Future UK solar system science

A new Roadmap for Solar System Research in the UK has been published, and the Solar System Advisory Panel report on the processes involved in updating the previous iteration

Solar system research in the UK is booming, with an active, growing community of researchers. Yet this is also a critical time, with demand and new opportunities outstripping available resource.

In the last few years, one of the biggest tasks for the Solar System Advisory Panel (SSAP) has been preparing an updated version of its Roadmap for Solar System Research. The new version was issued in December 2022, and is available online (De Moortel *et al.* 2022).

The idea of the roadmap is that it guides the STFC Science Board as to where the community is, where it thinks it is going and what the main impediments and opportunities are. As the Astronomy Grants Panel (AGP) is totally independent of SSAP (see box 'Routes to funding'), the Solar System Roadmap is not a charter that directly drives future funding awards. Instead, it reassures the Science Board that there is a strong, vital, UK-based community, achieving fundamental and important advances, aligned with the opportunities provided by various space agencies, for example the UK Space Agency (UKSA), as well as NASA, the European Space Agency (ESA), the Japanese Space Agency (JAXA), the Canadian Space Agency (CSA) and so on. It should also persuade the Science Board that the key technologies and computing breakthroughs that are necessary for a healthy future are being advanced.

The previous version of this roadmap was issued in 2015 (Grady *et al.* 2015), and before that in 2012 (Grady *et al.* 2012). With a seven-year gap since the last version, a major reappraisal of the field was deemed appropriate; one of the key findings of the work is just how much the field has advanced in such a short period.

Consultation details

All members of SSAP contributed to this work, over a period of more than a year, holding regular online group meetings throughout the Covid-19 pandemic. From the beginning, the SSAP sought significant input from the wider community, via a variety of routes. A call for 'white papers' on areas of interest was issued in 2021. In response, 55 white papers were submitted, giving a substantial body of information to guide the panel's work and confidence that it accurately reflected the views and interests of the solar system community. This was followed by distribution of an online questionnaire in autumn 2021, asking for comments on the existing roadmap and any suggested changes, accompanied by a community survey on broad issues ranging from funding priorities to career development opportunities (79 responses). A second call for comments on the summaries of the white papers and questionnaire responses was distributed online in early 2022 (receiving 29 responses to the questionnaire, and written comments from eight people).

Members of SSAP read and extensively discussed the white papers, using their contents to guide their deliberations. Similarly, the questionnaire feedback and other inputs were carefully reviewed and all comments considered. The community response to the question of changes to the key scientific challenges was interesting. Around 95% of the 2021 questionnaire responses said none of the existing challenges should be removed, but 40% felt there was a need for revisions, and 34% suggested additions. Thus, the 2022 roadmap is an evolution of the previous one, recognising the continuing developments in the field.

One point that was repeatedly raised by the community throughout the consultation period was that the lack of funding was critical; almost every area of research and technical development offered significant opportunities that could be exploited with more funding. It was pointed out that both ESA and NASA are currently preparing for large future missions, and UK involvement needs appropriate funding levels. Further to this, about 63% of the respondents to the 2021 online questionnaire (and 60% in 2022), felt the issue of access to space missions was extremely important, and so the relationship between STFC and UKSA needed more attention.

As well as the science topics themselves, the community clearly felt strongly in several broader areas, namely: developing a more diverse, representative community of scientists equally accessible to all; ensuring proper career development in the early phases of a career; and sustainability.

As our draft roadmap progressed, incorporating this feedback, preliminary reports on progress were made in 2022 at the British Planetary Science Conference (BPSC), UK Solar Physics and Magnetosphere Ionosphere Solar Terrestrial community meetings and the National Astronomy Meeting (NAM).

Main roadmap findings

The roadmap provides a brief overview of UK interests in solar system research, and the recommendations made by SSAP are shown in Table 1. The roadmap grouped activities in three main themes: Solar variability and its impact on us; Planets and life; and Space plasma processes. Such divisions are to a degree arbitrary and cover a wide range of topics inside each theme. However, they do permit an ordering of material with some common interests. Indeed, taking a holistic view, scientific results from one area may have influence on questions in the other themes, but a degree of compartmentalisation is helpful in planning. This means that research in each theme is not totally separate; there will be overlap, for example, where a single space mission carries instruments for several purposes, thus contributing to more than one theme. In addition, crosscutting and underpinning support (e.g. high-performance computing) by its very nature often supports more than one theme.

In all the themes, SSAP found that significant progress was being made, with work advancing on emerging topics as well as on key issues identified in previous versions of the roadmap. The first theme, 'Solar variability and its impact on us', acknowledges the impact that the Sun has on both the Earth and the whole solar system. Understanding stellar processes that can influence the near space around a star (i.e. the solar system) is therefore a vital undertaking. Processes deep inside the Sun, variability of the surface and atmospheric magnetism, the solar

Table 1: Main recommendations from the Roadmap for Solar System Research 2022

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.

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 three-year funding cycle.

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.

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.

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.

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.

SSAP recommends that STFC builds on the success of programmes such as 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.

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).

That 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.

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.

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.

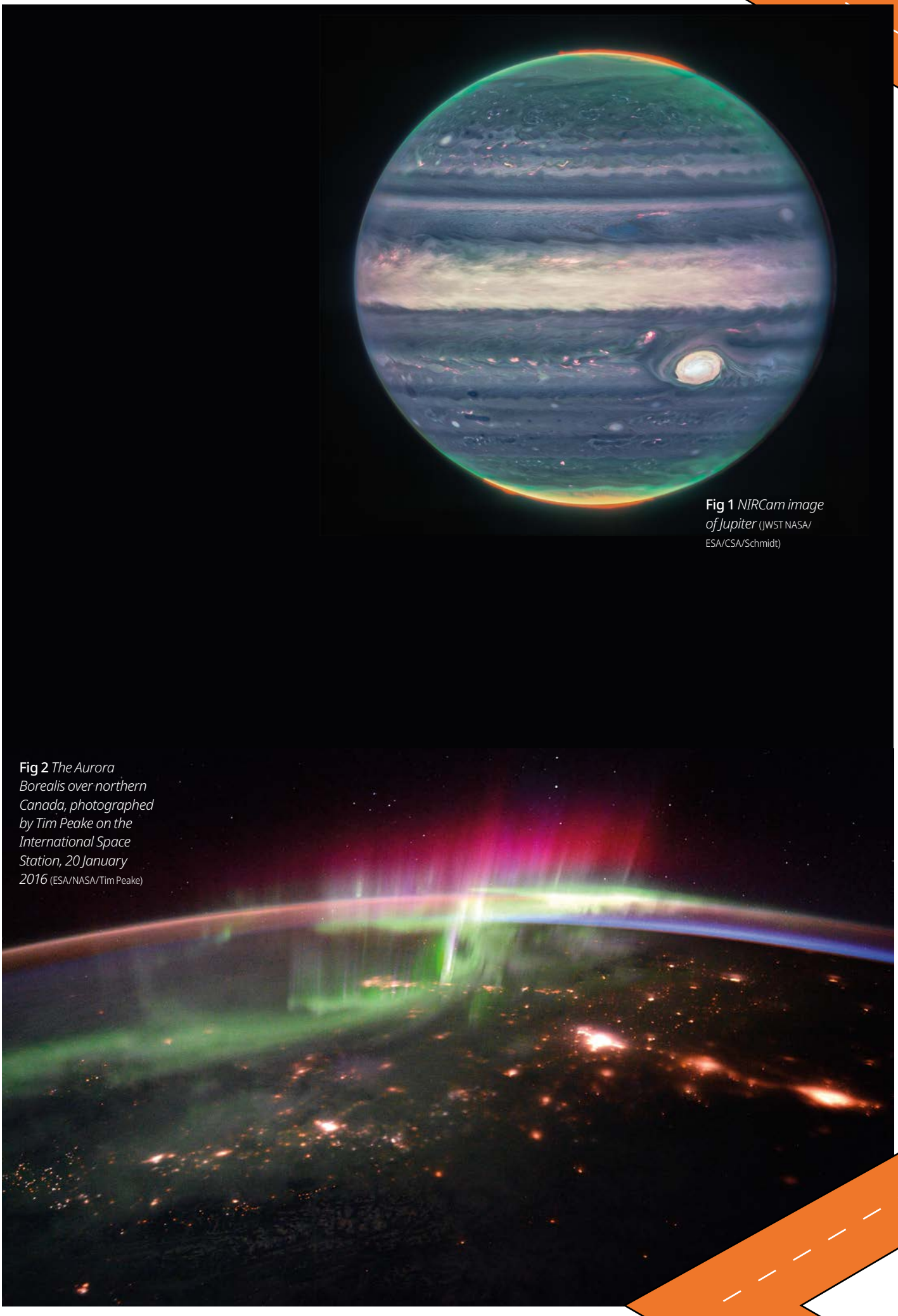

Fig 1 *NIRCam image of Jupiter* (JWST NASA/ESA/CSA/Schmidt)

Fig 2 *The Aurora Borealis over northern Canada, photographed by Tim Peake on the International Space Station, 20 January 2016* (ESA/NASA/Tim Peake)

wind, connections with planetary atmospheres and magnetospheres are all important. Recent observations at higher spatial and temporal cadence reveal activity at all scales and the importance of the chromosphere in the mass and energy cycle of the solar atmosphere. Figure 1 shows aurorae at the north and south poles of Jupiter, and figure 2 shows the Aurora Borealis on Earth, an illustration of the connection between solar activity and the planets (with strong and widespread aurora seen on Earth in early 2023 for example). Space weather (including short-term effects on the ever increasing satellite population as well as the technology here on Earth) is recognised by the Cabinet Office as a major risk and is included in the UK's National Risk Register.

The UK has internationally leading teams working on many aspects of the science of the Sun. There are strengths in involvement in current and future space missions and in ground-based observatories (including contributions to the Daniel K. Inouye Solar Telescope), development of new instrumentation, modelling of solar and terrestrial interactions, and advances in the theories and computational models behind many aspects of solar processes. This breadth in expertise means the UK community is well poised to take on leading roles in upcoming international missions.

As well as remote-sensing observations and *in-situ* measurements of the Sun and at the Earth, the UK community also plays leading roles in studying solar interactions with other planets. At Mercury and Venus, UK teams will play leading roles on BepiColombo and EnVISION respectively, which will significantly advance our understanding of these bodies over the next decade. For the outer solar system, there is world-leading expertise in, for example, coupled magnetosphere-ionosphere-thermosphere complexes at Jupiter and Saturn. UK expertise and leadership in these and other aspects of this theme is widely recognised internationally.

Under the second theme, 'Planets and Life', a major development in recent years has been the opening up of the whole solar system to more detailed research. The inner planets, the Moon, Mars, asteroids and comets, as well as the outer solar system are now all subject to ongoing or increasing exploration and study. This will continue, with key missions to all these regions. The Artemis programme for return to the Moon, for example, together with the scientific opportunities that new lunar landings and a lunar orbiting Gateway space station present, will be hugely significant. The giant planets and their moons will also return to sharp focus, with current, planned and proposed new missions such as JUICE and Europa Clipper to these bodies. By their nature, such missions are often expensive, requiring heavy launchers, and many years of planning, construction and flight time before they even reach their destinations, thus requiring an appropriately supportive eco-system for the scientists and engineers involved in such work. Indeed, even missions in the inner solar system usually last years. Stop-start support does not work well with such projects.

Moreover, it is not all in space. Sample return missions such as JAXA's Hayabusa1 and 2 and NASA's OSIRIS-REx asteroid missions, and Mars Sample Return (MSR) in 2032, are delivering pristine materials from known locations in the solar system. Increasingly, the study of extra-terrestrial samples will therefore be carried out here on Earth, requiring a network of well-equipped laboratories and sample handling

Fig 3: *Winchcombe meteorite.* Top: *Footage of the fireball enabled the pre-atmospheric orbit and strewn field of the Winchcombe meteorite to be calculated* (Richard Fleet / UK Meteor Network) Bottom: *A fragment of the pristine Winchcombe carbonaceous chondrite meteorite. The fragment is about 2cm across and has a small patch of brown/red fusion crust* (Trustees of the Natural History Museum, London).

and curatorial facilities. The first stages of MSR have started with the successful drilling into Jezero Crater by NASA's Perseverance Rover. The UK is well placed to contribute both technology (such as instrumentation for analysis within containment) and science advances from MSR. This extends the heritage and ongoing work investigating meteorites, Apollo-era lunar samples, cometary dust captured in space, and suchlike.

The strength of the UK in this field was illustrated by the nationwide response to the serendipitous fall of the Winchcombe meteorite in 2021; see figure 3 (King *et al.* 2022). The flight of this body across the UK skies was mapped by the UK's fireball camera networks, aiding not only its rapid recovery, but providing orbital information. Over 120 scientists from around 20 UK institutions then formed teams to study the recovered material, showing the UK's strength in depth in this area.

The third theme, 'Space Plasma Processes', recognises that plasma processes are widespread throughout the solar system and play a vital role in explaining a wide-range of solar system phenomena. Yet, plasmas are subtle in nature and complex to model. Key questions are emerging and being worked on. It is vital to understand how waves propagate in inhomogeneous plasmas, for example, and how turbulence affects plasmas is critical to fully model plasmas in many areas of the solar system. How individual plasma processes can combine is also still to be fully understood. Similarly, how plasmas accelerate charged particles to high, non-thermal energies awaits a fuller elucidation. Beyond plasmas, magnetic fields are of fundamental importance in understanding

Routes to funding

Support for research in this field comes from a variety of sources. In the UK, the STFC is a major source of funding for solar system research. STFC covers several other areas as well as the solar system (e.g. the rest of astronomy and also nuclear and particle physics) and to help its main advisory body (Science Board, bit.ly/43OPelh), it has dedicated advisory panels devoted to each area it covers. The advisory panel which covers solar system activities is called the Solar System Advisory Panel (SSAP, bit.ly/41FbQ5W). SSAP provides a link from Science Board to the broader community of users, and helps provide input on both general policy matters and specific issues that arise. One thing it does not do, however, is recommend the awards of grants from STFC – that is the remit of the separate Astronomy Grants Panel (AGP), which covers astronomy and all solar system related research. Membership of SSAP varies with time, but is drawn widely from across the UK, covering a range of fields from solar terrestrial physics to planetary science, with experts in analysis of data from space missions, modelling, laboratory experiments, instrument development, etc. STFC panels and committees have regular turnover (typically three-year terms), and new volunteers are regularly sought, and can indeed self-nominate; if you are interested in volunteering, watch out for the next call (for general details of the process, see bit.ly/3N0uyRo).

the evolution of many bodies, yet are also poorly understood. At the Sun, why some solar cycles are more dominant than others awaits explanation, with new data expected from the Solar Orbiter spacecraft as it moves to higher solar latitudes. In addition, where planetary magnetic fields exist, their generation and how they are sustained with time (or not in the case of Mars) is a challenge. As more data is obtained over the next decades from a variety of missions to the Sun and planets (in both the inner and outer solar system), there is a need for major advances in modelling of plasmas and magnetic phenomena. These are thus exciting and challenging times in this field.

In addition to the science in the various themes, SSAP also recognised the ever-increasing importance of the working environment. Whilst much of this is dependent upon the universities and research institutions that train PhDs and employ the technical staff, researchers and faculty members, the STFC and UKRI play a broader role in requiring and supporting developments in diversity and sustainability.

Wider context

Inside the UK, STFC is not the only significant player in solar system research. The UK Space Agency (UKSA) also plays an important role. UKSA is the government agency that coordinates UK efforts, industrial and public sector, in accessing and exploiting space. It organises UK space missions and related efforts, and liaises with international agencies. The relationship between STFC and UKSA is therefore of fundamental importance to the scientific community, and SSAP regards keeping this link strong as a major requirement for a healthy research environment.

Furthermore, the UK is not a solo act with regard to solar system research. The UKSA negotiates the UK's role in ESA programmes and provides bilateral access to other agencies (e.g. NASA, JAXA, CSA, etc.). In addition to this, many researchers maintain individual relationships with overseas agencies, often holding formal or informal investigator status on space missions. These latter relationships are a testimony to the high international regard in which UK scientists are held, and provide welcome access to cutting-edge data from missions. For example, many UK scientists won access to samples of the Ryugu asteroid under the first general international (competitive) call JAXA held as part of the Hayabusa2 sample return mission. Similarly, there have been a large number of successful UK observing proposals for the Daniel K. Inouye Solar Telescope, with the UK making up 14% of recent successful proposals (the second largest national contribution behind the US). Having funding which can support such a broad-based university community is therefore vital to maintain a thriving, world-leading community.

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Conclusions

In summary, the 2022 Roadmap for Solar System Science offers a snapshot of UK solar system research at a moment in time. A large community of researchers is active in the UK, recognised internationally for their excellence. Moreover, these are exciting times, with many new space missions underway or planned, backed by laboratory research and computational modelling. It is clear from the community feedback, and the widespread activities observed by the SSAP members during preparation of this roadmap, that many opportunities exist and are being grasped enthusiastically. There are issues, particularly with funding which is at the core of many of them. However, other issues vital to the health of the UK solar system research community include: how resources are allocated, the relationship between STFC and UKSA and STFC and other UKRI funding agencies, how key national priorities are set, broadening the community to be more representative, and ensuring a community with good morale where individuals can see a positive future and an equal career path. Meanwhile, for more details, read the roadmap itself (De Moortel *et al.* 2022).

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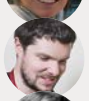


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REFERENCES

National Risk Register 2020 bit.ly/3orQScz
King A *et al.* 2022 *Science Advances* **8(46)**, eabq3925, 2022.
Arridge CS *et al.* *Solar System Roadmap* 2015 bit.ly/43HJhGV
De Moortel *et al.* *Solar System Roadmap* 2022 bit.ly/40pbLCf