Summary of responses to SSAP Community Questionnaire, July 2021

SSAP, March 2022

There were a total of 79 responses (34 Solar Physics; 12 Magnetospheric/ionospheric/thermospheric Physics; 31 Planetary Science). All respondents identified as scientist/researcher.

Career Stage: 10 PhD student; 17 Postdoctoral Research Fellow; 9 Early Career Academic; 38 Established Academic; 5 Emeritus/Other.

Q4 The STFC Science Challenges can be found at https://stfc.ukri.org/research/science-challenges/ (updated from page 7 in the 2015 Roadmap). Should any Key Science Challenges be removed?

Response: 71 No; 4 Yes

Given the response here, it seems the majority of the community do not think any of the Key Science Challenges should be removed. However, several people commented B2 (*What effects do the Sun and other stars have on their local environment?*) and B6 (*What are the processes that drive space weather?*) could be merged.

Q5 Should any Key Science Challenges be changed/revised?

Response: 47 No; 32 Yes

A wide variety of answers here with a common theme of making sure that advances since 2015 are taken into account.

For reference, current Key Science Challenges are:

B:1. How does the Sun and other stars work and what drives their variability?
B:2 What effects do the Sun and other stars have on their local environment?
B:3. What processes govern how planetary systems form and evolve?
B:4. What are the conditions for life and how widespread are they?
B:5. How diverse are exoplanets and is our earth typical?
B:6. What are the processes that drive space weather?

Magnetospheric/ionospheric/thermospheric Physics

- Widespread feeling that exoplanets are given too much emphasis and other areas neglected.
- There is a wide field (essentially the whole of STP, ranging from small scale physics to global, system scale processes) omitted from the key challenges.
- Several views that B.3, B.4 and B5 should be merged to two areas and re-aligned.
- Plasma processes are thought to play an important in the formation of planetary system, e.g. transferring angular momentum outward from the proto-star via the magneto-rotational instability.
- Either merging B2 and B6 or making the distinction clearer.

Planetary science

- Increase importance of planetary structure and history.

- Broaden the planetary challenges beyond habitability and life, multi-scale characterisation across disciplines is needed.
- Consider more processes than just the impact of the Sun.
- Consider the ongoing evolution of planetary bodies on all size scales (including moons, comets, asteroids).
- Geology and chemistry should get more of a mention to cover the full range of planetary processes.
- Atmospheric processes need a bigger mention.

Solar Physics

- Mention key facilities such as DKIST and EST
- Merge B2 and B6

[Please note that responses to Q6-9 have been included in the White Paper Summary.]

Q6 Should any new Key Science Challenges be added?

Response: 49 No; 25 Yes

Q7 Please list any emerging technologies or capabilities that should be included in the Roadmap that will help answer the Key Science Challenges.

Q8 Please identify which of the Key Science Challenges require major investment in new capability,
infrastructure and underpinning technologies. Please describe the nature of this new investment and indicated if the Challenge is an existing one or a new one proposed in Q6.

Q9 What in your view are the key opportunities for UK researchers to play leading roles in large international Solar System projects?

Q10 The UK Space Agency and STFC operate a 'dual-key' approach whereby UKSA supports mission
participation and STFC supports mission exploitation. In your consideration is the current arrangement fit for purpose?

Response: 46 No; 27 Yes

The responses from the community clearly demonstrate dissatisfaction with the arrangements that currently exist between UKSA and STFC. Most of the comments are very well informed and provide specific comments about why this is the case. There is considered to be no clear definition of the approach; there is no alignment of long-term strategy; UKSA has weak scientific authority, and yet the mechanism by which STFC advises is seen as opaque; the system doubles the workload because it is necessary to convince UKSA and STFC of the merits of an idea; and the timescales for UKSA funding instrumentation and STFC exploitation are completely different, and completely divorced, and this has been to the detriment of the productivity of a community already under considerable demands for efficiencies. A minority of responses acknowledge that they do not know how the dual-key system is supposed to work (hence identifying a worrying breakdown in communication between the community and the agencies that serve it).

Q11 Are you 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)?

Response: 39 (Very) Satisfied; 33 (Very) Dissatisfied

The responses here are balanced but overall, there is agreement that after more than a decade of flat-cash funding, there simply is not enough money. General points that are repeated in several comments include the need for a more responsive funding system, the need for more exploitation funding (in particular more PDRAs) and funding for e.g. software engineering positions. The suspension of the PRD scheme is mentioned, making it harder to get funding for blue skies development to TRL 5/6.

Q12 Within the exploitation (grant) funding line, are you satisfied with the balance between PI, PDRA and PhD funding?

Response: 26 (Very) Satisfied; 50 (Very) Dissatisfied

Of the responses received to this question, dissatisfaction arises from the level of funding available at PDRA level. A number of ideas were suggested, for example reducing the funding at PhD level, or at PI level. On the other hand, PI FEC was considered to be unsustainably low. It is clear from the responses that a number of universities are now requiring significant funding of PI time for PI's to be considered 'research active'. In some institutions, unfunded PI research time is no longer protected.

Other concerns raised were that the 3-year grant funding cycle does not allow PIs to build up a group, that an ERC-like system should be considered that allows access to grants at all career stages and a repeated call to reinstate the junior post-doctoral fellowships.

Q13 Please list the key technologies in Solar System research where the UK is world leading.

The responses to this question provide clear evidence that the UK is world leading across all the various sectors that make up the key technologies used in Solar System research, including:

- in situ measurement of space plasmas (e.g. magnetometers, thermal plasma instruments)
- remote sensing (e.g. IR detection, X-ray (spectroscopy, Magneto-Optical Filters), UV spectroscopy (and provision of atomic data), heliospheric imaging, visual and camera system technology more generally);
- ground based detection (e.g. radio, solar observations, coherent scatter radar, ground magnetometry);
- laboratory analysis (e.g. volatile analysis, micro- and nano-scale sample analysis, mass spectrometry, microscopy).

Finally a number of responses mentioned leadership in small satellite technology, CubeSats, and miniaturisation of instruments, and noted the timeliness and importance of this.

Q14 Please list any capabilities or technologies which are cross cutting or multidisciplinary and the other areas they relate to.

The responses to this question show the highly interdisciplinary nature of UK Solar System science, and the opportunities for spin-off technology or applications to other areas.

- Earth Observation: e.g., the development and use of spacecraft in low Earth orbit; use of IR technology (vegetation, landscape diversity); use of ground based radar and atmospheric modelling, etc.

- Instrumentation: e.g., space weather observation and forecasting, detector technology spin offs for sensing and imaging, magneto-optical filter technology with application to laser communications, etc.
- Other facility science: e.g., radio facilities used for astrophysics and high energy physics; planetary simulation facilities and world-leading laboratory facilities for geological analysis, etc.
- Theory and modelling: e.g., atomic physics calculations; numerical modelling; space plasma theory and modelling for astrophysics and fusion; exoplanet modelling
- Machine Learning and Artificial Intelligence for big data

Q15 What are the scientific challenges in Solar System Research to be solved in the next 20-30 years?

The response to Q15 has been included in the White Paper Summary.

[Please note that the responses to Q16-18 have been given in a combined response after Q18.]

Q16 What in your view are the barriers for creating a healthy career pathway for academic staff, technicians, engineers, software engineers, PDRAs and PhD students?

Q17 Do you have any suggestions to address these barriers?

Response: 14 No; 58 Yes

Q18 What changes or activities could STFC promote within the field of Solar System research to support increasing diversity, equality and inclusion?

The response to questions 16-18 of the questionnaire highlighted a number of widespread concerns among the community regarding working conditions and career progression. Foremost among these was a concern regarding the number, and duration, of PDRA posts, which highlighted issues with career progression into academia from PhD level, and the insecure nature of many positions, linked to short-term grants. Aside from increasing funding levels, recommendations include supportive discussions with PhD students and early career researchers about their expectations and understanding of an academic career, and support for industrial experience through placements or collaboration. Community feedback also favoured providing longer-term positions to reduce PDRA stress and provide job stability.

The questionnaire also brought to light the issue of metric-driven performance analysis, serious workload concerns, and challenging workplace culture across the career groups. PDRA responders highlighted the pressure to publish, and inconsistent support provided by academic research councils and research groups. Established academics highlighted unsustainable pressure to carry out unrealistic workloads, alongside concerns regarding metric-driven performance indicators.
Finally, the established academic group also brought to light the issue of a lack of strategic planning to support long-term, high priority research and technical projects, including supporting technical and software engineering posts. Flat cash research funding over recent years has spread financial support extremely thinly across the sector over recent years, and a review of the current funding model was suggested.

Summary of themes emerging from white papers submitted to the SSAP request for information, July 2021

SSAP, March 2022

Introduction

The STFC Solar System Advisory Panel is undertaking a review of the "Roadmap for Solar System Research", to be presented to Science Board in 2022. As part of the review process, in July 2021 the SSAP consulted with the community, inviting community members to complete a survey, and submit white papers on science investigations (including space missions, ground-based experimental facilities, or computing infrastructure) and impact and knowledge exchange (e.g. societal and community impact, technology development).

SSAP received 50 white papers on science investigations, and in this document we summarise the major themes that emerge from these white papers. This summary is presented with the intention of giving the community a progress update, and will be used to further inform the writing of an updated roadmap.

Mirroring the responses of the community, this summary is organised as follows. In part 1, notes on the planetary science investigations are presented. In part 2, notes on solar/magnetospheric science investigations are presented. In each section we have used the questions from the questionnaire as an organisational guide, and have focussed on themes relating to the following:

- [Q 6,7] Emerging technologies or capabilities that should be included in the Roadmap that will help answer the [existing or any new] Key Science Challenges?
- [Q 8] Which of the Key Science Challenges require major investment in new capability, infrastructure and underpinning technologies?
- [Q 9] Key opportunities for UK researchers to play leading roles in large international Solar System projects?
- [Q 15] What are the scientific challenges in Solar System Research to be solved in the next 20-30 years?

SSAP hopes that this summary proves useful to the community and thanks the community again for its support in this process.

1. Planetary Notes

The UK National Space Strategy published in 2021 highlights Mars Sample Return, the Artemis programme, Space Situational Awareness, and the need for the UK to be a space science superpower. It also highlights UK-led and bilateral missions as new priorities in addition to ongoing ESA participation. The UK SSAP Community welcomes this emphasis on Solar System science but notes that without an associated increase in research and technology funding via STFC and UKSA these aims are unlikely to reach their full potential. In particular, the bilateral opportunities that the National Space Strategy and the BEIS government department in charge of space strategy emphasise require adequate funding from the recently announced increases in UK R&D spending.

The UK's membership of ESA continues to be a key platform for our Solar System science. The Voyage 2050 plan has a priority of large missions to explore Moons of the Giant Planets. These will be determining habitability of ocean worlds, searching for biological signatures, and studying the connection of moon interiors, near-surface environments, and the implications for the exchange of mass and energy into the overall moon-planet systems. This could potentially include Europa Sample Return. This will be a major area of research in the coming decades, with the majority of liquid water in the Solar System now known to lie within these icy ocean worlds. Understanding the internal structure of these worlds will be a major planetary science endeavour, along with the astrobiological interest in the organic content of the water and ice.

Investigating the processes and relationships that shape the past and present atmospheres, surfaces, and interiors of planets, moons, and small bodies in our Solar System is a major objective of the planetary and terrestrial science community. We note that several responses to the questionnaire highlighted that the previous roadmap covers the formation and evolution of the Solar System, but does not consider how present-day planetary systems work, which may be an area for further exploitation.

6, 7 …emerging technologies or capabilities that should be included in the Roadmap that will help answer the [existing or any new] Key Science Challenges.

The proposed CUBES ground-based instrument covering the near-UV spectral region is expected to be available at the ESO Very Large Telescope in 2028. It will be used to determine the composition of cometary ices and icy satellites and better understand conditions at the time of planet formation in the Solar System. In addition, the Vera C. Rubin Observatory will come online in early 2024 and spend 10 years completing the Legacy Survey of Space and Time (LSST). As part of this, it is expected to discover and monitor >5 million main belt asteroids, 40,000 Trans-Neptunian objects, tens of interstellar objects, and >10,000 comets. UK-based researchers have LSST data rights through the LSST:UK consortium supported by STFC. Such ground-based observatories and related missions are particularly timely with ESA's Voyage 2050 prioritising "Moons of the Giant Planets". This may present opportunities for UK developed science payloads on large missions to the outer Solar System in the 2035 - 2050 timeframe. In addition, the UK has existing leadership in exploration of outer Solar System bodies through ESA's Comet Interceptor mission. Comet Interceptor is set to launch in 2029 and aims to characterise a pristine comet (or potentially an interstellar object) to better understand their composition and chemical and physical diversity.

The laboratory analysis of extraterrestrial samples continues to be a crucial area for understanding the Solar System and ground-truthing remote observations of planets, moons and small bodies. Extraterrestrial samples available for analysis include those recently returned from asteroid Ryugu by the Hayabusa2 spacecraft, and in 2023 NASA's OSIRIS-REx mission will deliver materials from asteroid Bennu. Several nations have recently returned (e.g., CNSA's Chang'e 5 mission), or are planning to return, new lunar samples in the next decade. Mars Sample Return (MSR) is scheduled for around 2032 via a UK-built Fetch rover due for launch to Jezero Crater in 2028 to collect samples cached by the NASA Perseverance Rover. JAXA's Martian Moons eXplorer (MMX) will launch in 2024 and return samples of Phobos in 2029.

In addition, newly discovered meteorites - martian, asteroidal and lunar meteorites together with micrometeorites and interplanetary dust particles - will continue to provide a new and expanding selection of Solar System materials. Laboratory analysis of each new set of extraterrestrial samples will provide the UK community with key opportunities to better understand the formation and

evolution of planetary systems. However, exploitation requires support for laboratory and curation facilities, and the development of new cutting-edge analytical techniques. The COVID pandemic has also seen some analytical instruments set-up for remote working, potentially widening access in the future.

Freshly-fallen meteorites can be found in the UK by establishing fireball camera networks. This capability was demonstrated in early 2021 when UK networks enabled rapid recovery and verification of the Winchcombe meteorite fall, providing a new carbonaceous chondrite that can be studied in its pristine state without terrestrial contamination. The expansion of fireball camera networks has also created a large database of all-sky images and datasets that can be exploited for multidisciplinary studies across planetary science, astronomy, meteorology, and planetary defence. For example, applying data mining methods to this dataset has the potential to track satellites and space debris in the near-Earth environment or provide new insights into solar flare events.

The study of exoplanets is a rapidly expanding field. Results need to be placed into context with our own Solar System, either through ground-based observations, laboratory analysis, or theoretical studies. There is an emerging need to bridge the gap between astronomy and planetary science communities in this area, especially with the development of missions such as ESA's Ariel mission, which is scheduled to launch in 2029. Ariel will study the chemical composition and thermal structure of exoplanets and their relationship to the host star. Other potential exoplanet missions, such as the Large Interferometer for Exoplanets (LIFE), will aim to characterise terrestrial exoplanet atmospheres and search for biosignatures.

Furthermore, small and low-cost missions (e.g. CubeSats) are expected to provide new access to the space environment and other bodies in the Solar System, leading to a significant increase in the number of missions to planets, moons, asteroids and comets. Such missions will likely transform our understanding of planetary bodies, their habitability and potential for in-situ resource utilisation (ISRU). Another technological capability highlighted by the community was machine-learning and big data methods. These could effectively be applied to remote sensing observations of planetary surface and atmospheres.

8 ...<u>which of the Key Science Challenges require major investment in new capability, infrastructure and underpinning technologies.</u>

Overall, a need for continued and further investment in computing facilities was a common theme. Investment is required to improve modelling capabilities, through long-term grants that would enable team(s) to produce world-leading numerical code(s). Investment in small-satellites and constellations was another common theme, taking advantage of the UK's commitment to Space (e.g. space-ports). However, there is no available grant funding route to develop space-based missions. Sample Return missions in the past have been landmark ways in which our understanding of the formation and evolution of the Solar System has advanced. This is expected to continue in the 2020s and 2030s as return missions from asteroids (OSIRIS REx, comets, martian moons MMX), the Moon (approx. 10 - 20 missions are currently planned) and, within the early 2030s, drill cores returned from the Mars2020 rover via the UK-built Fetch rover.

Portions of the Mars2020 drill cores will be released for study from a Mars Sample Receiving Facility (which is expected to be located in the United States) after planetary protection protocols have been satisfied. UK-designed Double Walled Isolator equipment and instruments could allow characterisation of the samples whilst under containment in the Sample Receiving Facility in the US

or elsewhere. After release, the UK will hope to curate and analyse some of the samples. A UK-based curation facility, perhaps under the auspices of ESA, could be based at the Harwell Campus in Oxfordshire, making use of proximity to its facilities such as the Diamond Light Source and be built in combination with a new Natural History Museum campus.

In addition to asteroidal, lunar, and martian samples, such a facility might also house meteorites returned from a UK-led Antarctic meteorite recovery programme. Such a programme would combine both UK planetary materials expertise and the British Antarctic Survey heritage of a wide variety of polar studies, providing a source of new meteoritic samples for study. The Winchcombe meteorite fall in early 2021 demonstrated the potential high science return that a UK Fireball network also has as a way of providing important new meteorite samples for study.

A Sample Curation Facility could be equipped with state-of-the-art equipment, such as proposed through the LARES initiative, although the amount and types of equipment to be based at a Curation Facility relative to existing ground-based micro- and nano-scale analytical facilities that are based in UK universities and research facilities such as Harwell is an important strategic question that remains to be determined by the planetary community. Nevertheless, specific areas flagged as requiring investment in the UK include analysis of radioisotopes to determine the timescales of planetary processes, and analytical capabilities to measure multiple mineralogical, geochemical and organic biosignatures. A challenge raised in several of the responses is how to obtain long-term support for dedicated scientific and technical staff and provide opportunities and training for early career researchers.

The importance of research into the development and utilisation of planetary analogues was also mentioned in some responses. These materials, in combination with environmental simulation facilities, can help interpret data returned from past, present, and future planetary missions, and support our understanding and exploration of the Moon, Mars and other Solar System bodies.

9 ...key opportunities for UK researchers to play leading roles in large international Solar System projects?

The UKSA Aurora science programme has enabled UK researchers to take leading roles in Mars exploration with both current missions (MSL, Mars2020, Insight, TGO) and planned ones, notably ExoMars2022 and Mars Ice Mapper. A notable set-back to the planetary community's planned research is a delay to the September 2022 launch of the ExoMars rover due to the Ukraine crisis. At the time of writing it is unclear what alternative, such as a 2024 launch, may be possible. However, the planetary community is clear that the major investment in building the science community's expertise and developing instruments (PanCam and Raman in particular) should be preserved either through a later launch of ExoMars or, if necessary, through new bilateral, ESA/NASA mission opportunities.

The Aurora science programme has supported academics, fellowships, PDRAs and PhD studentships through yearly grant rounds. Continuing long term support from Aurora or a similar programme is essential so that the UK's investments in ExoMars, Mars Sample Return and other missions deliver their full potential science return. Related to this is the UK planetary community's commitment to the field of astrobiology and the search for life elsewhere in the universe.

A scheme like Aurora may also be appropriate to enable UK researchers to play leading roles in upcoming lunar exploration and science activities. For example, the UK is leading development of

the ProSPA chemical laboratory for lunar landers, and in NASA CLiPs missions, the Lunar Thermal Mapper and NASAs Lunar Trailblazer, UK researchers are playing significant roles in other areas of lunar exploration and planned analysis of returned samples. All of these activities would benefit from a dedicated lunar funding scheme.

The UK has a lead scientist role in the EnVision mission, which was selected by ESA in 2021 as its fifth Medium-class space science mission and is scheduled to launch in 2031-2033. The mission aims to investigate the climate, surface geology and interior structure of Venus and better understand its relationship to Earth. Such missions need to be supported by ground-based observations and laboratory and theoretical studies. Venus has become an important focus for the planetary community due to the reported detection of phosphine in its upper atmosphere by a UK-led research team. Its presence could be due to an unknown chemical process or possibly biological in origin, and requires further theoretical, laboratory, and in-situ studies, and support for the growing area of astrobiology in the UK.

In addition, the UK has significant science and instrument leadership on Comet Interceptor, ESA's first F-class mission, which aims to characterise a pristine comet entering the inner Solar System for the first time.

15 What are the scientific challenges in Solar System Research to be solved in the next 20-30 years?

The Inner Solar System

Venus is the only other Earth-sized planet which we can study in detail beyond our own and fundamental questions remain about how geologically active it is. EnVision will address how the surface and interior of Venus evolved and how Venus' atmosphere and climate have been controlled by geological processes. EnVision will be complementary to the NASA orbiters VERITAS and DAVINCI+ that are set to investigate Venus in 2028 and 2029, respectively.

In the short-to-medium term, Mercury will also 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. Finally, future missions might include the first lander on the surface of Mercury.

The Moon

NASA is planning to return astronauts to the lunar surface from around 2025 through the Artemis programme. Both human and robotic missions to the Moon in the coming years will provide new surface data and returned samples in previously unexplored terrains. Key science questions include was there a 'Heavy Bombardment' cataclysm in the inner Solar System ca. 4 billion years ago? What is the source(s) of life-enabling volatiles (H, C, N) in inner Solar System planetary bodies such as the lunar surface and how much water ice is there at the poles, in what form, and how is it distributed?

Indeed, given that there are between 10 and 20 missions proposed to visit the Moon in the next decade, including plans by NASA and China to send astronauts, the UK needs a coordinated approach to support its participation, via mission involvement, instrument design, and provision and

science exploitation (the latter including sample return and ground-based facilities). There will also be the need to help design structures for lunar habitats and methods for in-situ resource utilisation. This is an activity beyond just science and requires coordination with UKSA (with a programme akin to Aurora which supports Mars studies).

Mars

ExoMars2022 as originally planned, Mars Ice Mapper and Mars Sample Return are set to transform our understanding of the martian system in the next decade, as Mars Science Laboratory, Insight, the HiRISE camera, CRISM, Trace Gas Orbiter have in the past decades. Key questions that will be addressed by these missions include, What is the nature and abundance of organic compounds in sedimentary rocks on Mars? How has the martian crust chemically and mineralogically evolved over geological time? How do the hydrological (including ice distribution) and rock cycles operate on Mars? What is the composition of the martian atmosphere and how has it evolved over time? Answering these questions will support our understanding of habitable environments, the detection of signs of ancient life, and potential locations for human exploration on Mars.

The Outer Solar System

The Giant Planets will increasingly jump into focus as missions visit and revisit these bodies and their satellites. Indeed the opening up of science in the outer Solar System will be one of the main features of world-wide growth in Solar System research in the coming decades. Key questions include What is the bulk elemental and isotopic composition of Giant Planet atmospheres, and what does this tell us about their formation and evolution? What environmental processes shape conditions within and below the clouds on Giant Planets? What are the physical and chemical properties of Gas Giant satellites? Do Gas Giant satellites host habitable environments, and if so, what is the nature and abundance of organic compounds and other biosignatures?

Minor bodies (Asteroids and Comets)

Samples have been, or are about to be, returned from several asteroids, with the opportunity for UK lab-based analysis by various groups. UK scientists are now analysing C-class asteroid Ryugu with university electron microscopy, Harwell ePSIC and Diamond synchrotron facilities. Samples from the Bennu B-class asteroid will return in 2023. This work will continue throughout the coming decade and provide detailed insights into processes and timescales in the early Solar System and ground-truth remote sensing observations.

Meteorite studies continue to grow in significance, with fireball camera networks increasing the recovery of freshly-fallen meteorites with known pre-atmospheric orbits (see the 2021 Winchcombe meteorite). Other countries are also expanding their meteorite studies and the UK can play a leading role via bilateral collaborations. These falls offer the opportunity for analysis of new, uncontaminated material from a wide range of sources, sampling a greater number of Solar System bodies than is possible with a limited number of space missions (where the provenance of the material is more fully known). This work is thus both complementary and synergistic to asteroid missions.

2. Solar/Magnetospheric Notes

7 …emerging technologies or capabilities that should be included in the Roadmap that will help answer the Key Science Challenges.

Many of the responses to the request for white papers identified the key role that miniaturisation of payloads and platforms will play in unlocking the next generation of space missions, particularly for magnetospheric science. It was also noted that the UK Solar System community has a significant advantage in this area, given prior investment in instrumentation development (for example also funded through STFC at TRL 1-3) taken together with the UK's industrial position having a notable focus on small satellite platforms and services. This would enable the UK to participate in low-cost high-science-return missions, bilaterals, and also lead the development of constellation-class observatories, for example within the ESA science programme.

A further theme that was identified by multiple respondents was the role that AI and machine learning can play in developing more capable and more productive science missions; for example in data selection, autonomous mode operation and in communications. It is clear that through other funding mechanisms, the UK is building significant capabilities in this area (and with UKRI playing an important role catalysing this). However, the pull-through of AI/ML into space science missions remains an opportunity to be fully exploited, and so the future strategy should ensure that this happens to the fullest extent possible. A second dimension to AI/ML is its use in the curation and analysis of the ever-increasing volumes of data generated by prior UK investment, to maximise the science return. Closely tied to this was the view raised by several respondents about the need to be closely involved in the next generation of high-performance-computing (HPC) architecture (e.g. Excalibur), so that numerical capabilities remain competitive.

Finally, as motivation in their white papers, many respondents noted that the UK is world-leading in several specific areas of instrumentation capability (which we do not list here, but this relates to both space-based and ground-based, remote sensing and in situ), and commented that to retain this leadership, it was necessary to invest in the next generation of technological development, often at low TRL levels, to ensure that in the next two decades the UK retains its cutting edge position.

8 ...which of the Key Science Challenges require major investment in new capability, infrastructure and underpinning technologies.

As also mentioned in the summary under question 7, more than one respondent identified that there is a critical need for strong fundamental theoretical research across the SSAP to address questions under science challenge 'B' and ultimately this requires supporting HPC infrastructure to deliver scientific leadership. For example, it was identified that multi-scale simulations incorporating the system, intermediate and kinetic scales are necessary for probing the fundamental physics of plasmas (solar, magnetospheric, heliospheric), as well as improving space weather forecasting. This will require significant computational resources. Some respondents felt that although the UK was probably a leader in this field about two decades ago, the subsequent provision of HPC facilities has not been sufficient to maintain that position. Moreover, high performance computing is required for the exploitation of the increasingly large observational data sets coming from vanguard facilities; along with modern, computationally intensive, software required for the analysis (e.g. machine learning algorithms). Hence, there is a clear call from the community for major investment in the UKs HPC facilities. Further, there is a need for improvements in the UKs capabilities to develop and deliver world leading numerical models (e.g. Solar Atmospheric Modelling Suite, Radiation belt model, Radiative MHD). Respondents suggested this could be enabled through long-term grants that would permit a team to dedicate time and resources to producing substantial software.

A second theme that arose in response to the 'B' science challenges was the idea of investment in small/low-cost missions (e.g. cube-sats and constellations, sub-orbital flights, balloon and rocket

launches), as technological developments in this area would revolutionise our ability to explore the plasma environment of the near Earth atmosphere and the atmosphere of the Sun. Responses noted the UK Government's commitment to the UK space industry (i.e. the National Space Strategy) and future local opportunities for launching missions (through planned UK space-ports), and identified specific opportunities for STFC to offer greater opportunity for the technological development of small satellites (a growing and emerging market within the UK) and the potential for scientific instrument integration. Following from this, replies proposed investments in many areas, for example: instrumentation laboratories; space qualification testing facilities and blue-skies development. This would enable the UK to play a leading role in this area through low cost mission launches and provide a Technology Readiness Level pathway for UK-built space instrumentation valuable for international missions. Particular technologies that require investment are formation flying spacecraft, high-bandwidth communications systems (e.g. laser free-space optics), miniaturisation of instrumentation, on-board smart data processing, i.e. bringing GPU power processing into space. An interesting complementary point extremely relevant for STFC's mission is the fact that this will provide hands-on post-doctoral, graduate and indeed undergraduate level opportunities to train the next generation of highly qualified space personnel (scientist and engineers) in space-related hardware development and build phases.

However, some responses seemed to indicate that there is no clear grant funding route to develop space-based missions, and space instrument teams have issues in obtaining sufficient funding to maintain a programme of instrument development between mission opportunities. This makes it very difficult to stay at the cutting edge of instrument development for future missions. Responses gave the very strong message that the dual-key approach between STFC and UKSA does not work, with the specific consequence of a relative lack of ongoing innovation in UK instrumentation as compared to peers in Europe.

Consistent with answers to question 7, input here also noted that machine learning methodologies are becoming an integral part of exploiting the ever growing archive of astrophysical data ('Big Data' in the heliosphere). Consequently, development and use of related techniques and software will be required to make significant advances across the SSAP area, e.g. analysing planetary surfaces; cloud parameterizations for Solar System planetary atmospheric models; space weather forecasting; large, multi-point networks of observations from space and ground-based facilities (e.g. AMPERE, SuperMAG). However, in order to maximise the potential science return that can be extracted from machine learning, the capabilities within the community need to be developed. It was suggested that this could happen through the provision of/support for training and education in programming/software development, working with large data sets (e.g. cloud computing, scalable science platforms, distributed/parallel computing), as well as theoretical and practical foundations in machine learning methodologies. This returns to the theme of training and skills development which also links to in-demand, transferable skills for lateral career progression.

Measuring the magnetic field and plasma conditions of the solar atmosphere presents major challenges but is currently very much at the forefront of the community's thinking and is critical for almost all research of the solar atmosphere (e.g. atmospheric heating, flares, CMEs, space weather). In the next few years, multiple respondents mentioned that DKIST provides the opportunity to advance such measurements and support for understanding and exploiting the novel data is required. New instrumentation is also required to achieve the goal of vector magnetic field measurements, in the form of Integral Field Units (IFUs). This technology is still in its infancy and the development of large-field IFUs require investment, along with investment in sensor technology (e.g. InGas technology for the near infrared with MCT for the far infrared). In the longer term, this will

require investment in facilities, and subsequent science exploitation, such as SOLAR C EUVST and the European Solar Telescope. The panel also notes the MUSE mission recently selected by NASA.

In magnetospheric physics, investment in specific high-impact international missions, and development of mission concepts were identified as necessary to meet category 'B' science challenges. Several responses mentioned the idea for 'constellation class' missions and the panel notes the Plasma Observatory concept submitted to Voyage 2050, as well as the recent selection of the Helioswarm mission by NASA. Such missions can be directed to understanding space plasma physics and cross-scale coupling, and/or the global dynamics of the magnetosphere. For magnetospheric dynamics, dual auroral observations would offer insight into hemispheric asymmetry especially when combined with ground-based data (e.g. EISCAT 3D). Other concepts are directed at further understanding the fundamental physics controlling space plasmas, for example the Debye mission.

Spanning solar physics and magnetospheric physics were comments relating to space weather, and the need to invest in both space weather specific missions, as this would provide further data and observations to advance the science of space weather. Examples mentioned include Lagrange (now Vigil), SWFO and other missions. This reflects a growing understanding that the concept of Research to Operations (R2O) is now supplanted by R2O2R, recognising the fact that operational missions have a role in advancing science, although they do not supplant the need for cutting edge facilities directed at basic research.

9 ...<u>key opportunities for UK researchers to play leading roles in large international Solar System projects?</u>

There is large support from the community for Solar-C EUVST (EUV Solar Telescope). Ideally, the UK would be a key partner through the development of instrumentation. This would require a reversal of the recent decision to withdraw UK support, before other EU member states are awarded the contract. The loss of the UK involvement in the Solar-C mission represents a significant loss in science leadership in an area where the UK has traditionally had great strength and well-established international leadership. The unexpected and sudden withdrawal also has significant consequences for the UK's relationship with JAXA.

Involvement in design, development and build of the European Solar Telescope is supported by a significant section of the UK Solar Physics community, although only if additional funding is made available. This aligns with the significant support it has across the European Solar Physics community and provides an opportunity for the UK to play a leading role in an international facility.

The Multi-Slit Solar Explorer (MUSE) has recently been selected by NASA for Phase B (launch expected 2026). It is a multi-slit spectrometer to observe the Sun in extreme ultraviolet radiation and obtain the highest resolution images ever of the transition region and the corona. MUSE has several UK Co-I's on the science team.

The UK is already leading the prototyping of ground-based, robotic Solar Activity Magnetic Monitors (SAMM) to deliver continuous observations of the solar atmospheric magnetic field. This will potentially form part of an international network of nodes (SAMnet, e.g., China, Italy, Austria, Columbia, South Africa). Motivation is to improve forecasting capabilities to be more economic (i.e. at much reduced costs) on timescales of days (desired by industry).

The fundamental role of ESA is clear: respondents specifically identified participating in missions such as Comet Interceptor, BepiColombo, JUICE, ESA Large Lunar Lander (EL3), and Voyage 2050 mission concepts at all levels as being crucial opportunities for them to play a leading role. SMILE has UK involvement, showcasing British expertise in X-ray imaging. Leicester is PI institute of the Soft X-ray Imager (SXI), and as a Co-I institute for the Ultraviolet Imager (UVI), as well as creating SMILE Data Fusion Facility.

However, the reach of the UK community goes well beyond ESA, and numerous international missions led by NASA in particular were identified as examples of key opportunities for the UK. This is exemplified by the UK role on the NASA IMAP mission, with provision of the magnetometer instrument. Moreover, the planned ESA launch schedule is arguably becoming so stretched that individual disciplines within solar system science are potentially at serious risk of not receiving sufficient opportunity. Hence, certain responses suggested the UKSA bias towards ESA missions is perhaps misguided, although this was not obviously a majority view. It was felt that without a solid bilateral funding line - in line with that promised in the new National Space Strategy in the UK - we will not be able to maintain and develop instrumental and scientific capabilities on the international scene. Finally we note some respondents also identified the need for small missions on shorter timescales to 'fill the gaps' between large ESA missions in specific science areas and thus sustain science excellence and leadership. This would also ensure a continuing critical mass of experimental expertise within the wider community.

15 What are the scientific challenges in Solar System Research to be solved in the next 20-30 years?

Responses provided in the white papers provided a wide variety of input, but we note the following common themes, among others:

* Understanding the fundamental building blocks of solar magnetism, in particular how small-scale and weak magnetic fields contribute to the structure, dynamics and evolution of the Sun's atmosphere. Requires investment in high-resolution instrumentation with highly sensitive polarimetric capabilities (e.g. Integral Field Units). DKIST will provide high resolution data but next generation of instrumentation is still required, e.g. IFUs suggested for DKIST 2nd generation or EST.

* 3D vector measurements of coronal magnetic fields. Crucial for examining coronal heating and solar wind acceleration. Also vital for predictions of space weather events and understanding the solar eruptive events that lead to them, e.g. SEPs, CME's. 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. Further development of coronal seismology can play a bridging role, with the capability to provide 1D/2D magnetic field estimates.

* Understanding the physics of the chromosphere including determining the role of partially ionised plasmas in the dynamics of the Sun and being able to model non-thermal electron populations and non-local, non-LTE physics. This will involve developing state-of-the-art models of a time-dependent chromosphere, coupling the microphysics to the large-scale MHD evolution to give a complete understanding of the key physics.

* Improving Space Weather predictions including onset of solar flares and coronal mass ejections (CMEs) on the Sun; forecasting solar wind properties at the Earth; radiation levels around the Earth that cause damage to satellites and disrupt aviation; electrical currents around the Earth that disrupt power supplies.

* Understanding the coupling of the solar wind, magnetosphere, ionosphere and radiation belts across multiple scales, including the conversion and partitioning of magnetic/kinetic energy, how particles are energised and accelerated wave particle interactions. In particular, determining key energization processes driving the end point impacts on the magnetosphere and ionosphere; and how solar energetic particles (SEPs) are accelerated, with SEPs being a crucial component of the interplanetary environment, strongly affecting the Earth. Equally, understanding the relative roles of reconnection, turbulence and shocks for acceleration, through multi-scale measurements (upstream solar wind, magnetosphere and ionosphere), is of pivotal importance for space weather science and brings together the solar and magnetospheric communities.

* Understanding the fundamental physics and mechanisms of space plasmas, most notably the role of magnetic reconnection, shocks, wave-particle interactions and turbulence in controlling the flow of energy, momentum and material through the solar wind and planetary magnetospheres. This recognises the fact that the space environment is the best laboratory to perform such measurements and can inform the role of plasma physics in other astrophysical and laboratory environments.

Summary

The UK has a successful and vibrant Solar System research community. There have been many successes since the last roadmap in 2015. The community's continuing success and international impact is currently constrained by overly tight funding. SSAP hopes that the recent announcements in 2022 of the National Space Strategy, and more recently that the government plans to increase R&D spending by £5 billion to £20 billion per annum by 2024-2025, lead to the investment in the scientists and scientific facilities required to deliver our full potential in Solar System space science.