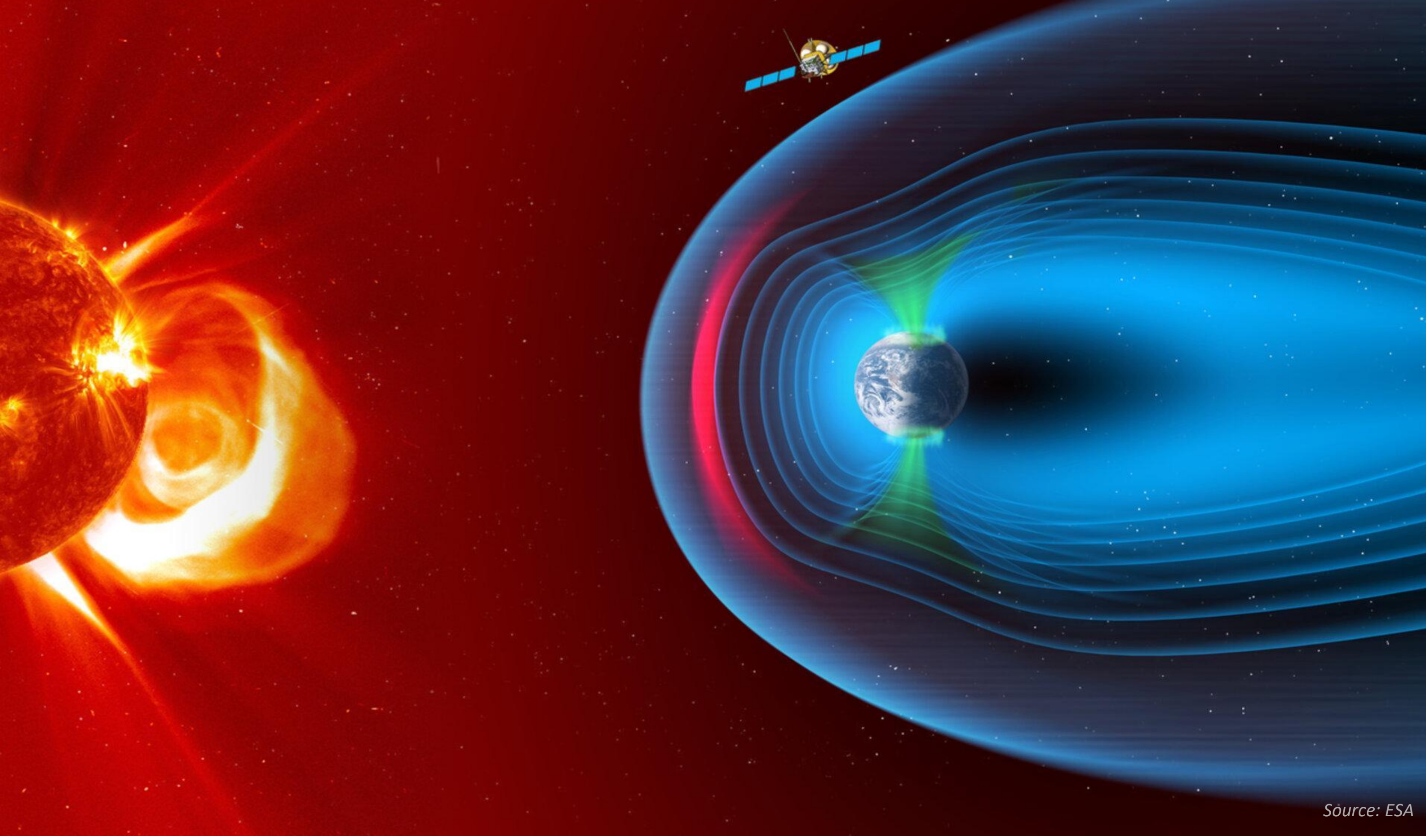

UK Space Science: a summary of the research community and its benefits

Full Report for SPAN
SPACE ACADEMIC NETWORK

FINAL REPORT

know.space

April 2021

Contents

About us

know.space[1] is a specialist space economics consultancy, based in London and Dublin. Founded by the leading sector experts, Greg Sadlier and Will Lecky, it is motivated by a single mission: to be the source of **authoritative economic knowledge for the space sector**.

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Images

Cover and Header: 'ESA: The Smile Mission', ©ESA/ATG medialab. The Solar wind Magnetosphere Ionosphere Link Explorer, or SMILE, is a joint mission between the European Space Agency (ESA) and the Chinese Academy of Sciences (CAS). SMILE aims to build a more complete understanding of the Sun-Earth connection by measuring the solar wind and its dynamic interaction with the magnetosphere and is due for launch in 2021. The UK shares Principal Investigator leadership.

[1] **know.**consulting Ltd. (CRN: 12152408; VAT: 333424820), trading as **know.**space.

Executive Summary

In late 2020, the Space Academic Network (SPAN) commissioned **know.**space to assess the nature and benefits of the UK space science research base. The research for this report was carried out between November 2020 and February 2021, consisting of desk-based research and a series of 20 in-depth interviews with leading figures in the UK space science community. We looked at both the **nature** of and the **benefits** from the UK's space science activity.

The agreed scope of the study was research in:

- Astronomy, Astrophysics and Cosmology;
- Lunar and Planetary Science (not including Earth Observation); and
- Solar Physics, Space Weather and Plasma Physics.

On the **nature of the UK's space science community:**

- We identified **53 universities** with active space science research functions, with 16 of those having more than 50 active researchers, and over **2,000 university-based researchers** at postdoctoral level and above engaged in (within scope) space science research.
- These researchers and universities are **based all over the UK**, with at least dozens of researchers in every region and devolved administration.
- Space science research is often **highly interdisciplinary** in its nature, with missions and data use bringing in skills from a wide range of non-space fields.
- These researcher numbers are likely to be **underestimates**, as they only include those identifiable from desk-based research.
- We also used a relatively narrow definition of space science (e.g. not including Earth Observation or human spaceflight) and typically do not count those involved in engineering R&D and other 'enabling' roles in researcher numbers;
- A **wide range of non-university organisations and networks** play key roles in the UK's space science research activity, from other public organisations such as UKRI-STFC and NPL through to companies such as Airbus DS, Thales Alenia Space, Teledyne e2v and others – employing many more researchers.

On **benefits from space science research:**

- The UK clearly has many world-leading strengths, and benefits resulting from research activity in in-scope areas are both **widespread and substantial.**
- The UK can cite **world-class leadership in many different (sub) fields of space science**, while many of our interviews highlighted the UK's particular strengths in **instrumentation**, such as for CCD image sensors, infrared detectors, magnetometers, X-ray optics and other sub-millimetre remote sensing.
- While quantitative benefits are only part of the story, there is good evidence of **high return on investment** on the UK's space science investments.
- A common theme is the **long timeframes** associated with the emergence of benefits – for example, advances today often depend on discoveries from decades ago. We caution against an overly short-term focus on benefits.

- It is also clear that **success begets success**, and the UK's leading roles in past missions have helped to build capability and long run competitiveness.
- There are sizeable benefits across the mission lifecycle, in:
    - The **design, manufacture & operation** of satellite and spacecraft, with estimates of the attributable benefit to the UK economy in the billions, and the UK playing leading roles in many high-profile missions and 'punching above its weight' in terms of Principal Investigator leadership;
    - The **scientific advances** that result from new missions, with dozens of examples of UK achievements and bibliometric analysis showing the UK is 2nd globally in terms of the share of the top 10% highly-cited publications in space literature, and 1st in relevant space science categories as measured by a field-weighted citation impact approach; and
    - The **spillover and indirect benefits**, reflecting that space science missions operate at the cutting edge of technical capabilities, generating knowledge and know-how that can be applied elsewhere. Beyond technical spillovers, the challenges of searching for tiny signals in large noise that characterise many space science missions are common to many other space and non-space fields. The associated skills and advances in AI, Machine Learning and 'big data handling' are widely applicable, both within the space sector in Earth Observation, and far beyond, for example in the finance sector.

The **Gaia mission** is a strong example of where the UK's key role in the design, manufacturing, operations, ground segment, data processing and scientific leadership has led to tangible benefits in terms of jobs, skills, revenues, reputation, knowledge, inspiration, and spillovers.

Beyond the economic and scientific benefits, there are many other themes of benefit arising from the UK's space science research activity. These include:

- **Cultural** benefits, reflecting society's placing of a strong intrinsic value on efforts to improve our understanding of the universe;
- **Inspirational** benefits, reflecting that the space sciences stimulate our imagination and drive more students towards studying STEM subjects;
- **Strategic** benefits, where the UK's involvement in international endeavours help it to make a bigger contribution on the world stage;
- **Diplomatic** benefits, where the UK position as a space science superpower creates 'soft power' and drives benefit in areas well beyond space science;
- **Skills** benefits, where capabilities developed by space science researchers are highly in demand by companies across the economy; and
- **Technological** benefits, where space science missions spur on the development of new products, services and techniques.

Introduction

In late 2020, the Space Academic Network (SPAN) commissioned **know.**space to assess the nature and benefits of the UK space science research base. The research for this report was carried out between November 2020 and February 2021.

For the **nature** element of the study, resources such the Royal Astronomical Society's 2016 '*Demographic Survey of the UK Astronomy and Geophysics communities*' provide a useful mapping of relevant research activity in the UK. Other resources, such as the UK Space Agency's '*Size and Health of the UK Space Industry*' series, the Satellite Applications Catapult '*UK Space Capabilities catalogue*' and the Knowledge Transfer Network's '*Space & Satellite Applications UK Landscape Map*' are similarly useful, though do not engage in detail with the characteristics of the UK space science research base.

Our aim in this element of our research is to **complement** these resources by providing an **up-to-date mapping of the size and capabilities** of the UK space science research base, covering researchers, institutions, disciplinary breakdown and other key characteristics. As our approach focused on desk-based research, we believe it will provide a useful different perspective to more survey-based approaches.

On the **benefits** element of the study, reflecting that the challenge of making the case for UK space science research funding is not a new one, there is a **constant need to strengthen the evidence base on benefits and impact**. As such, a core focus of this study was to 'get beyond the numbers' to assess impact in new ways.

Leveraging our strengths as independent and impartial analysts, we consulted with 20 leading figures in the space science research community to gain **different perspectives on benefits and impact**, and to seek views on topics such as perceived UK strengths, and examples of 'spillover' impacts. These interviews were then complemented by a comprehensive desk-based research exercise, to identify relevant studies on the benefits of space science funding, including **case studies** to showcase different themes of impact.

The ultimate purpose of this report is to enable (i) a **better understanding of the size and nature of the UK space science research base,** and (ii) **a stronger case to be made for future funding** through highlighting the benefits of UK funding and activity. It is not, however, intended to be a detailed economic evaluation or value for money analysis.

Scope

The definition of space science used in this study is scientific space missions that are focused beyond the Earth, e.g. not including scientific Earth Observation missions, but including robotic space exploration.

Space engineering (materials, propulsion, etc.) and other fields that enable space science missions are not directly in scope for the study, but we recognise their fundamental interconnectedness and have commented on these (and other interdisciplinary links) where appropriate. We use the following high-level taxonomy in this study:

- **Astronomy, Astrophysics and Cosmology;**
- **Lunar and Planetary Science;** and
- **Solar Physics, Space Weather and Plasma Physics**

Methodology

This report was developed following a 4-step methodology:

1. Initial desk-based research

For the **nature** part of the study, we reviewed existing resources, such as those referenced above by the UK Space Agency, Satellite Applications Catapult, KTN and RAS, to build an understanding of the state of the evidence base and to identify gaps. In total, we reviewed well over 100 resources, including reports, articles, official mission websites, press releases, media resources, and unpublished resources given to us by SPAN and others.

We then conducted a detailed, bottom-up review of university websites and other resources such as publicly available member lists for SPAN, the Space Universities Network, academic representations at UK and international space conferences to identify:

- Different **institutions** active in space research;
- The location of **clusters** of expertise in the UK;
- Researcher **headcount** in teams / organisations & their **characteristics**; and
- The **disciplinary focus** and nature of their research activity.

For **impact**, we reviewed **previous evaluations of space science programmes**, including:

- UK Space Agency, January 2020, *An assessment of the industrial impacts of UK funding through the ESA Space Science Programme*;
- European Space Agency (ESA), May 2019, *Socio-economic impact assessment of ESA's Science Programme (Executive Summary)*;
- UK Space Agency, 2017, *Impact Evaluation report: Herschel SPIRE instrument*
- ESA, 2016, *Final report on the Space Economy 2016 (Executive Summary)*; and
- booz&co, 2014, *Evaluation of socio-economic impacts from space activities in the EU*.

We also reviewed **wider reports, publications and media resources** such as:

- RAS, March 2016, *Astronomy Means Business: How UK research benefits industry, education and science;*
- London Economics, 2018, *Spillovers in the Space Sector*, and 2015, *Return on Public Space Investments;*
- Impact case studies from universities and UKRI-STFC;
- Case study news stories published on gov.uk; and
- Unpublished resources provided through SPAN and the UK Space Agency.

From our extensive experience of delivering over 100 space-related studies, including numerous business cases and impact studies relating to space science, we also leveraged the knowledge of **know.**space team members to identify other resources and to complement the above with in-house knowledge.

2. Stakeholder consultations

We conducted **20 detailed interviews** with leading figures from across the UK space science community. Most of these interviews were with academics within universities; however, to gain a broader perspective we also spoke to key individuals within wider organisations (numbers do not sum to 20 as some organisations had multiple interviewees, reflecting different disciplinary focuses). This was intended to give a snapshot of different views, rather than a comprehensive consultation exercise.

Universities
Cardiff University
Durham University
Imperial College London
The Open University
UCL (Mullard Space Science Laboratory)
University of Birmingham
University of Cambridge
University of Leicester
University of Portsmouth
University of Warwick

Wider organisations
RAL Space
Royal Astronomical Society
The SPAN Board
UK Astronomy Technology Centre
UK Space Agency
Unaffiliated

A full list of interviewees is provided in an Annex.

We used these interviews to ask questions around:

- What 'impact' means to them, and how to best demonstrate it;
- Perspectives on UK strengths & recent breakthroughs;
- Recommendations for further resources to review;
- How best to categorising benefits;
- Wider benefits/impacts and spillovers; and
- Facilities, interdisciplinary working, and international cooperation.

Where possible, we also used these discussions to sense-check our emerging findings on the nature of the research base, e.g. to verify approximate numbers of active space science researchers in a given organisation or department.

3. Further desk-based research & evidence synthesis

Our initial desk-based research unearthed further avenues to explore, and interviews with consultees similarly generated ideas for new reports and other resources to assess.

Following a review of these additional materials, we took a step back to holistically review the evidence that had been collated and generated, to develop emerging findings and themes for the impact reporting.

4. Reporting & Deliverables

Finally, we brought together the findings of the analysis, presenting them in a series of visualisations, supplemented by commentary. These are summarised in the following sections.

Nature of the UK space science research base

Here we present findings on the size and nature of the UK space science research base, as measured by the number of research organisations active in space science research, fields of research, and regional distribution. The section also includes an analysis of researchers' academic positions, field of research, and discussion of non-university researchers and organisations involved in UK space science research activity.

Universities

We identified **53 universities** active in space science research, defined as universities with at least one researcher active in the areas set out in the 'Scope' section above.

Figure 1: Universities with an active space science research function[2]

Universities		
Aberystwyth University	The Open University	University of Leicester
Birkbeck, University of London	Ulster University	University of Lincoln
Cardiff University	University College London	University of Manchester
Cranfield University	University of Bath	University of Nottingham
Durham University	University of Birmingham	University of Oxford
Edge Hill University	University of Bradford	University of Portsmouth
Heriot-Watt University	University of Bristol	University of Reading
Imperial College London	University of Cambridge	University of Salford
King's College London	University of Central Lancashire	University of Sheffield
Lancaster University	University of Dundee	University of Southampton
Liverpool John Moores Univ.	University of Edinburgh	University of St Andrews
Newcastle University	University of Exeter	University of Strathclyde
Northumbria University	University of Glasgow	University of Surrey
Nottingham Trent University	University of Hertfordshire	University of Sussex
Queen Mary University	University of Hull	University of Warwick
Queens University Belfast	University of Keele	University of Wolverhampton
Royal Holloway University	University of Kent	University of York
Swansea University	University of Leeds	

Naturally, the extent of space science research activity varies significantly across institutions. Many universities have large research functions and are active across many different areas of space science. Counting post-doctoral researchers and those at later career stages only, we found that **4 institutions have more than 100 active space science** researchers[3], and **16 have more than 50 researchers**. Half of researchers (51%) are based in the top 10 universities as measured by numbers of space science researchers, and over three quarters (77%) in the top 20.

At the other end of the scale, there are several universities that may have no explicit space-related department or faculty, but where researchers - often a small number - are active in

[2] Defined as those with at least one active space science researcher.
[3] Figures are likely to include some researchers focused solely on ground-based astronomy, as it was typically not possible from information available on websites etc to split researchers into space-based and ground-based groups

relevant areas of research. These include, for example, biologists involved in astrobiology, and geologists involved in planetary science. In the middle, there are many universities that may have a 'narrow but tall' specialism in a particular area such as solar physics or space weather, often driven by leading researchers and their teams. We identified 12 universities with fewer than 10 active researchers, and 22 with fewer than 20, illustrating clusters of specialised activity.

These numbers are likely to **underestimate** total researcher headcount, as there will be researchers who are not listed on websites or easily identifiable through other resources. For example, not all universities have a complete and up to date list of their postdoctoral researchers. We also tried to err on the side of caution when determining whether researchers should be deemed to be in or out of scope.

In addition, there are some UK universities with research activity in supporting areas, such as imaging and sensing analysis or engineering / materials science, with tangential direct space science research activity. While we have not included these institutions, these could be added to headline numbers if a broader definition were used.

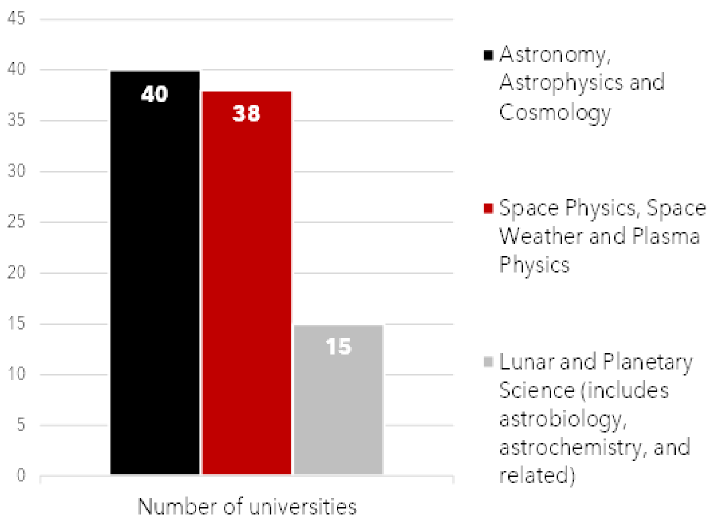
Universities by research area

We manually classified the research activity of each university to the taxonomy set out above. Reflecting that any single institution can be active in multiple areas of research, each university can be classified multiple times (i.e. numbers below do not sum to the total number of universities above). While our subjective categorisation carries some caveats (e.g. others may allocate the same institutions in different ways), Figure 2 presents the summarised results.

The space science taxonomy with most academic institutions in the UK is **Astronomy, Astrophysics and Cosmology,** accounting for **75%** of the in-scope universities. This is followed by **Solar Physics**, includes Space Weather and Plasma Physics, which was a research focus in **72%** of the universities. Around a quarter **(28%)** of universities conduct research on **lunar and planetary science** (including astrobiology and astrochemistry).

Figure 2: UK space science research by research topic

Research area	# of universities
Astronomy, Astrophysics and Cosmology	40
Solar Physics, Space Weather & Plasma Physics	38
Lunar & Planetary Science (includes astrobiology, astrochemistry, and related)	15



Source: know.space analysis

University researchers

Regional distribution

We identified researchers currently active in space science in the UK through a desk-based research approach, counting only those at post-doctoral level or above. With the caveat that this is intended to give a broad estimate rather than an accurate census and noting that the accuracy of any results depends on the extent to which university websites and other resources are (a) up to date, and (b) comprehensive, Figure 3 shows a regional distribution of space science researchers in each of the UK's twelve regions.[4]

We identified over **2,000 researchers** engaged in (within scope) space science research, at postdoctoral level and above. Space science-related **academic researchers are concentrated in the South East (20%) and London (17%)**, which together account for 740 (**36%)** of academic space science researchers in the UK. **Scotland** is home to **11%**, while **Wales and Northern Ireland** account for **5%** and **2%** of researchers respectively.

We also present population-weighted figures in Figure 3, to give an indication of relative regional specialisation. Here, the North East of England has the highest proportional share, with 44 space science researchers per million population, with South East England and Scotland the next highest.

Figure 3: Researchers by UK region & Devolved Administration

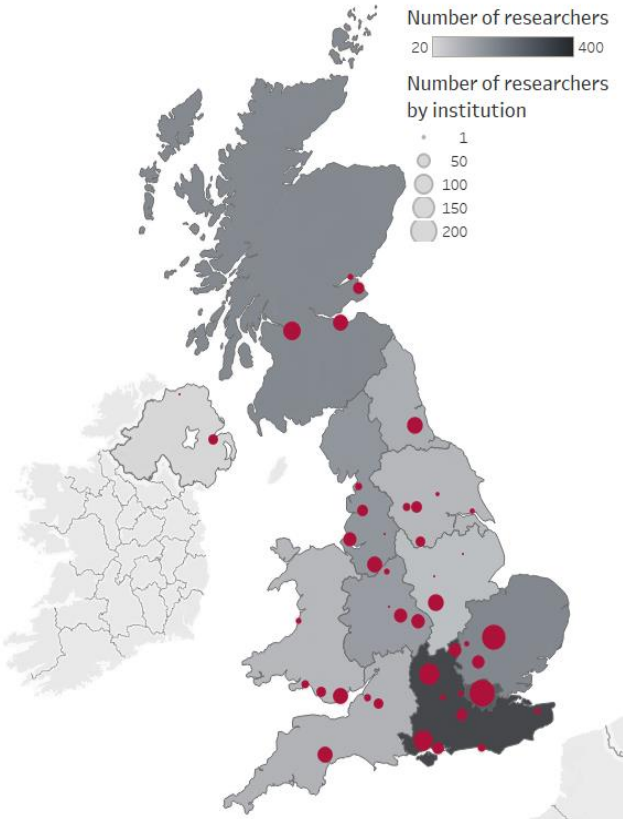
UK region	Number of space science researchers (rounded)	Researchers per 1 million population
South East	400	43
London	340	38
East of England	220	35
Scotland	220	40
North West	180	25
West Midlands	160	27
North East	120	44
South West	110	20
Wales	100	32
Yorkshire & the Humber	90	16
East Midlands	80	17
Northern Ireland	30	16
Total	**2,050**	

Source: know.space analysis

Figure 4 below shows a regional 'heat map' of space science-related active researchers by region and institution. Researchers are allocated to the primary campus location of their institution, though we note that many may in practice be located elsewhere (e.g. UCL-MSSL researchers based in Surrey rather than London).

[4] As measured by the standardised NUTS (Nomenclature of Territorial Units for Statistics) regions at NUTS1 level, i.e. major socio-economic regions.

Figure 4: UK space science researcher distribution



Source: know.space analysis

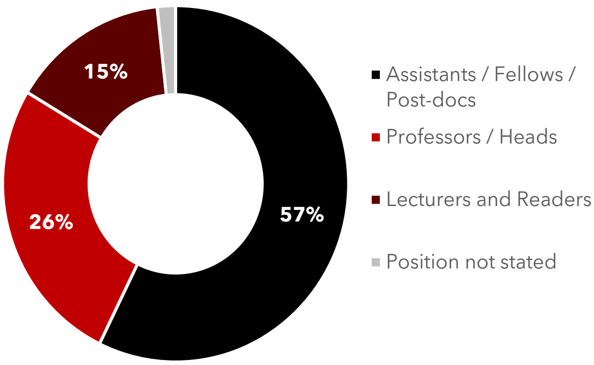
Researchers by career stage

Figure 5 breaks down space science researcher numbers by academic level. More than half (57%) of researchers are at postdoctoral, research assistant or fellow level, while **26% are professors, directors, or heads of department,** and 15% are in lecturer / reader roles. In interpreting these figures, however, we note that those in more senior positions are more likely to be captured by our desk-based research approach, which may affect these results.

Figure 5: University researchers by academic level

Academic level	# of researchers
Assistants / Fellows / Postdoctoral	1,170
Professors / Heads	540
Lecturers and Readers	300
Position not stated	40[5]
Total	**2,050**

Source: know.space analysis



[5] In some cases we were able to determine that researchers were in scope for the study, i.e. that they are actively undertaking space science-related research, but their position was not listed.

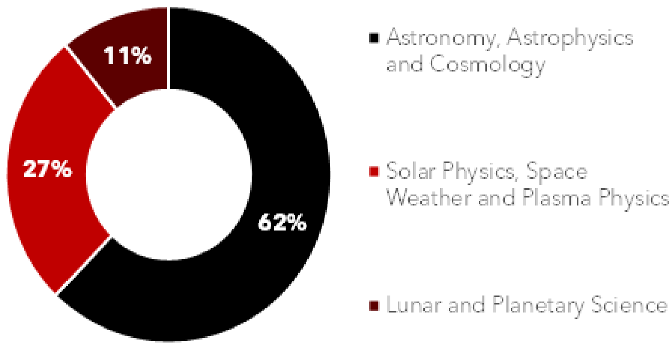
Researchers by field of research

We estimate that well over half of academic researchers **(62%)** conduct their research in **Astronomy, Astrophysics and/or Cosmology**. Research topics in this group include but are not limited to extragalactic astronomy and astrophysics, exoplanets, galaxies and observational cosmology, and theoretical particle astrophysics.

Around **a quarter (27%)** conduct research in **Solar Physics** (including space weather, plasma physics, gravitational physics, and quantum gravity), whilst the remaining 11% have a primary focus on **Planetary Science** (including astrobiology and astrochemistry).

Figure 6: University researchers by taxonomy

Taxonomy	# of Researchers
Astronomy, Astrophysics and Cosmology	1,280
Solar Physics, Space Weather & Plasma Physics	550
Lunar and Planetary Science	220
Total	**2,050**



Source: know.space analysis

Space science research is **fundamentally collaborative**. As an example, ESA's comet interceptor mission[6] comprises an international group of experts which includes planetary scientists and astronomers from UK's UCL-MSSL and University of Edinburgh as project leaders, with other UK universities involved in this project including the University of Oxford, University of Kent, and Cranfield University.

While most researchers are based in explicitly space-related departments, institutes or faculties, several researchers work on space science-related issues from within departments with broader focuses. Examples include:

- Computer scientists from the University of Dundee involved in planetary surface image and simulating planetary missions[7];
- Earth Scientists at Imperial College conducting research on planetary science and involved in missions such as NASA's Curiosity and the investigation of Martian climate and geology[8]; and
- An environmental scientist from Ulster university involved in ExoMars route planning[9].

There is a related theme from our stakeholder interviews that **space science research is often highly interdisciplinary** in its nature, with only a small number of interviewees

[6] ESA's new mission to intercept a comet, 2019: http://www.esa.int/Science_Exploration/Space_Science/ESA_s_new_mission_to_intercept_a_comet
[7] University of Dundee Computing staff: https://discovery.dundee.ac.uk/en/persons/iain-martin
[8] Imperial College Mars missions: https://www.imperial.ac.uk/be-inspired/social-and-multimedia/infographics/imperial-in-space/mars-missions/
[9] Ulster University awarded UK Space Agency funding to explore Mars Rover route, 2019: https://www.ulster.ac.uk/news/2019/august/ulster-university-awarded-uk-space-agency-funding-to-explore-mars-rover-route

reporting that their research is self-contained. A space science mission cannot take place without bringing in interdisciplinary expertise, and in the mission planning phase alone could for example require close working between researchers and engineers (electrical, chemical, mechanical, etc.), geologists and environmental scientists, biologists and chemists, statisticians and data analysts, and many others. 'Big data' is a common theme within space science missions. The techniques and methods used are often shared, and indeed co-develop over time as space and non-space science researchers with expertise in AI, Machine Learning and data science collaborate on shared challenges.

We explore examples of the benefits of interdisciplinary working later in this report, though for any consideration of researcher numbers it is important to recognise that **space science missions and research involve a wide range of experts, many from non-space fields**, and activity goes well beyond the 'pure' space science researchers discussed above.

Finally, while we have not included space medicine, outreach activities, and human spaceflight activities within the scope of the study, there are numerous academic researchers from other disciplines such as health or medicine who are also engaged in researching and planning future science and exploration activities. Again, with a wider definition, researcher numbers would be larger.

Non-university organisations, networks and researchers

Beyond universities, there are many other organisations that play important roles in the UK space science research community. These include other public institutions and private actors, plus societies and networks. It is not the aim of this study to provide a comprehensive list of all the organisations and actors relevant for the UK space science, though we discuss some of the key players in this section.

Public agencies and institutes

The **Science and Technologies Facilities Council** (STFC), part of UK Research & Innovation (UKRI), plays an integral role in the UK's space expertise – particularly through **RAL Space**, which is the space hub for UKRI. RAL Space employs more than 330 staff, many of whom are active space science researchers, and carries out world-class research and technology development, with significant involvement in more than 210 space missions[10], including:

- **Astronomy:** Ariel, Gaia, Herschel, Hubble, JWST, Lisa Pathfinder, XMM-Newton;
- **Solar Physics**: Hinode, Lagrange, Proba-3, SOHO, Solar Orbiter, STEREO; and
- **Planetary**: Beagle 2, Cassini/Huygens, ExoMars, InSight, Rosetta.

STFC's **UK Astronomy Technology Centre** (UK ATC) is also a national centre of excellence for the development of scientific instrumentation and facilities for both ground- and space-based astronomy, employing many researchers.

While not an employer of researchers directly, the **UK Space Agency** (UKSA) funds space science research both nationally and through the European Space Agency (ESA). Reflecting the importance of measurement in science missions, the **National Physical Laboratory** (NPL) also plays a key role in providing the foundation for future missions.

[10] https://www.ralspace.stfc.ac.uk/Pages/Missions.aspx

These organisations are together responsible for **many more researchers than those presented in the headline, university-based numbers above.**

Companies

Naturally, UK companies in the private sector play a critical role in the delivery of space science missions. **Airbus Defence and Space** have been closely involved in the design and manufacturing of missions such as Mars Express, Gaia, LISA Pathfinder, BepiColombo, JUICE, Solar Orbiter, ExoMars, and Orion.[11] The Stevenage site has an Assembly, Integration and Test workforce of over 300 employees, many of whom could be seen as researchers within the scope of this study but not included in headline researcher numbers (see discussion below).

Thales Alenia Space also plays an important role, with UK involvement in mission design and manufacture for BepiColombo and ExoMars since establishment in the UK in 2014. **Teledyne e2v** (discussed further below) is an example of a leading instrumentation provider with involvement in numerous missions. While we do not attempt to list all the companies active in some element of space science mission research and/or activity, more niche companies (e.g. Vorticity, who analysed the dynamic stability of the 2016 ExoMars probe to aid analysis of the parachute deployment) provide specialised solutions that enable missions such as entry, descent and landing systems for extra-terrestrial applications, used in missions including Huygens and the Mars Science Laboratory. In short, **missions can often involve dozens of actors from across the space industry value chain**.

Following agreement that the focus of this study should be more on 'core' space science research activity (i.e. use of data for scientific pursuits) rather than R&D for supporting engineering / design functions, we have not sought to approximate these researcher numbers in detail here. However, we note that a wider definition could be justified[12], and recommend that the numbers presented in previous sections should be understood as a relatively core/narrow estimate of space science research activity.

Other Actors

These include:

- **Societies** – e.g. the Royal Astronomical Society (RAS), British Interplanetary Society (BIS), UK Planetary Forum, UKSEDS (UK Students for the Exploration and Development of Space), and many others focused on astrobiology, astrochemistry, and interstellar travel, among others;
- **Networks** – e.g. SPAN, the Space Universities Network (SUN), the SPace Research & Innovation Network for Technology (SPRINT), the Knowledge Transfer Network (KTN), regional bodies (e.g. Northern Space Consortium, Scotland Space Network, London Space Network, Wales Space Academic Partnership) and advocacy groups;
- **Public / private collaborations** – e.g. the Future AI and Robotics for Space (FAIR-SPACE) Hub, which brings together leading experts from academia, industry and

[11] https://www.airbus.com/space/space-exploration.html

[12] For example, in the Frascati Manual the OECD define researchers as "professionals engaged in the conception or creation of new knowledge, products, processes, methods, and systems, and in the management of the projects concerned", which could be seen as encompassing many of these R&D professionals.

government, aimed at pushing the boundary of AI robotics for future space utilization and exploration; and
- **Public-facing organisations**: e.g. The Science Museum, National Space Centre, Natural History Museum and others focused on educational outreach.

Most of these play supporting roles, though some do engage in active and important space science research, as discussed in the benefits section below (e.g. the current Natural History Museum / Imperial College London research collaboration supporting the NASA Perseverance mission in return sample identification). We do not attempt to quantify numbers here due to risks of double-counting with university-based researchers, though they will add to the numbers discussed above.

While ground-based astronomy is not a core focus of this study, we also identified **232 local astronomy societies and groups**, plus **84 observatories**. While most are focused on outreach and education activities to members of the public interested in astronomy and space, some are used for active research purposes.

In summary, while our quantitative analysis is focused on university-based researchers who are demonstrably active in space science research, they are part of a **wider ecosystem** that supports the research endeavour, and there are many other researchers, key individuals and organisations that play essential direct and supporting roles.

Benefits from UK space science research

A clear theme from our research is that the UK has many world-leading strengths in space science research, and that the **benefits from research activity are both widespread and substantial**. UK space science research generates high returns, while spurring on technological progress, developing skills, and leading to a range of expansive indirect 'spillover' benefits. As in the previous section, we focus on in-scope research areas only, but recognise that broader definitions of space science (e.g. including Earth Observation-related science) would unearth wider benefits still.

Naturally, attempts to quantify and monetise benefits face limitations and do not tell the whole story around the impact of the various activities within the UK's space science community. We consider different 'themes' of benefit and impact below, though there is nevertheless good evidence that research delivers strong economic returns in quantitative terms.

For example, the return to UK space science and innovation investments has been estimated at between £2-7 of direct benefit per £1 of public investment, plus £4-14 of spillover benefits, suggesting a low-end estimate of **£6 returned per £1 invested**, including spillovers.[13] Furthermore, the longer a membership of a space-specific organisation (e.g. ESA), or the longer a programme or portfolio of programmes continues with consistent funding, the greater the rate of return.

One of the core themes that emerged from our desk-based research and discussions with leading figures in the space science community was the **long timeframes** associated with the emergence of benefits. Current economic activity builds on fundamental research of the past, and it can take many years – often decades – for research findings to translate into tangible economic impact.

Satellite navigation, for example, which supports industries worth £300 billion to the UK, relies on quantum theory and general relativity. It is the combination of publicly funded research ranging from general relativity (1919), to atomic clocks (1950s) and to the development of satellites (late 1950s) that together make GPS possible.[14] An excessively short-term focus on benefits may therefore risk overlooking the potentially huge benefits that can be unlocked by investments in fundamental research.

With this in mind, we consider benefits in terms of the **mission lifecycle**, before considering a thematic approach.

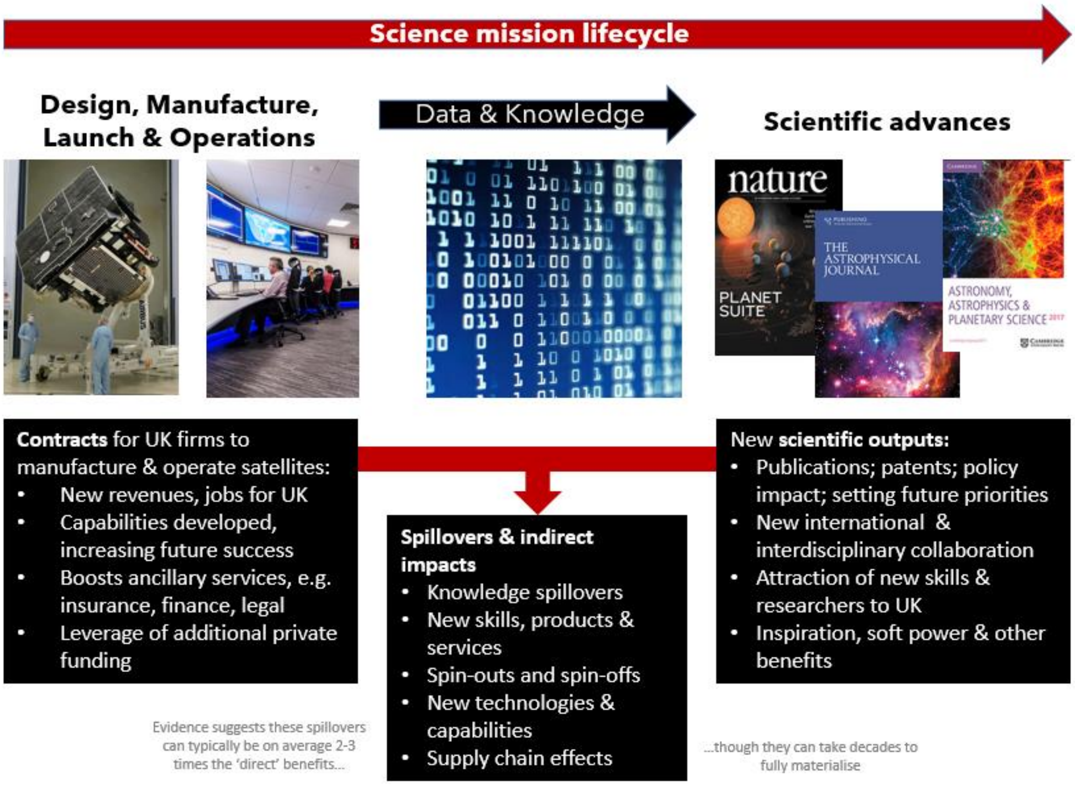
Benefits across the mission lifecycle

As shown in the below diagram, benefits can be considered at three different stages of the mission lifecycle:

- The **design, manufacture, launch and operation** of satellites and spacecraft;
- The **scientific advances** enabled by the new data and evidence generated; and
- The wider benefits stemming from knowledge, market, and network **spillovers**.

[13] London Economics, November 2015. *Return from Public Space Investments*
[14] https://stfc.ukri.org/files/impact-publications/satellite-navigation-case-study/

Figure 7: The space science mission lifecycle



Source: know.space analysis

Design, Manufacture, Launch & Operations

With the majority of the UK's space science research budget spent through the European Space Agency (ESA), there is immense economic value in being positioned as a 'space research superpower' before missions even begin. There are many examples of the UK securing major contract wins for UK companies and organisations. For example, drawing on the strong research base and the UK's expertise, facilities, and capabilities, as of January 2020 a recent study estimated that the UK had secured approximately €630m in ESA contracts from 2000-2018 on leading ESA missions (€300m for the Solar Orbiter mission, €130m for LISA Pathfinder, €126m for BepiColombo, and approximately €90m for Gaia).[15]

This assessment of the UK's participation in the ESA Space Science programmes found that participation since 2000 has led to **£1.4bn of achieved, fully attributed impact** (i.e. that would not have occurred without the UK's investments into the ESA space science programme) in terms of contracts awarded, plus **919 person-years of employment**. This economic impact was generated through employment, sales of spillover technology, consequent securing of other public funds/grants, productivity gains, new facilities, and additional internal investment.

Furthermore, this study estimated that at least a further **£1.1bn of benefits are at least partially attributable** to the UK's involvement, and an **additional 9,080 person-years of**

[15] Winning Moves, January 2020, *An assessment of the industrial impacts of UK funding through the ESA Space Science Programme*

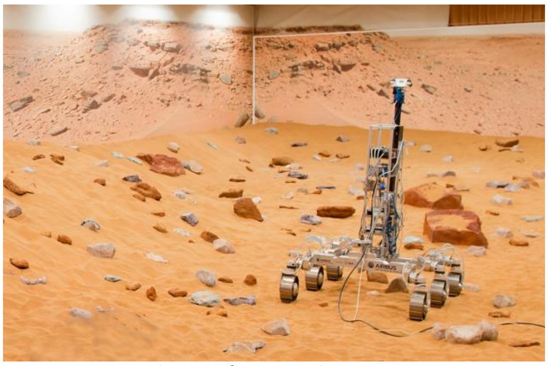
employment were safeguarded.[16] The authors also note that these figures are likely to be underestimates of the true impact, as they consider only the direct, industrial benefits (i.e. not considering the benefit of the scientific outputs themselves), and rely only on a sample of contract beneficiaries.

A full description of UK involvement in all ESA and other bilateral missions would require a comprehensive study of its own. For example, UCL alone noted mission involvement in Cassini, XMM-Newton, Cluster, Integral, NG-Swift, Hinode, Herschel, Gaia, Solar Orbiter, ExoMars, JWST, Euclid, JUICE, SMILE, PLATO, Ariel and Comet Interceptor. Other examples are discussed in the Nature section above and a holistic view across the UK space sector would find some involvement in many more major international science missions. Here, we highlight a few interesting examples and case studies from recent years which highlight UK strengths and benefits.

The UK's expertise in planetary science and the design and manufacturing of landing modules and rovers is internationally recognised. Notably, the rover for the **ExoMars mission** has been built in the UK through an academic-industry partnership, with Airbus DS as the lead builder of the ExoMars rover and SCISYS UK Ltd supporting the development of the rover on-board software and its autonomous operations.[17]

Several crucial instruments are directly attributable to UK-based research teams. One camera system, the PanCam (the panoramic camera system on the rover), is UK-led with scientists from University College London's Mullard Space Science Laboratory (MSSL) working with the University of Aberystwyth, Birkbeck College and the University of Leicester. PanCam will provide imagery of Mars' surface that will allow reconstruction by 3-D digital terrain mapping. The University of Leicester, University of Bradford and UKRI-STFC RAL Space are also key players in the development of the CCD camera on the Raman Laser Spectrometer (Raman LIBS) which can detect the presence of chemical compounds including minerals and specific types of biomarkers.

ExoMars rover prototype pictured in the Mars Yard at Airbus, Stevenage



Gaia is an ambitious mission to chart a three-dimensional map of our Galaxy, the Milky Way, in the process revealing the composition, formation and evolution of the Galaxy. Mission design and development of the RVS (radial velocity spectrometer) was undertaken by UCL's MSSL, which was closely involved with the subsequent industrial work, winning contracts from both ESA and Airbus. We consider Gaia as a case study in more detail below.

The **Solar Orbiter** mission has also seen UK scientists at the centre of design, manufacturing, and operation of the mission, while Engineers at Airbus in Stevenage designed and built the spacecraft. 4 of the 10 of the scientific instruments on board saw strong involvement from UK scientists, with researchers from Imperial and UCL MSSL

[16] Winning Moves, January 2020, *An assessment of the industrial impacts of UK funding through the ESA Space Science Programme*
[17] https://www.gov.uk/government/case-studies/exomars

leading the teams behind Solar Orbiter's Magnetometer (MAG) and Solar Wind Analyser (SWA) respectively. UCL researchers also played a key role in the Extreme Ultraviolet Imager, which will enable the scientists to study processes on the Sun in greater detail than ever before. RAL Space at UKRI-STFC led the consortium that developed and built the extreme ultraviolet imaging spectrometer (SPICE).[18]

For NASA's **Perseverance** mission, researchers at Imperial College London and the Natural History Museum will help to decide which samples are sent to Earth in a search for evidence of ancient microbial life on Mars, and will help NASA to oversee mission operations from a science and engineering point of view.[19]

Our research demonstrates that the UK can cite **world-class leadership in Solar Physics, X-ray Astronomy, Lunar and Planetary Geology, Exoplanets and Astrobiology**. Many of our interviews highlighted the UK's strengths in **instrumentation**, including for:

- Charge Coupled Device (CCD) image sensors, for the most challenging low light imaging and spectroscopy applications, from Hubble through to PLATO;
- Infrared detectors;
- Magnetometer instrumentation (for magnetic field analysis);
- Other sub-millimetre remote sensing; and
- X-ray optics (Swift, XMM-Newton)

With its HQ in Chelmsford, Essex and with two UK-based design, development and manufacturing facilities, **Teledyne e2V** were frequently mentioned as a leading company in this regard, with a strong track record of securing high profile contract wins and working with wider consortia to successfully deliver space science missions. They have designed and delivered sensors and subsystems for over 150 space and astronomy missions, from the upgrade of the Hubble Space Telescope, to exoplanet detection in NASA's Kepler mission, to helping map over 1 billion objects in the Milky Way in GAIA.[20]

In practical terms, these contract wins and strengths lead to jobs, revenues for UK firms, additional tax revenues for the exchequer, and value-added for the UK economy and society. **Funding builds capability and long run competitiveness**, positioning UK firms to win future contracts in the growing space market while developing skills. There was clear agreement that **success begets success** in this regard.

Scientific advances

The primary metric of success for space science is not the associated economic activity, important as that may be, but the scientific output and the progression of human knowledge. Here, both our desk-based research and interviews with the space science community highlighted wide-ranging UK strengths. Interviewees frequently stated that the UK is good at data analysis and understanding ways to make data better, which are valuable capabilities in terms of maximising scientific impact.

While the UK cannot rest on its laurels, interviewees gave many examples of UK achievements in space science over the years. These included:

[18] https://www.gov.uk/government/news/uk-built-spacecraft-captures-closest-ever-images-of-the-sun
[19] https://www.gov.uk/government/news/was-there-life-on-mars-uk-scientists-play-key-part-in-nasa-mission-to-red-planet
[20] https://www.teledyne-e2v.com/markets/space/space-science-imaging/

- Pioneering the development of space-borne techniques to probe the Sun's atmosphere, being the first to detect & track solar-ejected plasma clouds passing over the Earth with important consequences for space weather forecasting;
- Being the first to touch down on and analyse the surface of a planetary moon other than our own (Saturn's moon Titan) and developing an instrument that landed on a comet, showing the world that the building blocks of life can be found there;
- Building some of the largest ever focal planes, for missions such as Euclid and Plato;
- Being the first to detect water vapour in the atmosphere of a planet around another star, with its implications for life elsewhere in the Universe and now lead Europe's exploration of exoplanets;
- Hosting the only truly cross-disciplinary astrobiology research group in the world with access to world class environmental simulation facilities;
- Being responsible for unique X-Ray telescopes that investigate both planetary surfaces and explore gamma ray bursts – the most powerful explosions in the Universe;
- Being at the very heart of ground based gravitational wave detectors that herald a new age of astronomy, and now play the vital role on their future space-based counterparts; and
- Delivering major scientific advances in areas from exploration of the solar system (e.g. BepiColombo, ExoMars), and Solar Science (Solar Orbiter, STEREO), through to fundamental physics (Euclid, LISA), exoplanet hunting (ARIEL, PLATO) and charting the galaxy (Gaia); and
- Spearheading the development of new instrument design, and Machine Learning techniques with vast spin-off potential (see below).

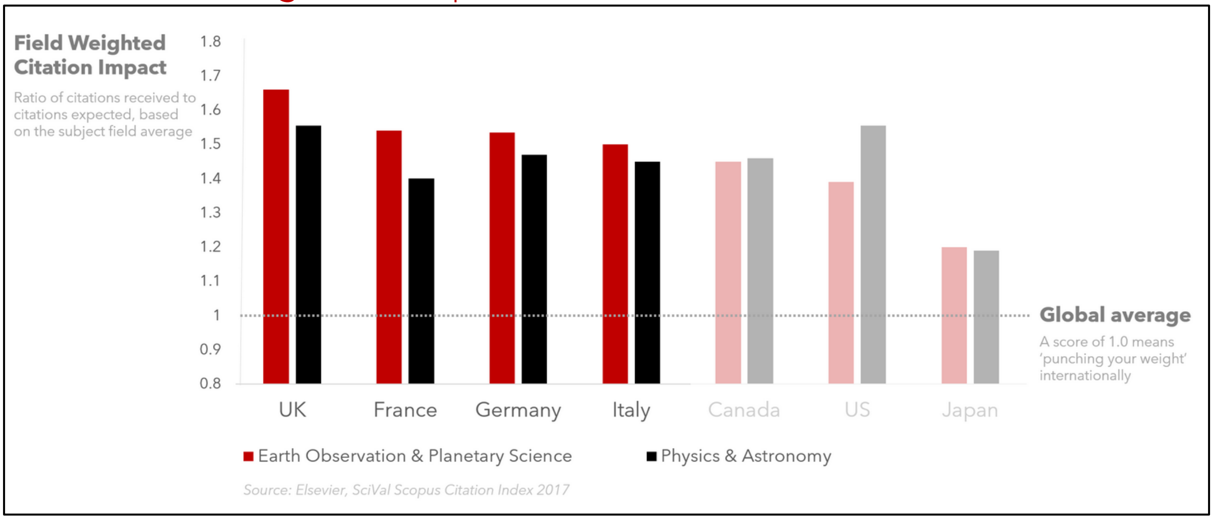
UK researchers are also playing leading roles in current, high-profile missions, such as the very recent example of the Perseverance mission discussed above. In 2020 an international team of astronomers led by a Cardiff University researcher announced the discovery of a rare molecule – **phosphine** – in the clouds of Venus. On Earth, this gas is only made industrially, or by microbes that thrive in oxygen-free environments.[21]

Many interviewees were keen to stress the **intrinsic value of new knowledge**, i.e. the value that society places on advances in fundamental understanding of the universe. Another common theme was the importance of space science in developing the UK's **knowledge economy**, and the recognition that excelling in different areas of research can have benefits that cannot necessarily be predicted, but that are sizeable and critical for driving innovation and longer-term growth in the economy.

As noted by the OECD, space science and exploration are key drivers for investments in innovation and science.[22] The UK plays a **leading role in the global space science community**, as shown by the Field Weighted Citation Impact (FWCI, the ratio of citations received to citations expected, based on the subject field average) for Physics & Astronomy and Earth Observation & Planetary Science[23], where the UK is world-leading.

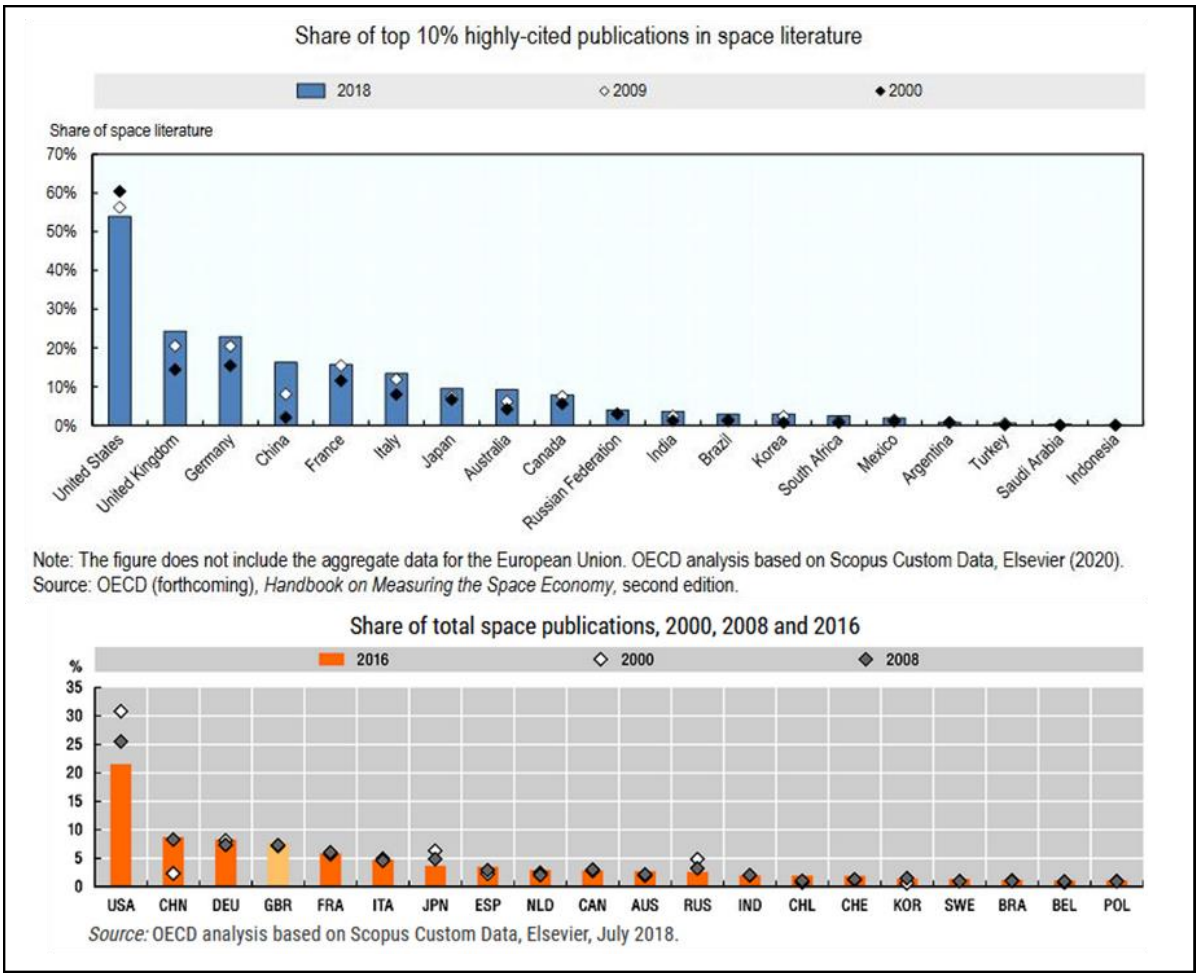
[21] https://ras.ac.uk/news-and-press/news/hints-life-venus
[22] OECD, *The Space Economy in Figures: How Space Contributes to the Global Economy*
[23] Earth Observation is not in scope for this study, though a more granular breakdown was not available.

Figure 8: UK Space Science-related fields and FWCI



The OECD's *Space Economy in Figures 2019* report and upcoming *Measuring the Economic Impact of the Space Sector*[24] shows that the UK is also one of the leading countries in terms of its share in scientific publications, ranking 4th globally in terms of its share of total space publications, and **2nd globally in terms of share of the top 10% highly-cited publications** in space literature:

Figure 9: OECD analysis of UK share of space publications



[24] https://www.oecd.org/innovation/inno/measuring-economic-impact-space-sector.pdf

More specific information provided by interviewees confirms these trends. For example, evidence provided by UCL shows that in Plasma Physics, a key research area of the Solar Orbiter mission, the UK is currently ranked 3rd in total share of published papers, behind only the US and China.

There is also an important theme around **international collaboration**, reflecting the high cost and global reach of satellites, meaning that many scientific missions are not possible to undertake on a unilateral basis. Indeed, for many ESA missions, their success relies on facilities and capabilities that are spread throughout multiple countries. In this way, UK investments in ESA and beyond, through bilateral agreements and other cooperation mechanisms, help to deliver benefits that could not obtain by investing nationally. These investments in turn provide access to extensive research infrastructure such as the International Space Station.

Interviewees noted that the UK has **specialised facilities and abilities that only exist in a very small number of locations worldwide**, for example with regard to calibration of infrared instrumentation, magnetic measurement, and interferometry. This can be an important way through which the UK secures leadership roles in international missions.

As discussed further below, many interviewees noted that the UK punches above its weight in terms of securing Principal Investigator (PI) leadership roles in ESA missions, which in turn helps the UK to secure a greater scientific return.

Spillover and indirect benefits

Space science missions operate at the cutting edge of technical capabilities, **generating knowledge and know-how that can be applied elsewhere**. 'Spillovers' are examples of when this knowledge or technology is transferred from one industry application to another within the space sector (internal), or from the space industry to another industry (external). Often, when thinking of spillovers from space science, we think of the classic examples of GPS navigation, food packaging, solar cells, and fire-resistant materials. In practice, though, the spillover story is more nuanced.

Knowledge and technology developed through major missions can lead to new applications in **future missions, different areas of space science, and/or in different fields both within and outside the space sector.** Wider 'ripple effects' reflecting the continuing and spreading results of research activity can then amplify these benefits.

There is good evidence that these spillover and indirect benefits can be substantial, often 2-3 times the direct benefits of R&D investments.[25] While difficult to quantify, in part reflecting the long lead times (often decades) until benefits are fully realised, there are several good examples of how space science missions and research have led to wider, often unexpected impacts.

[25] Frontier Economics, July 2014, *Rates of return to Investment in Science and Innovation*

Figure 11: Spillover types and examples

Spillover type	Examples
Within space science	Missions almost always help **inform future mission design**, and instruments can have wider uses beyond their original purpose. Even mission failure does not stop this flow: for the Beagle 2 mission, the Open University and University of Leicester researchers built small but sophisticated mass spectrometers for the ill-fated Mars lander, and are now applying that knowledge to **new instruments** to explore Mars and the Moon, in in collaboration with RAL Space and companies including AirbusDS, Fluid Gravity Engineering and Magna Parva.[26] Interviewees highlighted that missions cement UK strengths, leading to leadership roles in new ESA Missions, while retaining expertise and centres of excellence that help grow the industry in the future. Almost every mission with UK leadership reported some form of follow-on result in terms of similar roles in the design, planning and operation of future missions.
Within the space economy	Space science missions can help **grow other areas of the space sector**. Many interviewees highlighted the commonality in the challenges between space science missions and those in Earth Observation (EO), both of which are often searching for tiny signals in large noise. Advances in applied AI, Machine Learning and Big Data handling techniques developed as part of astronomy missions such as Euclid have **direct applications to EO missions** – and indeed in the wider economy, reflecting that this is ultimately about advanced statistical methods that can be applied elsewhere. An example given was techniques from Herschel and other astronomical observatories, which have been used as the basis for hardware being provided for the next generation of ESA MetOp satellites. Similarly, camera systems such as those developed by e2v Teledyne for low light level imaging have other commercial applications. Solar physics instruments can be used for space weather purposes, helping to protect Critical National Infrastructure on Earth (solar storms are for example on the UK's national risk register). These all create new opportunities for **productivity improvements, cost savings and other benefits.**
Within the wider economy & society	**Innovation is the primary driver of long run economic growth**, and hardware, software and knowledge from space science missions can spur on **new products, services and productivity/welfare-enhancing applications**. For example, while wider impacts from **ExoMars** are still emerging, as the 2022 mission has not yet launched, potential wider spillovers include:[27] • Buggies for airport transport which could contribute £10.2m to UK GDP; • Navigation sensors in areas with no GNSS access which could contribute £7.2m to UK GDP;

[26] https://ras.ac.uk/sites/default/files/2018-05/AstronomyMeansBusiness.pdf
[27] Reproduced from London Economics, *Spillovers in the Space Sector*, authored by Greg Sadlier of know.space in his previous role as LE Divisional Director for Space.

- Software architecture on Shannon class lifeboats (RNLI) which could contribute £3.5m to UK GDP and result in multi-million-pound contracts for Warrior armoured vehicles;
- Control systems for water pipe clearing;
- Using the miniaturised Raman instrument from ExoMars for investigating nuclear waste and characterising the degradation of active ingredients in pharmaceuticals;
- Using sterile environments from ExoMars in other applications.
- ExoMars' extraction technologies led to technology used to extract petroleum from rocks and treating heavy oil;
- Algorithms from ExoMars can be used to better detect melanoma; and
- Laser-based technologies from ExoMars used to find defects in steel production.

Few studies have attempted to quantify these benefits for space science missions, though the £16.5m STFC/UKRI investment into the **Herschel SPIRE** instrument was estimated to have led to **more than £4m** in spillovers in GVA terms.[28] A wider evaluation of the programme also concluded that it delivered "exceptional value for money for the UK taxpayer".[29] These market, knowledge and network spillovers included revenue, educational, reputational, and international cooperation benefits. The programme supported the development of Cardiff University spin-out company QMCI Ltd[30], which has generated sales based on the commercial applications of technology developed for astronomical instruments, and built academic-industry relationships with millions of pounds worth of follow-on contract wins as a result. Other spin-off companies have also since formed, and experience developed in instrument modelling and data-processing software has been leveraged for the ARIEL mission which is dedicated to the characterisation of extra-solar planets.

Benefits can also be less directly linked to the technology and knowledge advances. For example, project management experience developed through UK principal investigator status has been directly applied elsewhere by researchers at UCL's MSSL, who have examined how complex technology projects succeed in the real world, offering continuing professional development in project management, systems engineering and technology management. Clients have included ESA, GE, NATS, Mahindra and Transport for London, who paid £2.4m for these services between 2008 and 2013.[31]

Other examples of spillovers mentioned by interviewees include in the healthcare (e.g. imaging science and tumour detection), defence (e.g. "sniffing" air on submarines), utilities, IT, finance & insurance, oil & gas, transportation (e.g. airport scanners), and construction sectors.

[28] London Economics (2015). Return from Public Space Investments.
[29] UK Space Agency, March 2017, *Impact Evaluation Report: Herschel SPIRE Instrument*
[30] While the company existed before SPIRE, building on the R&D activities and facilities for the instrument, capabilities in highly sensitive, ultra-cold terahertz (THz) detectors were commercialised and brought to the global market
[31] https://ras.ac.uk/sites/default/files/2018-05/AstronomyMeansBusiness.pdf

Figure 12: SPRINT spillover case study

From comet sample collection to whisky counterfeit detection

SPRINT, the SPace Research and Innovation Network for Technology, helps provide businesses with unprecedented access to the expertise and facilities at top UK space universities to help accelerate the develop of new products and services through the commercial exploitation of space data and technologies. The seed for many of these products and services often starts with space science missions.

For example, a partnership between The Open University and the Scotch Whisky Research Institute (SWRI) is enabling the SWRI to evaluate innovative gas chromatography/mass spectrometry (GCMS) techniques to enhance its authentication capabilities, to more accurately detect counterfeit products and protect one of the UK's largest export sectors, worth £4.7bn to the UK economy.

Building off techniques developed for the **Ptolemy space instrument, part of the Rosetta mission**, The Open University is leveraging this expertise and their network of strategic partners to support the SWRI's anti-counterfeiting research and service provision for the distilling industry.

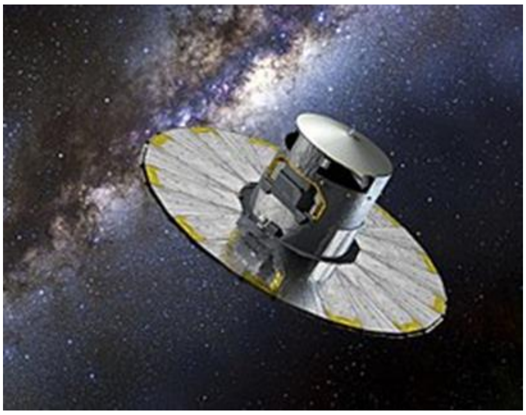
More detail: https://sprint.ac.uk/news-stories/new-collaboration-to-help-the-scotch-whisky-research-institute-enhance-counterfeit-detection/

Institutional missions create enormous amounts of scientific data, and innovative methods have been put in place to make maximal use of the datasets from these and other space science spacecraft and terrestrial telescopes.[32] One example is **crowdsourcing**, which has seen an increasing number of space science projects appearing in the last years.[33] In 2017, for the first time a multi-planet system was discovered entirely through crowdsourcing, in a project called Exoplanet Explorers, available on the online citizen science platform Zooniverse. The **Zooniverse platform, based at the University of Oxford**, hosts an additional 17 active space science projects (as of February 2021), for instance Galaxy Zoo, Planet Four and Solar Stormwatch.

[32] OECD, facts and figures

[33] Crowdsourcing refers to the 'outsourcing; of tasks to large groups of people, often amateur volunteers, generally by means of the Internet, which allow things to be conducted at a much larger scale, and ideally process data and information better and more quickly

In-depth case study: the Gaia mission



The Global Astrometric Interferometer for Astrophysics, or Gaia, has an ambitious mission: to provide a three-dimensional chart of positional and velocity measurements of a billion stars in the Milky Way. Thanks to 21st century technological advancements, largely researched and developed in the UK, Gaia makes mapping the stars in our galaxy possible -- while giving us exciting new insights into the composition, formation, and evolution of not just our own galaxy, but all galaxies.

The UK space science research community played a **key role in the design, manufacturing, and operations of the spacecraft, including in the ground segment, and continues to play a central role in the on-going data processing and scientific discovery**.

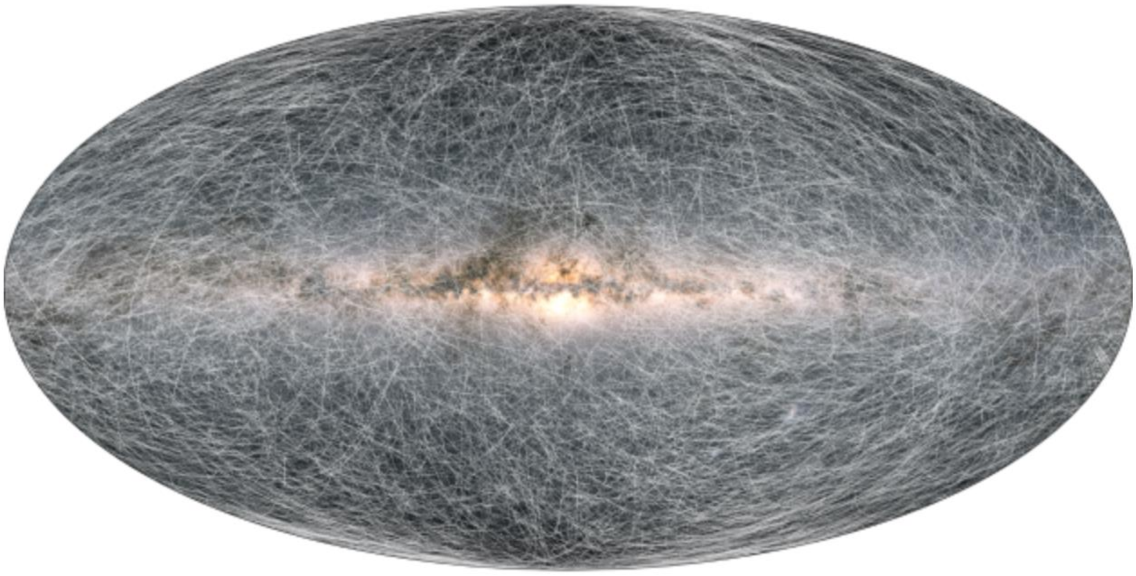
The heart of Gaia, the array of 106 CCDs, was built by Teledyne e2v. The Chelmsford based image-sensor manufacturer has a rich history of working closely with academic research teams, most notably the UCL Department of Space and Climate Physics. The control avionics were built by Astrium in Stevenage (now Airbus DS). The Mullard Space Science Laboratory at University College London played a central role in developing the Radial Velocity Spectrometer. In total, €90m worth of contracts were awarded to the UK.[34]

The total economic benefit of the UK's manufacturing involvement is much higher than €90m, however. Industry expertise has been developed through the sophisticated new developments in technology, innovations will spill over into other projects, and reputational gains from the success of the Gaia spacecraft will position the UK as a prime candidate for future manufacturing contracts. The Gaia mission was originally meant to end in 2022, but because the instruments were not degrading as quickly as initially expected, the mission was extended to 2025.[35]

After design, manufacturing, and successful launch begins the data processing. Here, again, UK scientists play a key role. The amount of data sent from Gaia to Earth poses a monumental data processing challenge: before the data is ready for release to the scientific community and public, it must be processed and analysed at 6 data centres across Europe. To do this, novel data analysis software had to be developed and tested by a consortium of 400 people across Europe, including some 50 people at 6 institutes in the UK, like the Cambridge Data Processing Centre.[36] Gaia's UK data processing facilities in Cambridge, Edinburgh, MSSL/UCL London, Leicester, Rutherford Appleton Lab, and Bristol lead the project-wide effort to discover new transient sources. The team in Cambridge specifically takes care of the data processing of the flux information, providing the required calibrated magnitudes of the stars measured.[37]

[34] https://www.gaia.ac.uk/gaia-uk; https://www.gov.uk/government/publications/an-assessment-of-the-industrial-impacts-of-uk-funding-through-the-esa-space-science-programme
[35] https://sci.esa.int/web/gaia/-/47354-fact-sheet
[36] https://sci.esa.int/web/gaia/-/47354-fact-sheet
[37] https://www.gaia.ac.uk/gaia-uk

Figure 13: Gaia's Stellar motion for the next 400 thousand years[38]



The academic impact of Gaia is already clear. There have on average been around **2400 publications a year** (46 papers a week, 6 papers a day) based on the data releases from the mission, with around 300 of the 2400 annual published papers from UK-based authors.[39] The range of Gaia's discoveries is large: aside from the mapping of the galaxy, Gaia has helped researchers discover supernovae of various types, cataclysmic variable stars, novae, flaring stars, gravitational microlensing events, active galactic nuclei and quasars, among many other astro-phenomena, that help push the boundaries of our understanding of astrophysics, astronomy, and cosmology.[40]

Beyond the obvious value of the scientific discoveries, Gaia's sophisticated data processing software has already seen **applications in other fields, such as medicine**. The data analysis software was developed to pick faint objects of interest out of dense star-field images. The main problem in cancer diagnosis from tissue samples is essentially the same, i.e. the question of what stands out in a fuzzy, noisy image. The techniques developed for Gaia also inform scientists on the efficacy of different treatments, helping scan tissue samples to identify which biomarkers are present when patients have better recovery rates. The potential of applying complicated data processing tools in medicine can help pave the way for more 'personalised medicine': treating patients according to the individual characteristics of their cancers.[41][42]

There are no doubt many more benefits to be had from the Gaia mission in the future, in terms of both scientific progress and spillover benefits. It is a strong example of tangible impact from UK space science activity, including:

- Involvement in the manufacturing which creates employment, training, and technological development in academic-industry partnerships;

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[38] Copyright: ESA/Gaia/DPAC; CC BY-SA 3.0 IGO. Acknowledgement: A. Brown, S. Jordan, T. Roegiers, X. Luria, E. Masana, T. Prusti and A. Moitinho

[39] Information provided directly by UCL from a 2019 Gaia Case Study presentation by: A Fazakerley, M Cropper, MSSL, & G Gilmore, Cambridge

[40] https://www.gaia.ac.uk/data/gaia-data-release-1/uk-contribution-gaia-dr1

[41] Information provided from a 2019 Gaia Case Study presentation by: A Fazakerley, M Cropper (MSSL), & G Gilmore, Cambridge

[42] https://gtr.ukri.org/projects?ref=ST%2FT003081%2F1

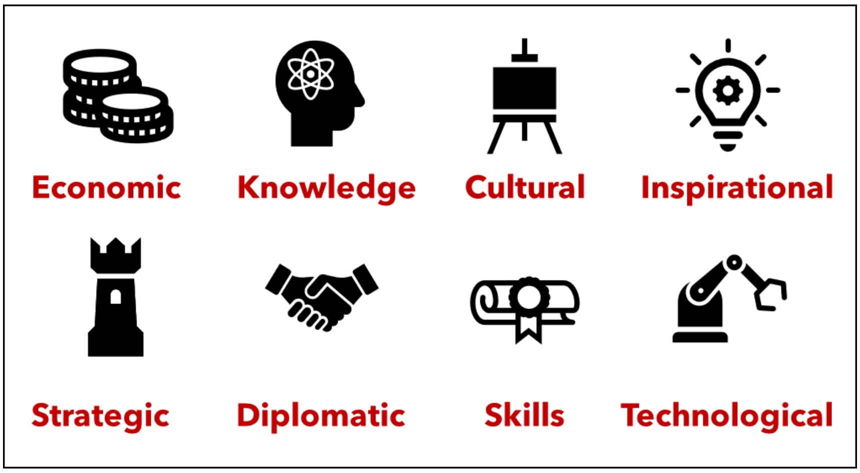
- Successful design and launch solidifying the UK's reputation and placing the UK as a prime candidate for the design, manufacture, and operation of future missions;
- An academic impact which is vast and measurable;
- A high inspiration value; and
- Already-emerging spillover benefits to wider society.

We explore some of these themes of benefit in more detail in the following section.

Themes of benefit

A different way of looking at the benefits of UK space science research is to consider the different 'types' or themes of benefit that we see. The following section has been heavily informed by the useful discussions we held with leading figures across the UK's space science community.

Figure 14: 8 themes of space science mission impact



Economic

Estimates of the economic return to the UK's investments in space science vary, with many analyses (rightly) pointing out that there are inherent limits to the extent to which benefits can be quantified and monetised.

A recent evaluation of the ESA Science programme concluded that the ESA investments resulted in **1.6 and 2.1 GDP and employment multipliers**, respectively[43], while a UK evaluation of the industrial impacts found a minimum return of at least £2.50 for each £1 invested for achieved, fully attributed benefits.[44] As the expansive spillover benefits and technology transfer impacts that are expected to (continue to) materialise over time, this return on investment could rise substantially.

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[43] pwc, Cambridge Econometrics, Science-Metrix and Planetek hellas, May 2019, *Socio-economic impact assessment of ESA's Science Programme (Executive Summary)*
[44] Winning moves

Knowledge

As explored in the Scientific Advances section, the knowledge benefits of space science missions are substantial, both in terms of the 'pure science' knowledge advances that are triggered, and in terms of the wider spillover benefits that accumulate over time.

The UK's scientific strengths and areas of expertise in space science, with disproportionate PI leadership (many interviewees noted that **the UK 'punches above its weight'** in this regard), help deliver a strong return for the UK. Interviewees noted that the **UK has always had a UK-led payload on ESA missions in recent years**. PI leadership is associated with the UK having a higher proportion of scientific papers: for example, for Hubble, the UK paid 14.5% of the European contribution but gained 24% of the European scientific papers produced.[45]

Cultural

A strong theme from our interviews (albeit with people who have chosen careers in space science) was that people in society place **a strong intrinsic value on efforts to improve our understanding of the universe**, and that missions have strong social and cultural benefits which, while inherently difficult to measure and quantify, are very real (in the words of one consultee, "how important is a picture of liquid water on Mars?"). Public awareness is stimulated by impressive images from celestial bodies, such as those produced by Hubble and SOHO, and by missions such as Rosetta.

The general public are genuinely interested in and excited by fundamental science, with stories on advances in our understanding of the universe regularly appearing on TV and wider media and gaining significant attention. The 2019 BBC series *The Planets*, for example, saw over 3 million UK viewers for many episodes.[46] Advances inspire **artistic and creative endeavours**, enhancing wellbeing and generating cultural capital. Some interviewees noted that the role of space science leadership in **national pride** can be underrated, while others noted the criticality of the ultimate end goal of making the Earth more habitable and looking beyond Earth for the safety of the species ("what could be more important than that?").

A 2019 ESA study also found that citizens viewed better understanding of the universe as one of the three main uses for space, and estimated that governments spent almost 25 times more on space activities than they do in practice (€245 per year per citizen estimated, compared to €10 actual cost).[47] One interpretation of this could be that citizens would be happy to spend more on space, including on space science missions.

Inspirational

The Space Sciences **stimulate our imagination**, while space science and exploration missions offer a unique and evolving perspective on humanity's place in the Universe,

[45] Source: UK Space Agency and European Space Agency data on science returns
[46] https://en.wikipedia.org/wiki/The_Planets_(2019_TV_series)
[47] https://www.esa.int/About_Us/Corporate_news/How_much_do_European_citizens_know_about_space

which is common to all. These missions fulfil people's curiosity, producing new data about the solar system and wider universe that bring us closer to answering our fundamental questions about the nature of the universe and our future.[48]

In addition to these drivers of inspiration, the highly challenging and technical nature of the missions can **drive more students towards studying STEM subjects**. As well as helping to address skills shortages in STEM (for example, nearly half of businesses say there is a shortage of STEM graduates in recruitment, with demand highest in applied science[49]), STEM graduates attract higher wages[50], improve productivity, and increase tax revenues for the exchequer, providing a direct economic benefit.

Strategic

The international profile of space science missions encourages collaboration, and the UK's success in securing leadership of space science missions in turn helps lead to future leadership positions, contracts to UK firms, and economic and social benefits. Space science missions help build international relationships, that then have impacts elsewhere. Interviewees noted that participation in ESA missions makes the UK be seen to do more and to make a **bigger contribution on the world stage**.

Many interviewees pointed out that space science research is a way to secure **large impacts from partnerships for relatively small sums.** Membership of ESA provides access to all scientific outputs, and there is a similar story with NASA and beyond, for example with the James Webb Space Telescope.

Diplomatic

A hard-to-quantify but extremely important way space science research impacts society is through the establishing of the UK as a '**space science superpower**'. Historically, the UK has been in the front and centre of the biggest ESA missions. A seat at the table is not just desirable for the UK-based researchers to help bear their own scientific ambitions to fruition; it also helps the UK draw contracts, employment, and knowledge spillovers into the UK economy. In other words, the 'soft power' impact can be thought of as the ability to localise as many of the benefits of scientific activity inside the UK economy.

UK scientists have received many International Awards in recognition of their leadership of high-profile space science missions, and regularly chair international panels. Their influence extends into space policy and regulations, providing the UK with a strong voice.

More broadly, the prestige brought to the UK through space science leadership can be thought of as part of a broader game, helping to secure **collaboration and benefits in areas far beyond space science.**

[48] International Space Exploration Coordination Group, September 2013, *Benefits Stemming from Space Exploration*
[49] Engineering UK (2018), The State of Engineering & Engineering UK (2020), Educational pathways into engineering
[50] Department for Education, August 2019, Labour market outcomes disaggregated by subject area using the Longitudinal Education Outcomes (LEO) data

Skills

For researchers who stay within the space science community, the skills they develop through their research help deliver future missions, and attract high-calibre international researchers to the UK.

Beyond the community, many researchers who work on space science missions go on to work in companies and organisations in other areas of the economy. Whether at graduate level or beyond, those involved in space science research learn valuable skills in programming, 3D imaging, data analysis and problem-solving that are highly sought after by employers. This **demand is found across the economy**: in the most recent Department for Education Employer Skills Survey, establishments with skill-shortage vacancies reported that applicants were lacking complex analytical skills (49% of respondents), self-management skills (59%), and digital skills (33%).[51]

From banking and finance (interviewees noted that astronomers are often in demand for their skills in predictive powers) through to industries like the UK computer animation industry (which is estimated by UKRI-STFC to be worth £20bn including £2bn generated by UK video and computer games[52]), the benefit from this supply of sought-after skills is substantial. Examples such as **Winton Capital providing funding for Royal Astronomical Society awards for post-doctoral researchers** provide clear evidence of this demand.[53]

Technological

The technological impact of space research is wide-ranging. As highlighted by ESA in their 'Down to Earth: How space technology improves our lives' report, **Many fundamental modern technologies we take for granted would not have been possible without key space science research**, such as infrared ear thermometers[54][55], invisible braces[56], improved airbags[57], material purity instruments for food and drinks[58], GPS, aircraft anti-icing systems, cordless vacuums[59], and so on. There is a constant

[51] Department for Education, UK Employer Skills Survey 2017
[52] https://ras.ac.uk/sites/default/files/2018-05/BeyondTheStars.pdf
[53] https://ras.ac.uk/awards-and-grants/awards/2284-winton-capital-award-g
[54] http://www.esa.int/Applications/Telecommunications_Integrated_Applications/Technology_Transfer/How_space_technology_improves_our_lives
[55] Diatek Corporation and NASA developed an aural thermometer that measures the thermal radiation emitted by the eardrum, similar to the way the temperature of stars and planets are measured. This method avoids contact with mucous membranes and permits rapid temperature measurement of newborn or incapacitated patients. NASA supported the Diatek Corporation through the Technology Affiliates Program.
[56] Invisible braces are a type of transparent ceramics called translucent polycrystalline alumina (TPA). A company known as Ceradyne developed TPA in conjunction with NASA Advanced Ceramics Research as protection for infrared antennae on heat-seeking missile trackers.
[57] A German company has used tactile sensor technology developed for the robotic arms on the International Space Station to improve passenger safety in cars.
[58] Space technology is now being used to help Spanish ham experts ensure that hams awarded the highly prized 'Jamón' label are worthy of the name, and one type of spectroscopy, Raman spectroscopy using infrared radiation, can also be used to find counterfeit drinks goods on Earth.
[59] For the Apollo space mission, NASA required a portable, self-contained drill capable of extracting core samples from below the lunar surface. Black & Decker was tasked with the job, and developed a computer program to optimize the design of the drill's motor and ensure minimal power consumption. That computer program led to the development of a cordless miniature vacuum cleaner called the DustBuster.

feedback loop between space scientists and industries to commercialise research discoveries, but even technological innovations that do not go-to-market still have enormous impact on society.

As explored in the Spillovers section above, space science missions spur on the development of new products, services and techniques in areas as wide ranging as high efficiency solar cells, to new materials and data handling techniques. As an example of the latter, space science missions such as Gaia transmit massive amounts of information each second, requiring new data processing capabilities and high-performance computing facilities. In the same way the World Wide Web (invented at CERN) changed the way we transmit and process information, systems currently developed in UK data processing centres have the potential to fundamentally change the way we store, process, and transmit data in the future.

Summary of findings

With over 50 universities and 2,000 university-based researchers – plus many more in other organisations such as UKRI-STFC, NPL and in industry – the UK's space science community is sizeable and has a real economic impact in terms of revenue, employment and skills-generation alone.

The UK has been and continues to be involved in a huge range of space science missions, leveraging wide-ranging and often near-unique capabilities to take leadership roles in missions with ESA and beyond. The UK can justifiably claim world-class leadership in many different areas of space science and has real strengths in hardware (instrumentation) as well as software (data processing & use).

Beyond the economic impact, the knowledge benefits are self-evident. The UK is amongst the world's leading countries in terms of research impact for space science-related areas of research. Success begets success, and while many interviewees cautioned that the UK cannot live off past glories in the long term, space science missions have helped the UK to develop strengths that help build capability and long run competitiveness.

Operating at the cutting edge of technical capabilities, missions generate new knowledge and know-how that can be applied elsewhere. Examples of applications of techniques and 'spin-off' products and services are numerous, and sizeable in terms of their impact. Often, the challenges faced by space science missions in terms of finding weak signals in large noise are similar to those faced in other areas, both within the space sector (in Earth Observation in particular) and far beyond. Advances in Machine Learning, Artificial Intelligence, autonomy and big data handling techniques have applications throughout the economy, while space scientists are often in demand for their skills in predictive powers, forecasting future events based on past data.

Cultural, inspirational, strategic, and diplomatic benefits are inherently difficult to quantify and neatly assess but can be in many ways at least as important as the pure economic and knowledge impacts. The benefits of space science go well beyond the research community and the space sector, spearheading innovation, improving wellbeing, and creating wide-ranging benefits across the economy and society. The UK's position of strength has been built over decades and provides a foundation for future opportunities, meaning that space sciences should continue to be at the heart of any strategy as we look ahead.

Annex: list of consultees

Prof. Adam Amara, University of Portsmouth

Prof. Andrew Fazakerley, UCL

Dr Caroline Harper & Mr Ryan King, UK Space Agency

Prof. Chris Lee, Visiting Prof. at University of Leicester and former UKSA Chief Scientist

Prof. David Southwood, Imperial College London

Prof. Don Pollacco, University of Warwick

Dr Ewan Fitzsimons, UK Astronomy Technology Centre

Prof. Gerry Gilmore, University of Cambridge

Prof. John Zarnecki, The Open University

Dr Leigh Fletcher, University of Leicester

Prof. Mark Cropper, UCL

Prof. Mark Sims, University of Leicester

Prof. Matt Griffin, Cardiff University

Mr Paul Eccleston, RAL

Prof. Richard Harrison, RAL

Prof. Richard Massey, Durham University

Dr Robert Massey, Royal Astronomical Society

Dr Victoria Pearson, The Open University

Prof. William Chaplin, University of Birmingham

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