1
Solar Orbiter	The Sun	2020	ESA	Theme 1
IMAP	Heliosphere	2025	NASA	Theme 1
PUNCH	The Sun	2025	NASA	Theme 1
Solar-C EUVST	The Sun	2025	JAXA	Theme 1
Vigil	The Sun and Heliosphere	2029	ESA	Theme 1
Hayabusa2	Asteroid	2014	JAXA	Theme 2
OSIRIS-REx	Asteroid	2016	NASA	Theme 2
DART/HERA	Asteroids	2022	NASA, ESA	Theme 2
Comet Interceptor	Comet	2029	ESA	Theme 2
JWST	Planets, exoplanets etc	2021		Themes 1, 2
Hubble	Giant Planet Aurora			
PLATO	Exoplanets	2026		Theme 2
ARIEL	Exoplanets	2029		Theme 2
Athena X-ray Observatory	Gas Giants, exoplanets	mid 2030s	ESA	Theme 1, 2
Magnetospheric Multiscale Mission	Magnetic Reconnection	2015	NASA	Theme 3
HelioSwarm	Plasma Turbulence	2028	NASA	Theme 3