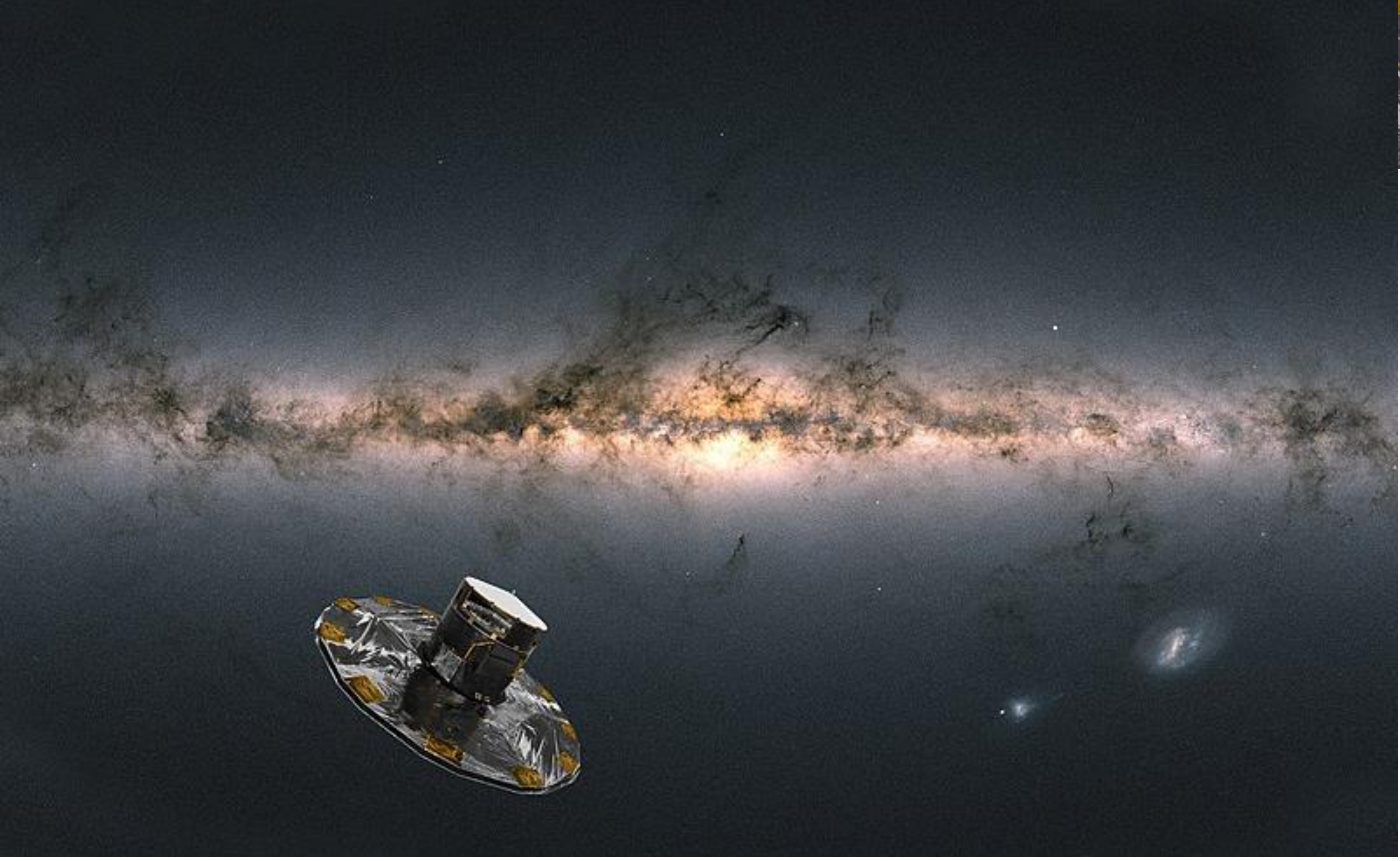

Gaia Interim Impact Evaluation

Interim Impact Report for the UK SPACE AGENCY

know.space

March 2023

know. */nəʊ/v.*

to understand clearly and with certainty

About us

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

www.know.space hello@know.space

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Cover image: Artist impression of ESA's Gaia satellite observing the Milky Way. Source: ESA. Spacecraft: ESA/ATG medialab; Milky Way: ESA/Gaia/DPAC; CC BY-SA 3.0 IGO. Acknowledgement: A. Moitinho.

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Executive Summary

Scope and methodology

Launched in 2013 and expected to operate until 2025, the European Space Agency's (ESA) **Gaia** mission is undertaking the ambitious task of providing a 3D chart of positional and velocity measurements of up to 2.5 billion stars, quasars, exoplanets, comets and asteroids. The mission aim is to construct by far **the largest and most precise 3D space catalogue** ever made.

For the UK, the UK Space Agency (UKSA) has so far committed more than £23m for processing and analysing data from the mission. **It is this national funding – rather than the mission as a whole – that is the focus of this evaluation**. The UK's national investments have enabled the UK space science research community to play a central role in the **ongoing data processing and scientific discovery**, which are significant tasks, given the considerable amount of data sent from Gaia to Earth.

In this evaluation we used a combination of **desk-based research**, **bibliometric analysis**, and **stakeholder engagement** (interviews and a survey) to identify the impact from the UK's national investments into the mission. As this was designed as an interim evaluation, the requirements were set within a **compressed timeframe,** which placed constraints on the depth of analysis. This does however provide an important touchpoint as the impact story will continue to unfold for years – even decades – to come, informing the proposed final evaluation expected to be delivered after the last data release. We identify four core themes of impact:

Scientific impact

The UKSA national funding for Gaia (together with other inputs such as STFC funding) has enabled a wide suite of activity focused on processing and analysing data from the mission. This has been a critical part of enabling the science impacts from the mission, which have been significant. Ultimately, **UKSA funding has helped enable the data that comes out to be high quality and well understood**.

There can be **little doubt that Gaia is a scientific success story**. Bibliometric indicators show a huge impact, both in an absolute and relative sense, while the value of Gaia data to wider astronomy and astrophysics research as a 'reference point' is clear. It is already a **hugely productive** mission in terms of scientific outputs (e.g. it is now the most productive space science mission from ESA in terms of refereed publications per year), and with the bulk of the scientific value yet to come, it is likely that this will be continuing success with **impact set to continue for years and decades**.

The UKSA investments have **helped secure scientific leadership roles for UK individuals and organisations**. The funding enables UK researchers to be close to the data, and to understand its strengths and limitations, enhancing their ability to exploit and gain valuable insight from the data.

UK competitiveness and reputation

The mission has clearly had a positive impact in terms of **enhancing the reach and reputation of the UK space sector**. The picture presented in this report is one of clear benefit both for the UK's reputation, and its competitiveness in the space science domain. There are numerous examples of where nationally-funded Gaia roles have led or is expected lead to UK involvement in other missions, such as PLATO, Euclid and – if it is taken forward – GaiaNIR.

Interviewees also noted many international networks where the UK national Gaia funding has helped **enhance UK influence and standing**, such as the GREAT (Gaia Research for European Astronomy Training) programme, which is led by the UK and a good example of where a leading role in the Gaia DPAC (Gaia Data Processing and Analysis Consortium) has enabled **additional funding to be leveraged** from external European sources, for the benefit of the UK and European science communities as a whole.

Skills and Inspiration

The UK national investments have undoubtedly led to the development of **sought-after skills in algorithm and database development, data science, and data analysis**, both across those directly involved in Gaia data work, and more broadly through training for the scientific community in how to use and analyse Gaia data, and the development of software tools to enable wider use of Gaia data. We found multiple examples of people involved in UKSA-funded Gaia activities moving to tech firms such as Google, research bodies, international NGOs, venture capital firms, and biotech firms, among others.

While not directly funded by UKSA, outreach activities have covered everything from TV interviews to news appearances, workshops, keynote speeches, and art exhibitions. While impact is not something we are able to measure at this time, these activities may have impacts through **inspiring the next generation** and **boosting STEM** uptake.

Innovation

The UK national funding was required to invent many of the techniques to get the accuracy needed from Gaia. This has led to the **development of new advanced statistical methods, algorithms, and capabilities**. Our assessment is that UK investment in Gaia has directly stimulated significant innovation in the field of 'big data' management and processing – a field that is, and will become increasingly, important in both the scientific and commercial domains. In the scientific domain, Gaia's innovations are being applied within **current space science missions**, and are **planned for future missions**. The innovations are also advancing **medical science**, with application to **cancer tumour mapping, diagnosis and treatment planning** that has the potential to save many lives. However, commercialisation of the innovations (e.g. spin-outs) are yet to be realised.

Conclusion

In any impact evaluation, we need to consider the **counterfactual**, i.e. what would have happened in the absence of UKSA investment. In this scenario, our view is that the **UK scientific return would have been significantly lower**. Many of the benefits come from *"being close to the data"* and UK institutions and individuals would have been far less involved in the mission. Similarly, the UK would have **lost the reputational benefits** from involvement in the data elements of a highly successful mission, would likely **not have secured all the follow-on roles** in other missions and activities, and **skills benefits would have been lost** as 'hands-on' complex work to develop new tools and solutions would have happened elsewhere and fewer training activities for the wider UK scientific community would have taken place. The UKSA national investments have been critical for the development of innovative big data techniques, and has this activity happened elsewhere, the **spillover benefits to other UK activities would likely have been significantly lower**.

Several stakeholders spoke of the impact that Gaia has had on the astronomy and astrophysics community's self-belief, and the confidence it has instilled that the UK can perform the sort of leading roles on these big missions effectively. In this way, it is seen to have **positively affected UK space science strategy and direction**, though inevitably difficult to measure.

In terms of lessons learned, Gaia – and the UK's national investments into the mission – has clearly been a success story. While there are good examples of knowledge flows and spillover benefits, we did hear suggestions that there could have been a more active focus on **cross-discipline synergies** (e.g. more actively seeking the transfer of techniques to Earth Observation, commercial data centres, or other areas). This was not an objective of the original funding, but could be brought in for other, similar missions in future to target and focus efforts more directly.

The scope of this study **did not include a process evaluation**, so we did not seek to assess factors such as what could have been done differently or what barrier / enablers to impact there were. Similarly, we **did not conduct an economic evaluation** that seeks to answer questions such as 'was it worth it'. However, given the substantial impacts in terms of science, skills, innovation and strong follow-on activities, all underpinned by the UK national investments that helped enable data to be high quality and well understood, we view that **the return on the UK funding has been considerable**.

1 Introduction

1.1 Scope

Launched in 2013 and expected to operate until 2025, the European Space Agency's (ESA) **Gaia** mission is undertaking the ambitious task of providing a 3D chart of positional and velocity measurements of up to 2.5 billion stars, quasars, exoplanets, comets and asteroids. The mission aim is to construct by far **the largest and most precise 3D space catalogue** ever made.

21st century technological advancements, many developed in the UK, mean that Gaia makes mapping the stars in our galaxy possible. Its Data Releases to the scientific community (most recently in June 2022) provide fundamental new information on topics ranging from stellar structure and evolution, galactic dynamics, and galactic structure, to cosmology and fundamental physics. This gives exciting new **insights into the composition, formation, and evolution of our galaxy and galaxies more generally**, helping enhance our understanding of the Universe.

Core funding for Gaia comes through the ESA space science (mandatory) programme, to which all ESA member states subscribe. As for other missions, in Gaia member states had the opportunity to provide further national funding to secure key roles (typically in instrumentation or science leadership) for UK individuals and organisations. For the UK, the UK Space Agency (UKSA) has so far committed over £23m for processing and analysing data from the mission. **It is this national funding – rather than the mission as a whole – that is the focus of this evaluation**. The impacts we consider are therefore those that link to this funding, rather than other important but out of scope benefits such as the role of Airbus UK (Astrium, at the time) in delivering the spacecraft and the development of industrial capabilities that stems from this.

Beyond the UKSA funding, STFC has also provided an additional £2.4m to support the catalogues derived from the data. While the remit of this study is to consider the impact resulting from the UKSA investment and not broader funding streams and activities, we note that almost all of **the impacts discussed in this report are a function of multiple ingredients** – the UKSA and STFC funding, in-kind contributions from UK research organisations, and of course the wider ESA suite of activity.

The UK's national investments have enabled the UK space science research community to play a central role in the **ongoing data processing and scientific discovery**, which are significant tasks, given the considerable amount of data sent from Gaia to Earth. The UK has major roles in 3 (out of 9) Gaia Data Processing & Analysis Consortium coordination units, and have been involved since the earliest days of the mission – with multiple UK members of the Gaia Science Team from Prof. Gerry Gilmore (University

UK organisations with academic team involvement in Gaia
University of Cambridge
University of Edinburgh
University of Leicester
UCL Mullard Space Science Laboratory
STFC RAL Space
The Open University
Brunel University London
University of Bristol

of Cambridge, Institute of Astronomy) during the study phase (1997-2000) through to Dr Nicholas Walton (Cambridge) who has been a member of the team since 2007. [2]

1.2 Methodology

This has been a rapid exercise to identify, collect and collate evidence on the impacts of UK investments in UK roles in the Gaia mission. All research and reporting was undertaken in March 2023.

1.2.1 Desk-based research

UKSA provided a range of programme documentation and data that were reviewed to populate the Theory of Change and design research materials (e.g. questionnaire).

1.2.2 Bibliometrics

The starting point for our bibliometric analysis was the list of post-launch peer-reviewed Gaia publications on the NASA Astrophysics Data System (ADS). The list is curated by ESA[3], and includes publications that meet at least one of the following criteria:

- Makes direct use of Gaia data.
- Predicts results from the Gaia mission.
- Describes the Gaia mission, its instruments, operations, software, or calibration

The list can be found here. We exported data from ADS to then enable further analysis using desk-based research, which we present in section 3 below.

Bibliometric indicators can at best be a proxy for scientific impact – they typically track *number of* rather than *value of* style indicators – but they provide a useful indication of the volume of scientific activity that a given mission or programme has led to.

1.2.3 Researchfish data

We interrogated additional data from Researchfish – an online reporting system used by funders to collect information on the outcomes and evidence the impact of their research.

1.2.4 Stakeholder consultations

Completed 13 consultations with key stakeholders, conducted as semi-structured interviews using a pre-shared Topic Guide, including:

- **Counterfactual** (situation without UKSA investment)
- Sense-checking **routes to impact**
- Views on the **evaluation questions**
- Identifying other **sources of evidence** for desk-based research
- Sense-checking **emerging findings** and outputs

[2] https://www.cosmos.esa.int/web/gaia/gaia-science-team. Other former UK members of the Science Team include Prof. Andrew Holland (2001-05), Dr Floor van Leeuwen (2003-07), and Prof. Mark Cropper (2006-07).

[3] Our thanks go to Timo Prusti, ESA Gaia Project Scientist, for his time to discuss and sense-check our approach.

1.2.5 Stakeholder survey

We also administered a short survey as a means to collect standardised **quantitative data** from project teams, and selected additional qualitative data to supplement the evidence collected through desk-based research and stakeholder consultations. The survey was coded into the **SmartSurvey** platform for easy engagement and dissemination.

We received **10 complete responses** to the survey, and these responses are summarised graphically in the relevant sections throughout this report. For the survey questionnaire, please see the **Annex**.

1.3 Caveats

There are well-established UKSA and wider monitoring processes around the Gaia investment such as Project Management Boards, Space Projects Review Panels, and other UKSA review mechanisms. From the narrower perspective of socio-economic impact, however, while Gaia was profiled as a case study in a 2021 know.space benefits report for the Space Academic Network (SPAN)[4], there has been **no holistic monitoring and evaluation framework** in place over the course of Gaia's lifecycle, meaning that socio-economic impact data and evidence have typically not been captured in a regular, consistent way.

With this in mind, many of the documents and sources of evidence provided to us contained 'fragments' of the impact story at different points in time, and there was a lack of (for example) any time series data. We have sought to bring these together into the complete story set out here, using new primary research to fill evidence gaps, though the **inherent challenges associated with carrying out retrospective evaluation** using incomplete data and evidence cannot be avoided. Often, where evidence has not been collected at the time, it can be difficult or impossible to generate later on.

We also faced constraints due to the **compressed timeframes** for the study. Key stakeholders faced diary constraints and 'day job' pressures that meant we were often unable to hold interviews until late on in the study, in turn meaning that new evidence often needed to be assimilated late on in the process. While we were able to speak to most of those we targeted, there were some gaps in coverage. There was also not time for a full, in-depth exploration of all impacts that the UK national investments have led to, so this study is unlikely to represent a comprehensive assessment of all impacts. Some stakeholders noted it was not possible to collate full data on some impact indicators (e.g. FTE staff positions supported) within the research window. It is likely that a longer study would have been able to collect a broader range of impact evidence – with more quantitative data, and broader capture of qualitative effects. **The study therefore, should be understood as a rapid, interim impact evaluation, with a full, final impact evaluation due to follow after the last data release**.

The scope of this study is also limited to an impact evaluation and **does not attempt any aspect of an economic evaluation** – such as monetising impacts, or seeking to answer questions such as 'was it worth it?'.

4 know.space (2021), *UK Space Science: a summary of the research community and its benefits*, study for the Space Academic Network (SPAN)

The **impact story from Gaia is far from complete**. As we discuss in following sections, stakeholders typically view that the majority of scientific value from the mission is yet to come. In this sense, this is an interim evaluation, with further impacts and benefits expected in coming years and decades. As we set out in section 3, for example, Gaia has a particularly strong role as 'underpinning infrastructure' for wider scientific endeavours With only 3 years of mission data so far released (expected to be over 10 years at mission completion), and with future data releases covering more dimensions within the data, much of the scientific value has not yet been realised. We suggest that **further evaluation** should be conducted at a suitable future point in time, such as in the early 2030s after the final data release, allowing for some lag for use of the data. While the scientific impact story will not be complete, it will allow for a fuller picture of the scientific value to be presented.

There are complexities behind measuring impacts from UK investment versus investment through ESA when there are complex inter-connected series of interventions, leading to **attribution** challenges. This was a core discussion point with stakeholders, i.e. what they saw as attributable to the UK national investment compared to other factors, though these issues are impossible to untangle fully – many or perhaps most outcomes are a factor of multiple inputs, of which the UK national investment is one. This is important to bear in mind when interpreting results set out here.

The nature of publications means that the bibliometric analysis of citations of Gaia-related papers is backward-looking and static. In reality, the scientific output in **research publications will increase further over time** (expected to 2030 and beyond). The results presented here should therefore be understood as a snapshot in time, rather than the final impacts.

2 Theory of Change & Evaluation Questions

As a starting point, following review of mission documentation and initial discussions with UKSA and other key stakeholders, we sought to develop a logic model and associated theory of change for the UK's national investments.

The logic model is not intended to be an end in itself, but a means to understand how the UKSA funding for Gaia **inputs and activities** led to direct **outputs**, which in turn lead to the benefits that have been realised / that are expected to be realised over the medium and longer term (**outcomes and impacts**).

The model is presented overleaf. Recognising that other funding and activity (e.g. STFC, ESA) is central to the realisation of these benefits, these are included where appropriate. We tested and validated the logic model with interviewees and the Gaia DPAC PLS Oversight Committee, making amendments in response to feedback.

Aside from being a useful visual representation of the flows through to impacts, this exercise also helped us identify the right high-level evaluation questions to ask interviewees in our primary research. We grouped these into 4 impact themes:

Table 1 *Impact themes and high-level evaluation questions*

Impact theme	Description	Evaluation questions
Science	The most fundamental of the impact categories, given the objectives of the mission to enhance the frontiers of our knowledge about the Universe. These impacts materialise over long timeframes, though we can use bibliometric analysis to see impact to date.	- Is Gaia on track to achieve its scientific aims? - What difference has the UK's national investment into Gaia made to securing UK scientific leadership?
UK competitiveness & reputation	Here we consider the impact that UK national investments into Gaia have had in terms of positioning UK organisations for future success, for example through roles on other science missions or through safeguarding or enhancing the UK's reputation in ESA and beyond.	- What difference has the UK's national investment in Gaia made in enhancing the reach and reputation of the UK's space sector?
Skills & inspiration	Those working on Gaia learn new skills that are highly prized, such as on big data analysis, while UK funding has helped train the scientific community in how to use and analyse Gaia data. Beyond these skills impacts, outreach activities help inspire the next generation and potentially increase STEM uptake.	- What difference has the UK's national investment in Gaia made to inspiring, attracting & retaining talent to upskill the UK workforce?
Innovation	Missions such as Gaia operate at the cutting edge of technical capabilities, delivering new knowledge that can be applied elsewhere. In this theme we explore impacts from knowledge transfer, economic benefits, and unpredictable but often sizeable 'spillover' benefits.	- What difference has Gaia made in stimulating innovation and commercial opportunities through data science and space technology?

Certain evaluation questions cut across all thematic areas and we consider them in all chapters, particularly in Conclusions. These include:

- How have different stakeholders been impacted differently?
- To what extent would outcomes have happened anyway (counterfactual)?
- What difference has Gaia made to the delivery of UKSA priorities, or UK space science strategy?
- What are the key lessons learned from the evaluation?

Figure 2 Logic model for UKSA national investments into Gaia

Inputs	UKSA funding for Gaia data processing & analysis (£23m)	STFC funding for early development & supporting data catalogues (£2.4m)	In-kind contributions and resource from UK universities / laboratories	UK researchers' experience (e.g. Hipparcos, large scale astronomy surveys)	Resource for UK leadership roles & programme management	Wider ESA mission funding & industrial activity for mission
Activities	Data analysis and scientific endeavour	Preparation and coordination of Data Releases	UK Gaia Data Flow System management & skills development	Public outreach coordination & implementation	Programme & Project Management & UK leadership roles	Engagement with ESA and ESA MS organisations
Outputs	Scientific data: mapping of c. 2.5 billion objects in our galaxy and beyond	Data Analysis software & training for scientific community in how to use and analyse data	High-skilled jobs and skills development	Inspiration and increased awareness of Gaia	Maintained / strengthened UK reputation	New partnerships & collaborations
Outputs	Publications and scientific outputs	Knowledge & Technology Transfer and spillovers	Strengthened UK capabilities	Increased STEM uptake	Future positioning	Follow-on contracts & grants
Outcomes	Major scientific advances in astronomy and astrophysics	New spin-outs, products & services (economic and welfare benefits)	UK space industry and wider UK economic growth	Strengthened UK scientific and space sector talent pool	Improved UK competitiveness / ability to secure roles in future missions	Better international links and influence within and beyond ESA
Impacts	Lead pioneering scientific discovery & inspire the nation	Grow and level up the UK space economy	Upskill and inspire our future workforce	Build global leadership & reputation		

3 Scientific impact

3.1 Quality of Gaia data

> *"Fundamentally, it's about the science. Missions such as this provide us with mind-blowingly fundamental additions to human knowledge"*
>
> *"Gaia produces the basic underpinning data that is essential to all astronomy – a huge volume of data to enable more precision in measuring (photometric) brightness and (astrometric) distance"*
>
> *"Everyone is going to use Gaia data to establish absolute reference"*
>
> *"It's a map. We need maps"*

A clear theme from our interviews and research was that over the whole sky and at high levels of precision, We heard that Gaia is by far the main source of data – used ubiquitously across astronomical research – and will remain so for many years to come.

The nature of space science missions if that they are complementary, and it is not about one mission 'versus' another. Missions such as Euclid – planned for launch in July 2023 – offer more focused capabilities that will have substantial value to the scientific community. Much of Gaia's value however (we heard from interviewees) comes in through its value as a 'reference frame' for astronomers and astrophysicists to use in their work. Interviewees spoke about the **high value of Gaia as 'infrastructure' for other missions and research** efforts to build on, and its substantial value in this regard.

Table 3 *Gaia in context: Selected ESA missions*

Mission	Launch	Description
Hipparcos	1989	ESA's pioneering space astrometry mission which pinpointed the positions of >100,000 stars with high precision, and >1 million stars with lesser precision.
Planck	2009	ESA's mission to observe the first light in the Universe – designed to image the temperature and polarization anisotropies of the Cosmic Background Radiation Field over the whole sky, with unprecedented sensitivity and angular resolution.
Gaia	2013	ESA's billion star surveyor – creating an extraordinarily precise three-dimensional map of >1 billion stars throughout our Milky Way galaxy and beyond, mapping their motions, luminosity, temperature and composition.
Euclid	2023	ESA's space-borne survey mission to map the dark universe, dedicated to investigating the origin of the universe's accelerating expansion, and the nature of dark energy, dark matter and gravity.
PLATO	2026	ESA's exoplanet hunter mission, studying terrestrial planets in orbits up to the habitable zone of Sun-like stars, and characterising these stars.
LISA	2037	ESA's first space-based gravitational wave observatory, dedicated to studying gravitational waves, and the first mission to probe the entire history of the Universe using these waves.

Source: Based on information from www.cosmos.esa.int

Gaia is organised differently to other ESA science missions. Usually, ESA procures the spacecraft, launch, systems and Member States provide scientific instruments often as an industry-academic collaboration. In the case of Gaia, ESA additionally procured the scientific instrument(s) directly from industry. The challenge for Gaia therefore is to organise, process, check and calibrate the observation data so that it can be best used.

As discussed above, it is difficult to separate the impact of the UKSA national funding from the wider mission activity, as everything is inevitably interconnected. However, interviewees noted how the science flows from the data, with **UKSA funding enabling the data that comes out to be high quality and well understood**. UK membership of the mission science team (e.g. Nicolas Walton since 2007) also means that the UK is embedded in the science direction and can push for UK priorities. UKSA national funding is seen as playing a strong role in this regard (as shown in the survey results later in this section).

3.2 Data releases and chronology

"We're maybe a third of the way through the scientific impact story - at most"

"Because we're measuring a time varying phenomenon, you get more and more information if you carry on measuring."

"The best is still very much to come: I have no doubts that we have not seen yet the full potential of the mission in terms of scientific advances"

Gaia has had several Data Releases (DRs), with DR4 and DR5 to follow in coming years.[5] These data releases are all contingent on UK software and data processing activities, so are strongly linked to the UKSA national funding (as part of a wider suite of necessary activities):

- **DR1** (https://www.cosmos.esa.int/web/gaia/data-release-1, September 2016): we heard from stakeholders how original expectations were that the release was not expected to have major scientific value, but was more about *"working with big data"*. This said, with DR1, Gaia increased the number of stars with usefully measured distances in the Milky Way twenty-fold.[6]
- **DR2** (https://www.cosmos.esa.int/web/gaia/data-release-2, April 2018) – again we heard from interviewees how this was a relatively *"limited"* dataset with only white light colours and positional information from the first period of the mission. The impact however was significant, leading to a kick-start in academic outputs, as shown below.
- **DR3** (Early data release https://www.cosmos.esa.int/web/gaia/early-data-release-3, December 2020; followed by full data release https://www.cosmos.esa.int/web/gaia/data-release-3, June 2022) – this added spectrophotometry, i.e. the distribution of colours, which was revolutionary in the sense that it was not just about seeing where objects are and how they are moving, but what *sort* of objects they were.
- **Gaia FPR** (Focused Product Release) - planned for Q4 2023, this will provide updated astrometry, and various dimensions not in previous releases, e.g. the first results of quasars' environment analysis for gravitational lenses search.

[5] See: https://www.cosmos.esa.int/web/gaia/release
[6] https://www.gov.uk/government/news/uk-scientists-take-a-step-closer-to-revealing-origins-of-our-galaxy

- **DR4** (not before the end of 2025) – will add further dimensions particularly around high-quality spectroscopy, enabling better understanding of what objects are, where they are, and how they are changing over time. It will add full astrometric, photometric, and radial-velocity catalogues, all available variable-star and non-single-star solutions, source classifications (probabilities) for identified objects, an exoplanet list and all epoch and transit data for all sources.
- **DR5** (not before the end of 2030) – subject to approvals of mission extensions, this data release will contain all collected data[7]. We heard from stakeholders how it is expected to increase the number of known planetary systems from 5,000 to 200,000, with the final dataset be *"10 times more accurate than previous ones"*. It will repeat the DR4 contents, but based on 10.5 years of data.

Data releases so far cover just under 3 years of mission time, while it is expected that there will be more than 10 years of data by the end. Several interviewees were also keen to stress that this data will have more dimensions and will be more scientifically valuable. In short, it will **improve existing core products** (e.g. more years of data and better coverage) while **introducing new products** (e.g. a Legacy Archive). Furthermore, impacts around skills, capabilities, reputation, and innovation can take many years to play out fully. The scientific impact we cover here is therefore an assessment of impact at a particular point in time, when the mission is still operational, with many benefits yet to come.

3.3 Bibliometric analysis

Our analysis in this section focuses on the scientific impact of Gaia as measured through bibliometric analysis. This is clearly a function of the wider mission and factors other than the UKSA investment, but it is also clear that the impact stems from UK software and data analysis capabilities, so has an obvious link to the UKSA investment.

The source for the charts and statistics presented here is **know.**space analysis based on NASA ADS data that uses the ESA list of refereed studies linked to Gaia.

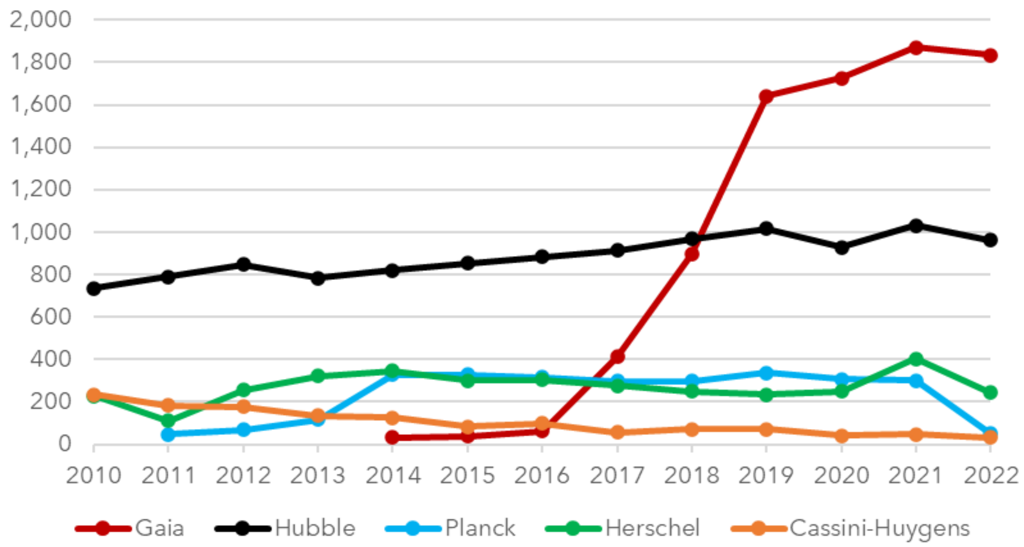
3.3.1 Scientific output

Gaia is now the most productive space science mission from ESA in terms of refereed publications per year. We can see that in recent years the number of Gaia publications has drastically increased, to levels of over 1600 a year or around **5 publications a day**. This represents a significantly higher volume of publications when compared to other missions, even missions such as Hubble / HST.[8] The following chart shows the relative impact of Gaia compared to 'similar' missions, to the extent that such a comparison can be made, using Plank and Herschel ESA missions that launched in 2009 (i.e. 4 years before Gaia), and Hubble and Cassini-Huygens as 'big hitter' comparisons.

[7] https://www.cosmos.esa.int/web/gaia/release

[8] Note: while this is a truncated data source for Hubble, in previous years the number of publications was lower rather than higher.

***Figure 4** Publications by year: selected space science missions*



Source: know.space analysis using NASA ADS and ESA-curated publication lists by mission

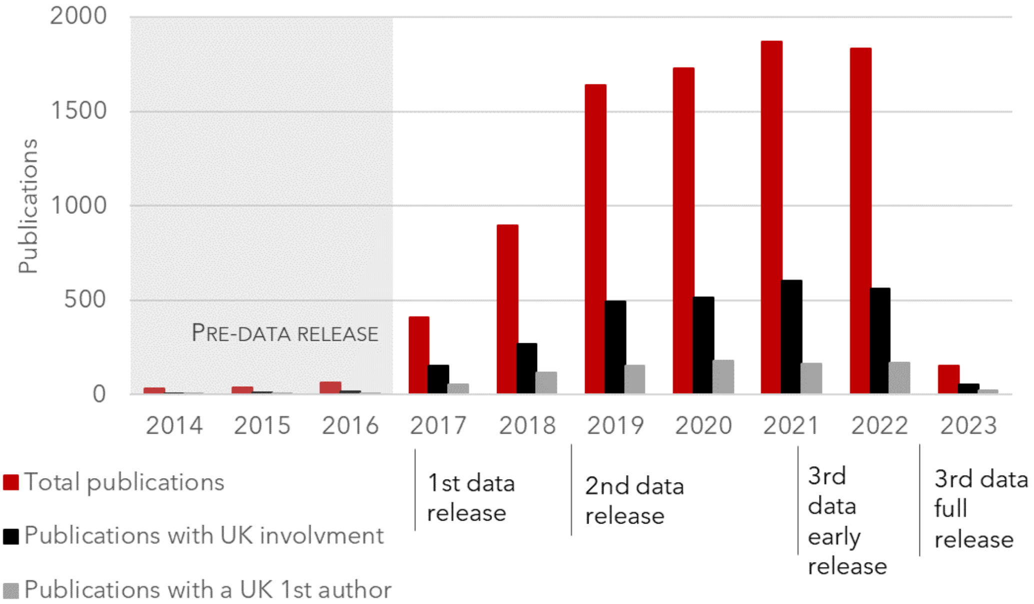
Interviewees noted that a lot of publications reference use of Gaia data without formally citing the relevant Gaia data papers, suggesting that the **true number of publications may be substantially higher than these data show**.

3.3.2 UK involvement

UK involvement has been strong. We can see the huge uptick in publications after the have been published first data release and beyond. Since 2019, **over 500 publications a year with a UK author** have been produced. The metric on UK first author carries some caveats[9], though since 2022 over 150 publications a year have had a UK author.

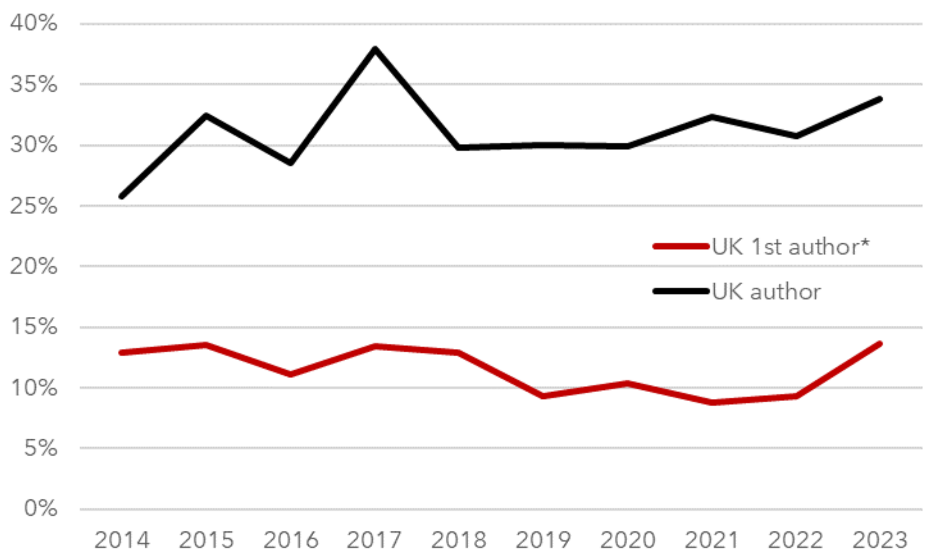
[9] Whether a first / corresponding author is deemed as being from the UK is calculated based on the author who is named first on a publication. This approach is used in many bibliometric studies though an important caveat is that in some cases the corresponding author is listed last and / or there may be multiple corresponding authors. Conventions as to the order co-authors are listed on publications varies by field and journal. This is therefore an imperfect indicator, and is intended to give an approximation rather than a definitively accurate number.

__Figure 5__ Publications by year: total publications and UK involvement



In percentage terms, this shows that **typically around one third of Gaia publications have a UK author**. This falls to around 10% on average when considering publications with a UK *first* author (noting above caveats) though for a large international mission this indicates **strong UK leadership** within scientific outputs.

__Figure 6__ Proportion of publications with a UK author or first (corresponding) author



In cumulative terms, at the time of writing in March 2023 there are now over **8,663** Gaia publications, of which **2,688** have a UK author (31%) and **874** have a UK first author (10%). Between 2020 and 2022, an average of **1,811** publications a year have been produced. The conclusions here are clearly that Gaia has had a huge scientific impact, as measured by volume, and that UK scientists have had substantial involvement, being involved in the production of almost a third of papers.

An alternative perspective on UK impact comes from keyword analysis. The UK leads mission photometry, underpinned by the data activities. The 8,663 refereed Gaia papers from ADS all have keywords associated with them, which allows filtering of results. Interestingly, we can see that "photometric techniques" is the second most common keyword, higher than keywords such as "astrometry". This is indicative of a level of attention and publication cadence related to photometric topics, showing impact of UK activities.

Interviewees provided insight on how UK leadership roles on the data (i.e. its quality and how best to use it) underpin the long list of UK papers. Whilst it is not clear exactly how many people are involved in the UK part of DPAC (the Gaia Data Processing and Analysis Consortium) – it is estimated at 20-30 people – equivalent to more than 5% of the DPAC, a significant share of the network which is very spread out across Europe.

3.3.3 Citations

Gaia publications since 2014 have been cited over 200,000 times, and UK authored papers are cited significantly more than average. For example:

- Papers with UK involvement constitute 46% of total citations, while accounting for 31% of publications
- UK first authored papers constitute 15% of total citations, while accounting for 10% of total publications
- The average number of citations for a UK-authored publications (first-authored or contributing author) is 35, compared to 23 for an 'average' Gaia paper

While it is important to stress that more citations does not mean that a mission is 'better' than another (it can for example reflect wider applicability as opposed to narrower depth of insight), to continue the comparative analysis presented earlier, Herschel refereed publications over this period have received around 140,000 citations, while Planck papers have received around 180,000 citations. While there is still substantial scientific value in these missions yet to come, their missions are completed rather than still operational. It is therefore **highly likely that Gaia will outperform other, similar missions in terms of citation impact**.

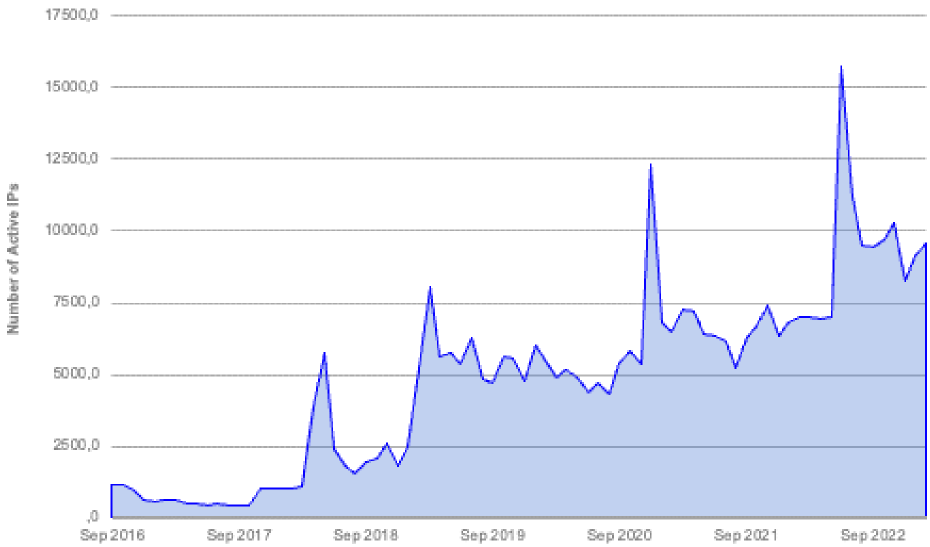
Our analysis of Gaia publications compared to all publications in the astronomy field (using NASA ADS) also suggests that **UK first-authorship and involvement in the production of Gaia publications is significantly higher than average**. When taking a sample from wider astronomy publications in various years, for example (chosen as 2013, 2017 and 2021 to obtain a spread), we found that on average around 4-5% of papers had a UK author – significantly lower than the 31% UK involvement rate for Gaia publications. While higher rates than average would be expected, given that we are assessing a mission with substantial UK involvement, the difference is marked.

We also heard anecdotal evidence on the impact of Gaia on improving researchers' citation impact. For example, **one senior scientist said that their involvement in Gaia has led to their citations increasing by a factor of 2.5** since data releases began.

3.3.4 Data usage

Data provided by ESA show that usage of Gaia data in the Gaia ESA Archive[10] has increased steadily over time. Unique users plot indicate that **the number of monthly users is now approaching 10,000**. Most peaks in the usage statistics correspond with mission data releases.

Figure 7 *Archive users (different IP addresses) downloading data or making queries per month*



Source: ESA

With the bulk of the scientific impact yet to come, this picture of increasing usage is likely to continue to build over time.

The scientific impact of the data has been significant, but relies not just on the quality of the data, but also the quality of the analysis. As shown in a case study on the right, we have also seen examples of software tool developed as a direct result of UKSA national funding being widely used.

Case Study: gaiaxpy as an enabler for scientific impact

To assist analysis of the Gaia data by the scientific community, the UK Data Processing and Analysis Consortium (particularly at the University of Cambridge) developed a python package called gaiaxpy, to facilitate the handling of blue and red photometer spectra data. This data became available for the first time in DR3 in 2020, and can be accessed in the Gaia archive. Accompanied tutorials for using the package were provided, and gaiaxpy has been downloaded **over 22,000 times** (as of March 2023).

When asked about how the UKSA funding specifically enables impact, interviewees noted that:

- The organisation of data to be added to the archive **made engagement 'easier'**
- Data products are made **available to the public**
- Python libraries have been made available to the public **astronomy community**
- Researchers have been able to **explore and exploit the data more easily**
- Papers accompanying the data facilitate **more and better use of the data**

[10] https://gea.esac.esa.int/archive/

3.3.5 Altmetrics

Altmetrics are a set of metrics used to capture the online attention and impact of research publications beyond traditional citation-based measures. They can be used to supplement bibliometric analysis to investigate the impact of research on a wider audience. While altmetrics can only provide a partial snapshot of broader scientific impact, they can provide valuable insights if used with nuance and are viewed in the appropriate context.

We tracked the wider online outreach of the top 20 cited Gaia publications using altmetrics.com, to gain an indication of the impacts of Gaia research on the engaged general public. Using this method, each publication is attributed an altmetric attention score, which is a weighted index that is generated through tracking the mentions of a publication across various digital sources, including social media, news outlets, blogs, Wikipedia articles, policy documents, and online referencing tools. We found that:

- The top 20 cited Gaia publications had an average attention score within the top 7% of publications from Astronomy journals within a similar timeframe.
- For the 12 of these 20 that featured a UK authors, their scores were all within the top 6% of publications
- The top 20 cited Gaia research papers have been referenced 528 times in Wikipedia articles, illustrating considerable online attention beyond citations.
- 88% of the Wikipedia references featured UK involvement (since attention is generally focussed around the data releases)

This indicates that Gaia research is not only valued within academia, but has also resonated with a broader audience online.

3.4 Scientific value of Gaia data

"Gaia data released so far has revolutionised many aspects of astrophysics and has enabled research beyond most previous missions / observatories"

Comprehensively setting out the scientific value of Gaia would be a mammoth undertaking, and a story that is still unfolding. ESA have presented a number of 'in-depth stories' showing the questions that Gaia can help answer – shown in the figure below.

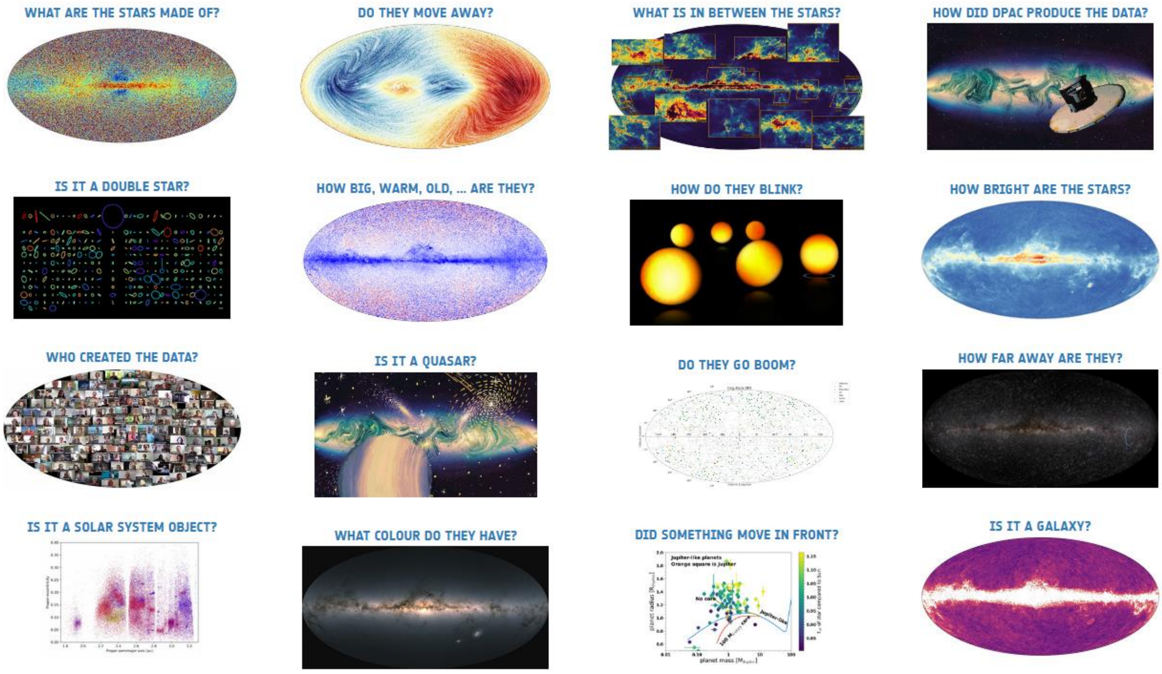
As a few token illustrations rather than any attempt to comprehensively capture the value of Gaia, insights that have been gained include:

- Gaia data has enabled the production of a high precision Hertzsprung-Russell diagram, which plots a star's intrinsic luminosity against its effective surface temperature. By accurately identifying stars of similar mass and composition, we can **see how our Sun will evolve in the future**[11]
- Gaia data has presented **challenges to the law of universal gravitation** (and support for the MOND theory): using data gathered by Gaia for five nearby star clusters, scientists found that all have many more stars in the front tail than in the back tail, which would be impossible if the law of universal gravitation is correct. Applying the MOND theory of gravitation (formulated by Mordehai Milgrom in 1983), they find that this theory predicts the observed phenomenon.[12]

[11] https://www.esa.int/Science_Exploration/Space_Science/Gaia/Gaia_reveals_the_past_and_future_of_the_Sun
[12] https://www.cosmos.esa.int/web/gaia/iow_20221026

- Direct evidence of both violent **past interactions of the Milky Way with other galaxies**, and internal bouts of intense star formation along its spiral arms.[13]

***Figure 8** ESA Gaia Data Release 3 'stories'*



Source: ESA – Gaia DR3 Stories (https://www.cosmos.esa.int/web/gaia/dr3-stories)

We heard how Gaia was the first big data open-source mission that put out complex data (i.e. many parameters associated with each data point), with a huge range of uses, including providing insights for example into:

- Galactic archaeology
- Nature of dark energy and dark matter
- Interactions between galaxies
- Comets & asteroids

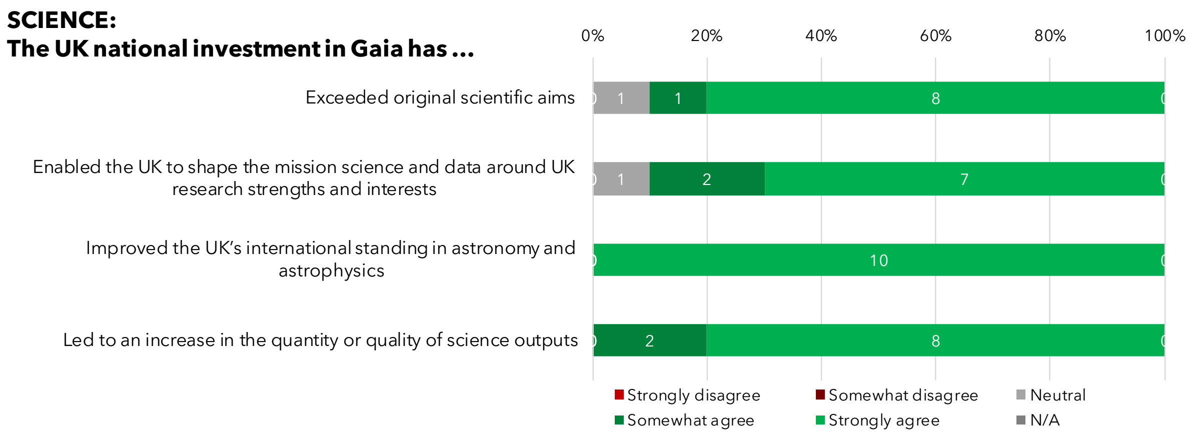
Gaia data also underpins substantial work within the wider astronomy and astrophysics community in the UK. There are a significant number of UK research programmes now relying on the availability of Gaia data releases. The Gaia project team provided evidence for example that in the recent 2014-2019 STFC consolidated grant round, Gaia was the space mission facility most frequently required by successful applicants.[14] A major direct impact of Gaia data processing was noted by interviewees as being to deliver science-ready information to support research by funded students, postdocs and faculty in STFC-funded university groups

Interviewees stressed that **Gaia is essential for UK astronomy research**, and the PhDs associated with those research projects across the UK. As we discuss in section 5 below, these PhDs also increase their data science abilities, enhancing sought after skills and creating wider economic benefit for the UK.

[13] https://www.ukri.org/news/gaia-gifts-most-detailed-ever-look-at-our-milky-way/
[14] Gaia project team 2021-2024 UKSA grant funding application, November 2020

Respondents to our survey were near-unanimous in their view that **Gaia has exceeded its original scientific aims** (9 of 10 respondents strongly agreed). The mission is now looking at around 2.5 billion objects, rather than the 1 billion originally envisaged, and many of those we spoke to expressed sentiment of having been taken aback by the level of impact that the mission has achieved.

Figure 9 *Stakeholder survey results: Scientific impact*



Source: know.space analysis of stakeholder survey responses
Note: n=10 survey responses.

Again, though, the value of Gaia data should not just be seen in terms of the direct science results it leads to, but in the wider value as underpinning architecture for the wider research community. It will have a wide range of indirect / second order impacts as an enabler.

One practical example provided by interviewees was on searching for White Dwarves (which are formed when a low-mass star has exhausted all its central nuclear fuel and lost its outer layers as a planetary nebula). Prior to Gaia, with – and limited to – brightness and distance measurements based on a Milky Way catalogue of a few thousand observations, researchers would often spend weeks or months of observatory time to investigate potential candidates. With Gaia, precise measurements of the brightness and distance can quickly confirm whether each star candidate is a White Dwarf or not, saving valuable time and dramatically improving the productivity of scientific research. This is only one of many examples, but illustrates how **Gaia data can save time, effort, and enhance wider research endeavours**.

3.5 Counterfactual

"We'd still have data access, but no expertise to leverage the capabilities"

"At a fundamental level UK participation has steered the mission to success given the involvement of astronomers with a proven track record in space astrometry and surveys in general"

"It keeps us in Europe scientifically: we're one of the top contributors and the top table, and trusted by partners"

In any impact evaluation, we need to consider the counterfactual, i.e. what would have happened in the absence of UKSA investment. As discussed in further detail in section 7,

the general consensus was that the mission would have gone ahead, though with UK roles picked up by other countries.

The impact this would have on mission *quality* is more difficult, though a majority of those we spoke to viewed that UK involvement has made the mission better (*"it's a good team, that we've kept together over the years"*), with several noting the UK's significant expertise prior to Gaia in this field (e.g. in the ESA Hipparcos mission and development and operations for large-scale data processing at Cambridge and elsewhere) that - without funding - would not have been used in Gaia, to the detriment of the overall outcome. Some noted the world-leading strengths of UK institutions that would not easily be replicated elsewhere, while others viewed that there would be negative impacts, but we would probably have seen *"the same sort of data"* coming out of the mission.

Without UK investment, there would still be Gaia data available to the UK. A good proportion of papers are written by researchers from countries who have not invested in Gaia, for example, and the UK would still be invested through the ESA science programme subscription.

However, we view it as highly likely is that **the UK science return would have been significantly lower**, and UK astronomers would not have exploited the data to the same extent. With less involvement from UK institutions and individuals in the mission, we would have seen a significant reduction in UK activity. Interviewees spoke of how UK researchers would lose *"being close to the data"*, and would not author the highly-cited papers that accompany data releases. UK teams have been able to develop the algorithms and understand how the data is constructed – its pitfalls and strengths – and this in turn means they are able to extract greater value from the data.

The open data release policy means that the UK would still have benefitted from the downstream catalogue -- just like anywhere else – but stakeholders viewed that the **national community would be much more fractured** without the continuum of interests from UKSA-funded instrumentation expertise, through UKRI-funded data analysis, and on to exploitation.

Some also noted the 'softer diplomatic' effects of meeting people working on instrumentation and data at meetings that can often inspire new analysis and theoretical work, noting that these benefits our missing from the UK's main non-European competitors (e.g., Australia, Canada, USA).

Some pointed to negative impacts this would have on the profile of the UK as a leading nation in astronomy. Linked to the reputational impacts we discuss in the next section, the UK national investments are seen as *"getting the UK a seat at the High Table"* (e.g. the DPAC Committee). UK involvement is also seen as giving hands-on experience and engagement. We also heard that some aspects (e.g. industrial engagement, public outreach, technological training as a result of ground-segment engineering) would be entirely absent in the UK were it not for UK national investments.

In terms of enabling (UK) scientific exploitation of Gaia data, it was noted that a source of expertise exists within the UK to help the community with using Gaia data, that only exists because of the UK national funding. If this funding has not been provided, UK researchers' ability to fruitfully use Gaia data would almost certainly have been decreased.

One view we heard was that in the absence of UKSA national funding, there would likely have been a difference in the amount of funding for data processing activities. We heard (from non-UK interviewees) that this would likely have meant that some follow-up activities might not have taken place. We heard that these activities as they have been delivered have been critical for identifying problems that otherwise might not have been picked up before data release, corroborated by another stakeholder who viewed that *"numerous issues would have taken significantly longer to resolve without the UK experience added to the project"*. This suggests a credible argument that data quality from the mission may have been worse without UK involvement.

Other stakeholders noted that without the UKSA funding, the UK would lose leadership of the highly impactful MSCA *(*Marie Skłodowska-Curie Actions *)* MW-Gaia Doctoral Network (discussed more in section 5), which was the only astronomy network in the 2021 MSCA Doctoral Network call.

Many interviewees were keen to stress the importance of seeing the UK's Gaia investments within the **bigger picture** – both in terms of Space Science, and in international relations more broadly. Involvement in Gaia is seen as the sort of necessary activity that keeps the UK as a major Space Science nation alongside other European countries. It is seen as providing 'buy in' to international collaborations, building trust.

3.6 Evaluation questions

The two primary evaluation questions we considered here are:

- Whether Gaia is on track to achieve its scientific aims; and
- What difference has the UK's national investment into Gaia made to securing UK scientific leadership?

For the first question, there can be **little doubt that Gaia is a scientific success story**. Bibliometric indicators show a huge impact, both in an absolute and relative sense, while the value of Gaia data to wider astronomy and astrophysics research as a 'reference point' is clear. It is already a **hugely productive** mission in terms of scientific outputs, and with the bulk of the scientific value yet to come, it is likely that this will be continuing success with **impact set to continue for years and decades**.

Of course, not all of this can be attributed to the UKSA investments. They are one part of a much larger suite of activity, and even as a critical part of data-related activities, this is a shared effort that involves many different organisations and ESA member states. This said, the UK-led data activities are central to the strong use and value of the outputs, which help underpin the impact discussed in this section.

The UKSA investments have also **clearly helped secure scientific leadership roles for UK individuals and organisations**, such as the Institute of Astronomy at the University of Cambridge, MSSL at UCL, the University of Edinburgh, RAL Space, the University of Leicester and the Open University. UKSA funding enables UK researchers to be close to the data, and to understand its strengths and limitations, enhancing their ability to exploit and gain valuable insight from the data. Having sufficient funding to enable UK leading one of the DPAC coordination unit meant that UK has had a voice in important decisions that shaped the mission and its release plan, and there are examples of other leadership positions and roles that would be lost without the UK national investments. Many of those we spoke to were keen to point to the value of these UK roles in terms of the bigger picture of space science activities and UK reputation, which we explore in more depth in the following section.

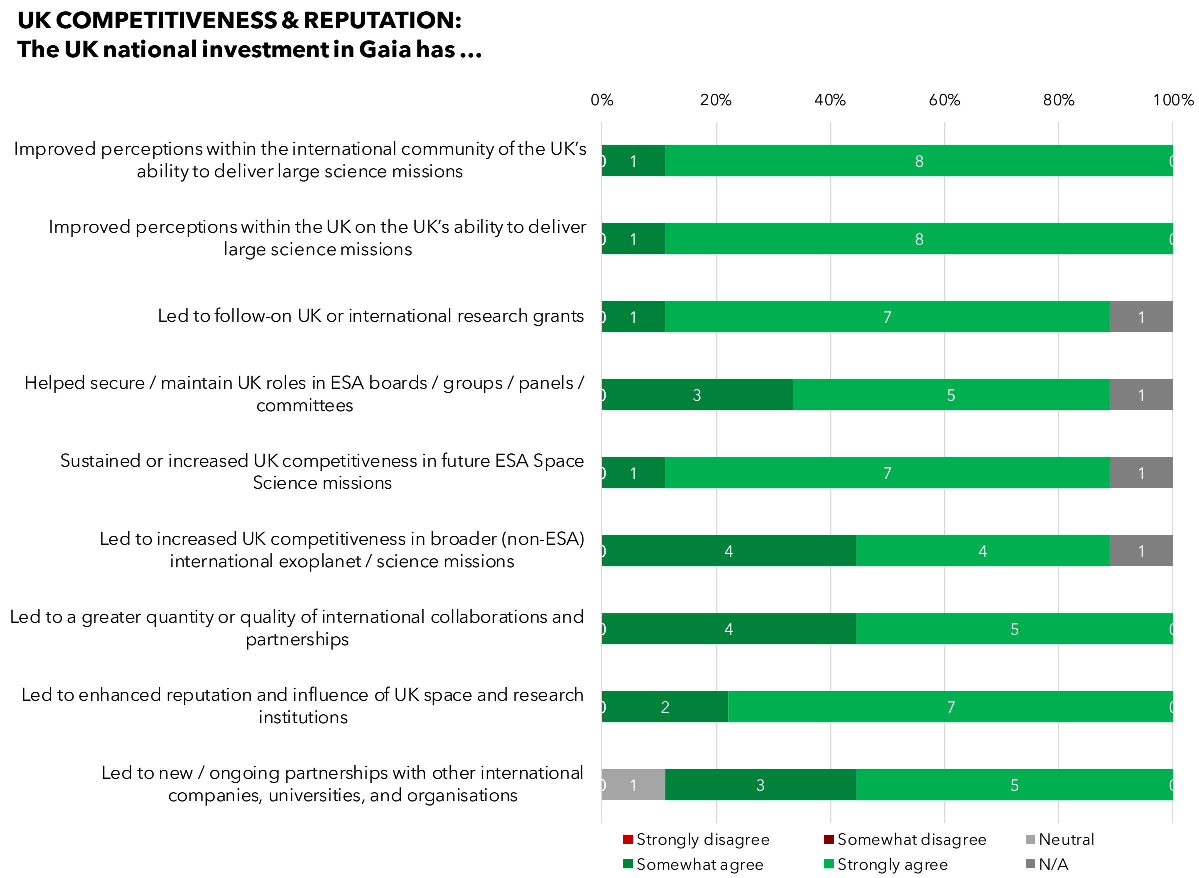
4 UK Competitiveness and Reputation impact

> *"The fact that we've done this work on Gaia puts us in a great position for whatever comes next"*
>
> *"This is about our place in the World – we're part of the G7 because we do these big things"*
>
> *"It's impossible to quantify NASA jealousy of Gaia!"*

4.1 UK reputation

While the sample size is small, our light-touch survey (which is designed to test general sentiment rather than provide statistically significant results) found near-unanimous agreement that the UK national investment in Gaia is perceived to have led to a range of benefits in terms of the UK's competitiveness and reputation:

Figure 10 *Stakeholder survey results: UK Competitiveness & Reputation impact*



Source: know.space analysis of stakeholder survey responses
Note: n=10 survey responses.

Free-text entries to the survey suggest that the slightly lower agreement in items mentioning new collaborations is due to some respondents viewing that they lack resource and on some occasions have to turn down requests for new collaborations due to lack of capacity, given that grants generally do not include provision for time spent

following up new partnerships. This may place some constraints on impact (i.e. the potential is there, though resource is not), though the overall picture is still highly positive in terms of the UK national funding's impact in this regard.

Those we spoke to were often keen to emphasise that the UK's national Gaia investments need to be seen within the context of the **bigger picture of the UK's role in space science, space, and even (in the view of some) the World** more generally.

Beyond improving others' views of the UK, there was also a common theme around successful missions such as Gaia helping to build **national confidence** in the UK's ability to deliver and take leadership roles in major, multi-national missions.

Several interviewees noted the impact in terms of enhancing **prestige** for the UK, both within the space science community but also as part of (in the words of one interviewee) the *"grander game"* of international relations. Benefits from this are often intangible and hard to measure directly, though they are seen as very real nonetheless.

The UKSA funding has had a direct impact in securing leading UK roles in one of the 9 DPAC data coordination units, which has meant that the UK was always involved in decisions on the roadmap for the data releases, and shaping the products and the impact of the mission. This provided the UK with a degree of **influence and control** within the wider Gaia consortium.

4.2 Roles on other missions

> *"The most likely [impacts] are participation in the data processing components of future missions"*

Most interviewees were keen to highlight the impact of the UK's involvement in Gaia in terms of leading to UK roles on other major missions. Many pointed out that data analysis techniques share many commonalities and noted the flow of tools, methods and indeed people between missions.

Gaia processing expertise was seen to have **established the UK groups as leaders in the analysis of complex space data**. The Gaia consortium groups are leveraging that expertise and knowledge in the delivery of a range of other major missions.

One that was frequently mentioned was the **PLATO** (PLAnetary Transits and Oscillation of stars) mission that has the objective of finding and studying a large number of extrasolar planetary systems, with emphasis on the properties of terrestrial planets in the habitable zone around solar-like stars. Don Pollacco (University of Warwick) is the science coordinator for PLATO, and the UK is involved in various data-related activities.

Euclid, planned to launch in July 2023, is an ESA mission to map the geometry of the Universe and better understand the mysterious dark matter and dark energy, which make up most of the energy budget of the cosmos. Interviewees noted that there is direct application of data techniques to Euclid, with *"lots of learning from Gaia's statistical methods"*. Various UK researchers are involved with the mission astrometry, in several cases with the same staff who worked on Gaia data. One interviewee also noted furthermore that the Euclid spacecraft is a *"daughter of Gaia"* in a technical sense.

We heard from multiple stakeholders how the UK national Gaia investments are likely to have played a role in the current discussions around potential UK involvement in the Canadian-led **CASTOR** (Cosmological Advanced Survey Telescope for Optical and ultraviolet Research) mission. In the words of one interviewee:

"We are part of the UK consortium currently negotiating to contribute to the data flow for the Canadian-led CASTOR mission. This potential involvement builds directly on our Gaia work and on Canadian interest in the expertise we have developed through it."

The UK is extremely well-placed to have strong leadership roles in several key aspects of the proposed Gaia follow-on mission, **GaiaNIR**. This mission would improve on Gaia to include the Near-Infra-Red (NIR), which would require the use of new types of detector. It has been selected as one of the key themes for an ESA Large mission[15], potentially launching in the mid-2040s. Work on the infrared detectors is being led by the UK (Cambridge, UCL, UK Astronomy Technology Centre) with initial work funded through the UKSA NSTP4 Technology for Space Science call.[16]

Other missions and projects mentioned where UK national investment in Gaia is perceived as having had a role in leading to follow-on contracts, grants or roles (i.e. stakeholders listed these in survey responses as missions where the UKSA Gaia investments have directly led to new contracts/roles) include:

- **CHEOPS** - ESA's CHaracterising ExOPlanet Satellite, the first mission dedicated to studying bright, nearby stars that are already known to host exoplanets, to make high-precision observations of the planet's size as it passes in front of its host star;
- **WEAVE** - WHT Enhanced Area Velocity Explorer, a facility upgrade for the 4.2m William Herschel Telescope (WHT) at the Observatorio del Roque de los Muchachos on the Island of La Palma;
- **4MOST** - a fibre-fed spectroscopic facility on the VISTA telescope with a large field-of-view to survey a significant fraction of the southern sky in a few years;
- **MOONS** - Multi-Object Optical and Near-infrared Spectrograph, A new instrument being built for the Very Large Telescope (VLT) at ESO's Paranal Observatory to reveal part of a hidden history of the cosmos;
- **SKA** – the Square Kilometre Array, the intergovernmental international radio telescope project being built in Australia (low-frequency) and South Africa, representing the two largest radio telescope arrays in the world; and
- **Vera Rubin** - an astronomical observatory currently under construction in Chile, with main task to carry out a synoptic astronomical survey: the Legacy Survey of Space and Time.

On this mission, we heard how there are already academia/industry discussions happening (e.g. Leonardo, Teledyne e2v) and momentum building. While such a mission would still be perhaps 20 years away from launch, it is important to maintain a long term perspective when considering potential follow-on impacts.

Interviewees also pointed towards some ground-based astronomy endeavours where UK nationally-funded Gaia roles have led to UK involvement, such as the **Rubin Observatory**

[15] https://www.esa.int/Science_Exploration/Space_Science/Voyage_2050_sets_sail_ESA_chooses_future_science_mission_themes – see *'from temperate exoplanets to the Milky Way'*

[16] https://www.gov.uk/government/publications/national-space-technology-programme-previously-funded-projects/previously-funded-projects#nstp4-technology-for-space-science-call-2021--2022

project[17] where we heard that UK participation was a result of the *"leadership and expertise honed and exhibited through Gaia"*.

4.3 International roles and networks

It is difficult to pinpoint any ESA leadership roles as having any direct impact from a single mission – again this is all part of a wider story – though multiple interviewees pointed out that two ESA Directors are from the UK, in scientific roles: Carole Mundell (Director of Science) and David Parker (Director of Human and Robotic Exploration). Interviewees did not claim that these appointments are due to UK investments into Gaia, though were sometimes keen to point out that (for example) *"all missions such as Gaia come into play here"*.

The importance of – and contribution of Gaia to - **staying visible** within ESA in order to get major roles on big missions was noted, such as on the JWST (James Webb Space Telescope) where the UK has had a significant role in particular on the MIRI (Mid InfraRed Instrument).

While not a function of UKSA funding alone, interviewees provided details of the following European projects which they view have directly benefited in terms of excellence, due to the UKSA support of the Gaia processing team in Cambridge:

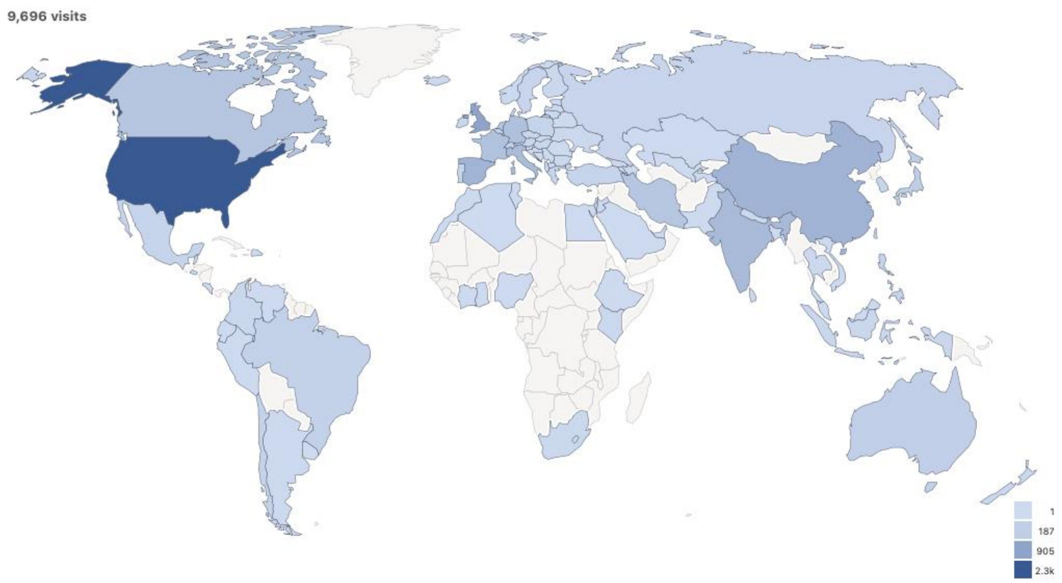
- **GREAT (Gaia Research for European Astronomy Training)** European Science Foundation Research Network Programme (2010-15) - these meetings and exchanges led to many new initiatives in astronomy. For example, one workshop under this programme was where the consortium formed that led the Gaia-ESO Spectroscopic survey. The programme, led by the UK, is an excellent example where a leading role in the Gaia DPAC has enabled additional funding to be leveraged from external European sources, for the benefit of the UK and European science communities as a whole.[18]
- **Gaia Research for European Astronomy Training** – Initial Training Network: led by the University of Cambridge, this trained a cohort of 17 PhDs across 13 institutes[19]
- **GENIUS** (Gaia European Network for Improved data User Services, 2013-17) – which developed advanced data services[20]
- **MW-Gaia COST Action** – A Cambridge-led initiative which enables networking between researchers in 29 European countries and more widely[21]
- **GaiaUnlimited** – which mines space data, aiming at determining the Gaia survey selection function and providing corresponding data and tools
- **MWGaia Doctoral Network** – this is a new EU Doctoral Network, originally led by Cambridge, but since handed over to Leiden due to Horizon Europe non-association (though UK universities can still participate). 12 PhD students will be funded.[22]

[17] https://www.lsst.org/
[18] https://www.great-esf.eu/about/about.html
[19] https://cordis.europa.eu/project/id/264895
[20] https://gaia.ub.edu/Twiki/bin/view/GENIUS/WebHome
[21] https://www.mw-gaia.org/
[22] https://www.mwgaiadn.eu/

The importance of Gaia is also highlighted in **Astronet**[23], the comprehensive long-term plan for the development of European astronomy, which aims to encourage a common science vision for all of European astronomy. Interviewees discussed how the UKSA-funded computing activities feed into Astronet road-mapping. This helps bring UK influence, and is expected to lead to better outcomes for the network. Through enhancing and growing these networks, with a strong UK presence, this helps drive forward UK leadership and influence, and strengthen the quality of scientific outputs.

More broadly, returning to the analysis of ESA Gaia Archive data usage, we can see that users are based all around the world:

Figure 11 *Map of ESA Gaia Archive visitors*



Source: ESA

Note: ESA also has partner data centres, at least one of which has similar usage statistics, so that for total use factor of two multiplication may be justified.

Reflecting the volume of research and ubiquity of Gaia use within astronomy, the map shows that USA is the biggest user of Gaia data.[24] The UK stands out as the biggest user in Europe, underpinning UK scientific impact, though (while again we note the internationally collaborative nature of Gaia data activities) broader use of the data can also **help UK researchers build connections and build astronomy networks** such as the GREAT programme discussed above, which has led to new UK funding, roles and even mission concepts.

We also heard how the UK national funding has helped develop **industry-academia networks**. UK industry had significant roles in Gaia, with for example Teledyne e2v building the array of 106 CCDs ('the heart of Gaia'), and Astrium (now Airbus D&S) leading on the control avionics. These roles are largely out of scope of this evaluation, as they were not funded through the UKSA national funding that is the focus our analysis, though many interviewees were keen to note that data funding has led to longer term benefits in this regard. For example, we heard how the Open University still work with Teledyne e2v, following on from data-related collaborations enabled by UKSA funding. We expand on this in sections 5 and 6.

[23] https://www.astronet-eu.org/
[24] It should be noted that UK and ESA researchers gain in turn from USA's public archives.

A proxy indicator for UK influence is through **awards** for UK researchers. Those we spoke to gave examples of prizes and awards that they see as directly linked to the UK national funding. Examples include:

- The 2023 Lancelot M. Berkeley – New York Community Trust Prize for Meritorious Work in Astronomy, awarded to the team behind Gaia
- An Arthur C Clarke Award in 2017, awarded to the UK Gaia Science Team in the 'Space Achievement - Academic Study/Research' category "for [their] role in processing and analysing data from the Gaia star mapping mission as its contribution to the European Data Processing and Analysis Consortium".

4.4 Counterfactual

Again, there were common themes of UK national funding helping secure the UK a 'seat at the high table'. With this funding, the UK would lose roles such as those at the DPAC Executive committee. This would lose the UK influence on the mission, in doing so reducing UK return, but also have a less tangible – though no less important – effect in terms of reducing UK influence more widely.

Several survey respondents and interviewees noted the **reputational impact** that failing to fund the national roles would have had for the UK, both as a leader and reliable partner. Interviewees noted, for example that *"the UK's standing in the field would have been very limited"*.

With the mission having demonstrably led to UK roles in other missions and strengthened networks, all of which hinges on (together with other inputs) UKSA national funding, it seems highly likely that the counterfactual would involve **lower levels of UK involvement, leadership and benefit** from follow-on activities. These include the UK roles on other missions (e.g. Euclid, Plato) and in impactful international networks (e.g. GREAT), which have led to new opportunities, influence and funding for UK researchers.

4.5 Evaluation questions

The core evaluation question here is on what difference has the UK's national investment in Gaia made in enhancing the reach and reputation of the UK space sector.

Our judgement here is that the impact here is both positive and significant, with the narrative and analysis presented in this section showing a clear story of benefit both for the UK's reputation, and for its competitiveness. We heard a clear story around the national investments benefitting UK prestige, national confidence, and influence within ESA and beyond.

We also have seen strong examples of where nationally-funded Gaia roles have led to significant UK involvement in other major missions, such as PLATO and Euclid, noting the commonalities in data analysis challenges. Should GaiaNIR be taken forward by ESA, UK researchers and organisations would also be very well placed to secure major roles.

While these factors are important considerations for how the findings set out here should be interpreted, stakeholders were typically without doubt that the national funding has had a very positive impact for the UK in these regards.

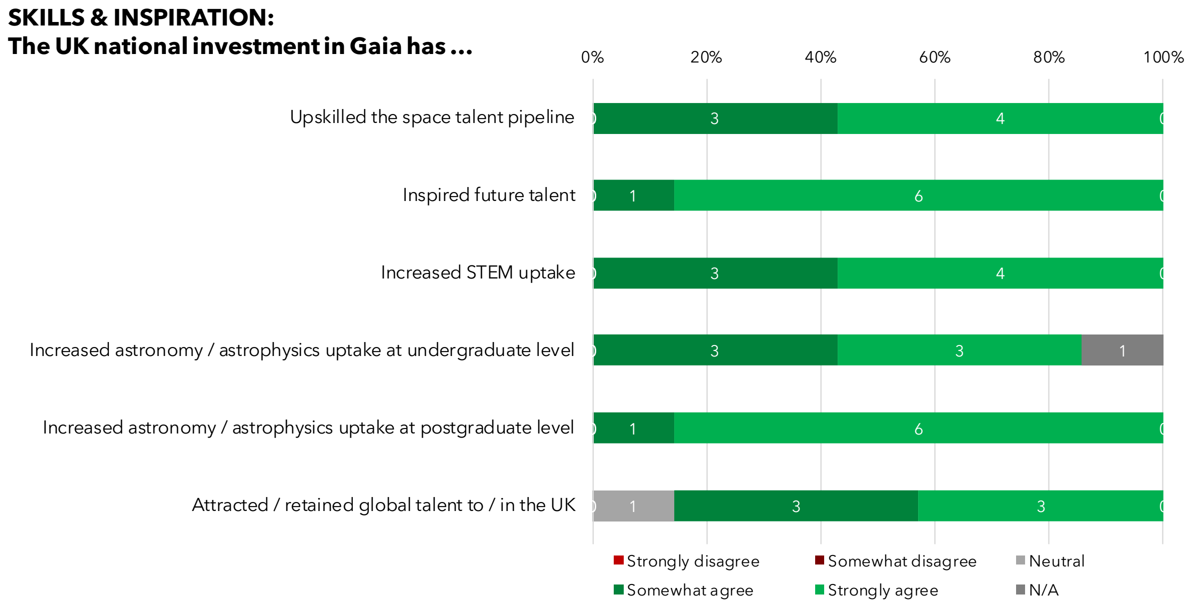
5 Skills and Inspiration impact

> *"People get so excited about Gaia"*
>
> *"Since Gaia Data is Big Data, research using Gaia data provides a natural context to develop the high-priority skills in modern large data management and machine learning tools which are a UKSA/UKRI priority"*
>
> *"The doctoral training schools have been fantastically successful"*

5.1 Role of Gaia in developing skills

Our small-scale survey showed near-unanimous sentiment that the UK national investment in Gaia has had a strong impact in developing the UK skills base, increasing STEM update, increasing undergraduate and postgraduate applications, and attracting and retaining global talent to the UK.

Figure 12 *Stakeholder survey results: Skills & Inspiration impact*



Source: know.space analysis of stakeholder survey responses
Note: n=10 survey responses.

5.1.1 Project teams

The UKSA-funded activities in Gaia have directly led to the development of new advanced statistical methods, algorithms, and capabilities. We heard a strong story around knowledge transfer, as staff involved in Gaia – from PhD to senior levels – gain **sought-after and widely-applicable new skills in algorithm and database development, data science, and data analysis**.

As explored in section 6, space missions such as Gaia operate at the cutting edge of technical capabilities, generating new know-how that can be applied elsewhere. **As people move on, they take new knowledge with them**, and he skills gained by those working on Gaia benefit them (and the wider economy) in whatever they go on to do next

– whether this is further work on the mission, other space science missions, other areas of the space sector (e.g. we heard how Earth Observation faces similar challenges of finding 'weak signals amongst large noise'), or the wider economy.

Interviewees noted how a significant direct economic impact of a scientific data processing project such as this is in training of **state-of-the-art software engineers**. Software specialists frequently move on, taking expert experience, and expanding the country's skill-base. For example, in order to reach a sustainable solution for the large data flows and high computational demands of the photometric processing within the limited budget available, solutions needed to be found that optimise the use of affordable hardware. These are challenges common to many businesses and organisations.

Many interviewees expressed the view that this can be a **double-edged sword**. From a broader UK economic (or HM Treasury) perspective, skilled data scientists and software engineers going into well-paid jobs in finance and tech sectors creates value and delivers additional tax revenues. However, from a space science perspective, the loss of talent is clearly an acute issue. Many of those we spoke to highlighted difficulties with finding replacements and training up new early career researchers.

As explored in section 4, training people in these activities also enables bids for future missions, helping to improve UK competitiveness. **Skills and competitiveness are intrinsically interlinked.**

While the UK national funding does not directly fund instrumentation and hardware activities, we heard from many interviewees how there is nevertheless an **industry-academia two-way knowledge exchange** process at play, that is seen to benefit both sides. Academics have been funded to work out how to calibrate data from instrumentation, meaning that staff have worked closely alongside Teledyne e2v staff in a mutually beneficial process that builds expertise and skills. Ultimately, the engineering questions stem from the science questions.

An obvious economic benefit from UK national Gaia funding is direct jobs supported. While our survey was small-scale (n=10) and does not capture the totality of jobs where UKSA funding would have played a role, we found at least **24 jobs** (FTE) with a direct link. This will be a subset of jobs given gaps in survey coverage, and does not capture the wider, indirect benefits that the funding can lead to.

5.1.2 Examples of 'next destination' flows

Tracking the movements of all people involved in UKSA-funded Gaia activities over the last decade is not possible, as the data to enable such an analysis has not been captured holistically. We were able to gain some insight from Gaia Oversight Committee reports (2009-2020) to track turnover and roles within the project team over time.

We found multiple examples of **internal promotions, but also movement of staff who were involved in UK Gaia project team work** to organisations such as:

- Google and other tech firms (both UK and international)
- Wellcome Trust
- International NGOs
- Space sector manufacturers

- UK Defence firms
- UK Venture Capital firms
- Other universities, for professorial roles
- Cybersecurity firms
- Biotech firms and start-ups
- R&D Ministries

While these are examples only, they serve to illustrate a wider **trend of movement into high-skill occupations** that create significant value for the wider economy (though naturally not all of these flows are within the UK). One interviewee noted for example that *"almost all of our PhDs end up in industry not academia"*.

This 'labour spillover' creates wider value for the UK economy, though those we spoke to were again keen to highlight that staff retention is a challenge, and from the narrower viewpoint of what is good for space science, the challenges are clear.

5.1.3 Wider training & doctoral training

A core activity enabled by the UK national funding is the **training for the scientific community in how to use and analyse Gaia data**. In a similar vein to the impacts discussed above, this helps build skills amongst the wider UK scientific community, and these skills can be applied elsewhere in future.

Interviewees were often keen to stress the importance of these activities, noting that the wide distribution of Gaia research across the UK has been enabled and supported by a series of UK-wide training workshops, illustrating hands-on use of Gaia data, which have been delivered to match each Data Release. These **big data skills** are then applicable to other research areas.

We heard highly positive sentiment on the impact of Centres for Doctoral Training (CDTs) and Doctoral Networks (e.g. MW-GaiaDN) in terms of skills development and spurring on wider UK socio-economic benefit. While the link to UKSA funding is more indirect, they are an important element of the Gaia impact story and one in which having quality data to work with is clearly essential.

One stakeholder spoke about how a CDT was deliberately set up by STFC to use Gaia data and evidence, and that it has been *"spectacularly successful"*, with for example a spin-off Masters course that is already heavily oversubscribed. STFC CDT projects in Data Intensive Science and machine learning analyses are hosted at the UK Gaia centres (Cambridge, Edinburgh, UCL and elsewhere) and provide a major training application often building on Gaia data for PhD projects.

The MSCA (Marie Skłodowska-Curie Actions) MW-Gaia Doctoral Network, mentioned in section 3, is seen as **inspiring a new generation of researchers**, with specific training for the next generation Gaia missions now underway, involving academia and high-tech industry (e.g., Airbus, Leonardo etc.). This was originally led from the University of Cambridge, though leadership was unfortunately lost due to the current non accession of the UK to the Horizon Europe programme (though UK researchers and organisations are still able to participate).

The **GREAT** (Gaia Research for European Astronomy Training) doctoral network programme has a strong UK leadership role, which builds off the UK's central role in Gaia.

It is a pan-European science-driven research infrastructure that brings together relevant scientific expertise to facilitate maximum exploitation of the Gaia mission. This was the only astronomy proposal out of 140 that was supported by the EU in the last call, and high-level industrial buy-in from organisations such as Thales Alenia Space, Airbus, OHB, and Leonardo.

While only a partial snapshot, ESA data lists 5 PhDs in UK institutes directly linked to Gaia.[25] These are:

Year	Name	Title	Institute
2020	Vioque, Miguel	A census of Herbig Ae/Be stars: new candidates and analysis from a Gaia perspective	University of Leeds
2020	Ciuca, Ioana	Inference in the Milky Way in the Gaia era	Mullard Space Science Laboratory, University College London
2018	Joyce, Simon	Observational tests of the theoretical white dwarf mass-radius relation	University of Leicester
2015	Blagorodnova, Nadejda	Characterising the Gaia Transient Sky	Institute of Astronomy, University of Cambridge
2015	Hunt, Jason	N-body dynamical modelling of the Milky Way Disc for the Gaia era	University College London

5.2 Inspiration

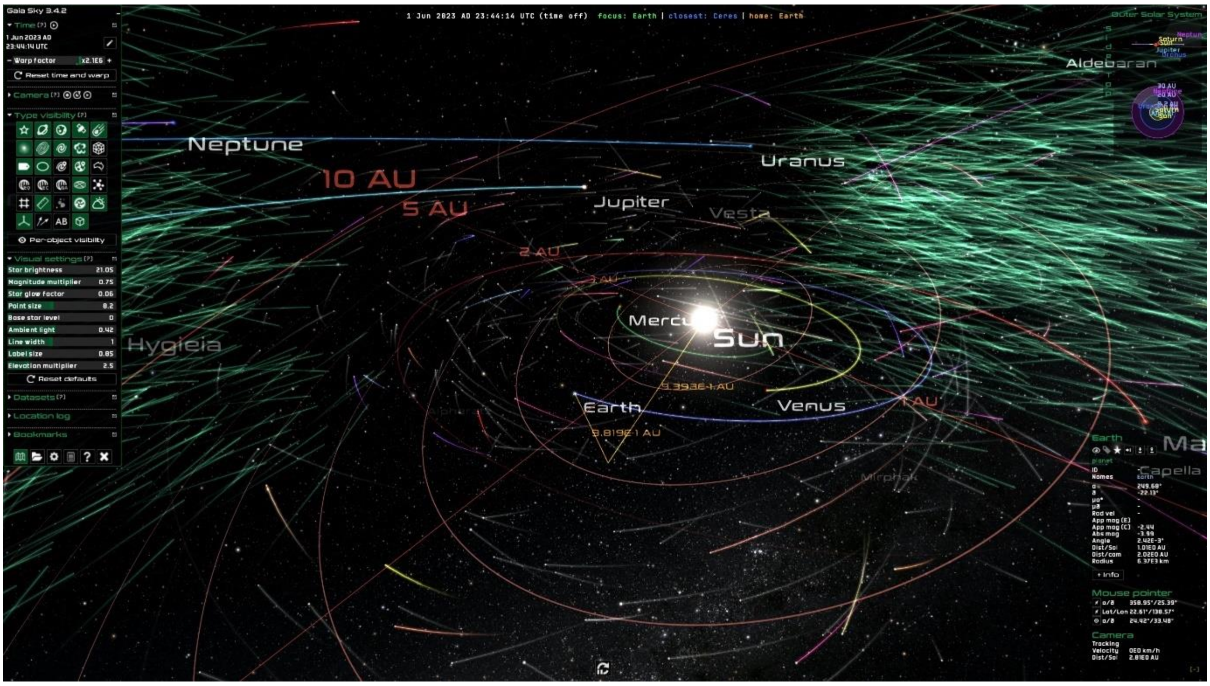
Big space science missions such as Gaia carry a significant inspirational value. They provide **opportunities for people of all ages** to learn about astronomy, physics, engineering, and data. With data available to the public, there are many opportunities for 'citizen science', allowing anyone to explore and analyse the data (often enabled by data products developed through UK funding), learning about the scientific process and contributing to real-world research efforts.

They also **inspire the next generation** of scientists, engineers, and explorers. They offer examples of what can be achieved, and can inspire young people. The focus of Gaia on studying the Milky Way and its stars can be fascinating to young people interested in astronomy and space science. The mission's focus on understanding the universe can inspire a new generation of scientists and researchers to pursue careers in this field, or to go into STEM careers.

'**A picture is worth a thousand words**' as the old adage goes. While many interviewees were keen to highlight the significant interest that Gaia tends to capture at public outreach events, others noted the challenge of visualising and communicating what is *"a reference manual"*. Compared to JWST or Hubble, for example, there tends to be fewer captivating images to grab attention. However, we heard about interesting initiatives on this front, such as *Gaia Sky*, which is an open-source 3D universe simulator with support for more than a billion objects.[26] Such tools open the Gaia data for exploration and use by a much wider audience, including the general public. An example screenshot is shown below.

[25] https://www.cosmos.esa.int/web/gaia/phd-theses
[26] University of Heidelberg, Gaia Sky (https://zah.uni-heidelberg.de/gaia/outreach/gaiasky)

Figure 13 Sample visualisation of the Solar System and Milky Way using Gaia data



Source: Gaia Sky

From our survey and analysis of Researchfish returns we found many examples of **outreach activities**. These include research talks, exhibitions, open days, festivals, school visits, work experience. Academics are not funded to carry out public outreach activities via the UKSA grants directly. though the UKSA investments do at least indirectly support these through enabling the underlying activities that outreach focuses on.

It is difficult to estimate the total number of relevant outreach activities (one survey respondent simply responded *"countless"* when asked, for example), though our analysis of Researchfish data identified 130 Outreach activities.

Of these 130 activities, 15 events listed as for 'professional practitioners' or within Higher Education setting, while 28 were for school-age audience, with a further 87 intended for the general public. Outreach activities with a noted link to UKSA grants included:

- TV interviews (notably on Stargazing Live 2014, with an estimated 2.3m audience)
- BBC News
- Radio and Podcast appearances
- Magazine articles
- Keynote speeches at conferences
- Press releases and media events
- Gaia National Outreach programme
- Exhibitions at science fairs and festivals
- University and Observatory open days
- Public lectures (within HEIs on project team but also in USA, Brazil, New Zealand, Iran, and other UK cities
- Invited society events
- Workshops for research students and teachers
- Art exhibitions – Gaia had a resident artist at MSSL who had a year-long exhibition which used Gaia data

Interviewees were keen to note that the societal benefits – such as inspiring students to study STEM – will continue for many years, reflecting the expectation (as discussed in section 3) that the majority of the scientific value is yet to come.

The Gaia-UK web pages (http://www.gaia.ac.uk) provide an up-to-date record of information for the public and scientists, listing outreach activities in the UK and related to the Gaia mission, in addition to being the primary place publishing the Science Alerts.

5.3 Counterfactual

As in the previous sections, the core message is that UK involvement in Gaia would have been far lower in the absence of UK national funding, meaning that many of the skills benefits discussed above would not have been realised.

5.4 Evaluation questions

The answer to the evaluation question of what difference UK national Gaia investments have made to inspiring, attracting, and retaining talent to upskill the UK workforce is a clear one: the UK investments have undoubtedly led to the development of sought-after skills across those directly involved in Gaia data work, and more broadly through training and upskilling activities. Whether these people go on to other roles in space science, the space sector, or wider UK economy, it is clear that they bring a wider economic benefit from the skills they have learned.

While UKSA funding does not fund outreach activities, it plays an indirect role in inspiration through the success of the mission. These impacts are hard to quantify, but are significant.

6 Innovation impact

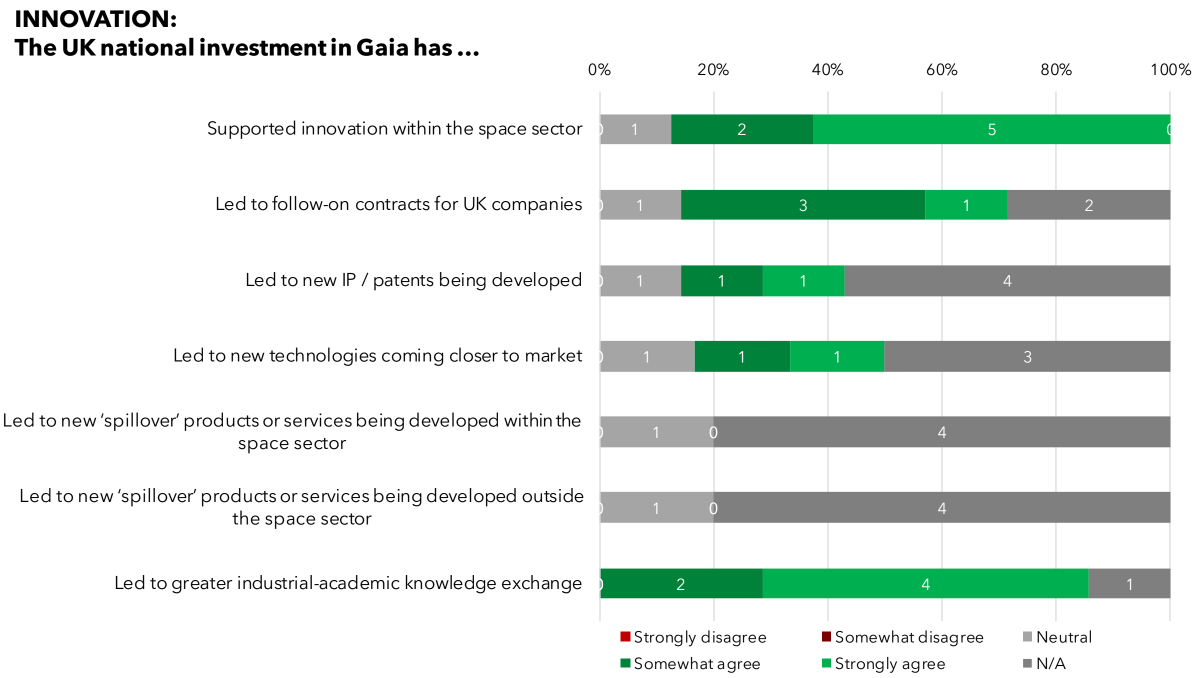
"For any big data mission, all techniques are related"

`"Gaia helps bring the community together, generating new White Paper style ideas for new activities"

As previously outlined, the scale and complexity of the Gaia data required substantial invention and innovation – predominantly around data management, documentation, quality control, statistical methods and algorithms.

The stakeholder responses again provide useful insights (note: the survey was designed to test general sentiment rather than provide statistically significant results, and the response sample is small, comprising funded researchers). It shows a more muted story of impact, compared with say scientific impact, but still highlights impact through **innovation stimulated within the space sector**, and **increased industrial-academic knowledge exchange**:

Figure 14 *Stakeholder survey results: Innovation impact*



Source: know.space analysis of stakeholder survey responses
Note: n=10 survey responses.

6.1 Innovative 'big data' techniques

As a survey mission aiming to provide astrometry, photometry, and spectroscopy of nearly 2 billion stars in the Milky Way, in addition to significant samples of extragalactic and solar system objects, the scale of the data is immense – for example, Gaia produces significantly more than data than will be produced by the James Webb Space Telescope.

The **primary challenge** – now that the spacecraft is launched and operating (technology was developed in the early stages by E2V to develop CCDs and Airbus-Astrium for the spacecraft) – is **data management**. And, though the UK has previous experience on the Hipparcos mission, the capabilities and systems required to manage such vast amounts of scientific data had not been done before.

UK public sector funding was required to invent many of the techniques to get the accuracy needed from Gaia. This has led to the development of new advanced statistical methods, algorithms, and capabilities (e.g. pioneering hardware and software management). As a direct result, the UK team (e.g. the Gaia Data Processing Centre at Cambridge) developed expertise in large-scale scientific data management.

The Gaia UK team's reputation for large-scale scientific data management expertise is internationally recognised – across Europe and on to the USA. Advances in the way Cambridge approached the data processing, which have been passed on to other users beyond. Methods used (e.g. multi-core parallel processing technique) were subsequently adopted by CNES in Toulouse (Gaia) and in ESA's data management system. The team often receive requests for help from other data centres and space science projects from all over the world (e.g. the Flat Iron Institute in NY, where they are running a workshop which is oversubscribed: >70 applications for 40 places) and from other ESA missions and communities.

We heard from interviewees that Gaia is currently the prototype for ESA's 'big data' missions, where full end-end data reduction and calibration is critical to delivery of mission products to the community. For the Gaia team this means development of software and algorithm expertise, which is then available for other UKRI/UKSA projects, or to strengthen UK industry.

These data techniques are also being used for Euclid (which we heard can be considered a 'daughter of Gaia' in some senses) and Plato, as discussed in section 4.2.

6.2 Spillovers to medical applications

Gaia generates huge amounts of data (~500GB/night). Researchers have developed sophisticated software to pick faint signals objects of interest out of dense star-field images (e.g. faint infra-red from a young star clouded in dust, a faint supernova going off in another galaxy, the wobble in a star's light as a planet transits in front). The team realised that similar techniques could be used to pick out signals from tumour samples, such as the proportion of cells that had been stained to denote high levels of particular chemicals that affect cancer prognosis or response to treatment.

This is a cross-transfer of astrometric techniques to **medical imaging for visualising cancer tumours** – from annotated star maps to annotated cell maps – visualising tumours, using techniques developed for Gaia's analysis systems.

Cancer Grand Challenges[27] is a Cancer Research UK and National Cancer Institute programme with £20m grants. Nic Walton leads data analysis team at the IoA, Cambridge as a co-Investigator of the **IMAXT** (Imaging and Molecular Annotation of Xenografts and Tumours) grand challenge team.[28] The IMAXT team is working to find a way to map

[27] https://cancergrandchallenges.org;
[28] See: https://cancergrandchallenges.org/news/imaxts-nic-walton-uniting-across-disciplines-share-learnings-data-science

tumours in 3D at the molecular and cellular level to develop the **world's first virtual reality map of cancer** – an entirely new way to study a tumour.

This capability allows scientists to screen 10,000s of tumour samples, investigating effectiveness of therapy when certain biomarkers are used to inform therapy – and could **revolutionise the diagnosis of cancer and enable more personalised medicine** in future, when patients are treated according to their individual characteristics.

DPCI hardware systems, where Cambridge University provides running costs in return for test access to enhance Hadoop security systems, are being evaluated for possible application to very large-scale medical record storage – a topic with timely significance. One consultee remarked that they had also heard of overlaps between Space Situational Awareness and survey astronomy techniques.

6.3 Spillover to visualisation software

Our research also discovered a contribution to TOPCAT (Tool for OPerations on Catalogues And Tables) – an analytical software used for tabular data in Astronomy, which provides 3-D data visualisation on large datasets using Java.

This tool was developed in the UK (University of Bristol initially, with further development for the UK DPAC teams to analyse Gaia data) and has become an important astronomical data visualisation tool, but it has capabilities beyond astronomy too. For example, the University of Nice has used the software in biological sciences – investigating mitosis, cell death and cellular events.

6.4 Counterfactual

It is clear that without UKSA (and STFC) funding, the UK teams would not have developed the considerable expertise in large-scale scientific data management, so these innovation benefits would not have been realised. As a result, these innovation impacts can be considered as **strongly additional**.

6.5 Evaluation questions

The primary evaluation question we considered here is:

- What difference has Gaia made so far in stimulating innovation and commercial opportunities through data science and space technology

Our assessment is that UK investment in Gaia has directly stimulated significant innovation in the field of 'big data' management and processing – a field that is, and will become increasingly, important in both the scientific and commercial domains – though realisation of the potential is mostly limited to science data to date.

In the scientific domain, Gaia's innovations are being applied within current space science missions, and is planned for future missions. The innovations are also advancing medical science, with application to cancer tumour visualisation and detection.

The commercial opportunities are assessed as potential for future development – for example in big data domains such as tech, data centres, and social media, in addition to medical imaging devices leveraging the promising trials (above).

7 Conclusions

The UKSA national funding for Gaia has enabled a wide suite of activity focused on processing and analysing data from the mission. This has been a critical part of enabling the science impacts from the mission, which have been significant. Ultimately, **UKSA funding has helped enable the data that comes out to be high quality and well understood**.

There can be **little doubt that Gaia is a scientific success story**. Bibliometric indicators show a huge impact, both in an absolute and relative sense, while the value of Gaia data to wider astronomy and astrophysics research as a 'reference point' is clear. It is already a **hugely productive** mission in terms of scientific outputs, and with the bulk of the scientific value yet to come, it is likely that this will be continuing success with **impact set to continue for years and decades**.

The UKSA investments have **helped secure scientific leadership roles for UK individuals and organisations**. UKSA funding enables UK researchers to be close to the data, and to understand its strengths and limitations, enhancing their ability to exploit and gain valuable insight from the data

The mission has clearly had a positive impact in terms of enhancing the **reach and reputation of the UK space sector**. The picture presented in this report is one of clear benefit both for the UK's reputation, and its competitiveness. There are numerous examples of where nationally-funded Gaia roles have led or is expected lead to UK involvement in other missions, such as PLATO, Euclid and – if it is taken forward – GaiaNIR.

The UK national investments have undoubtedly led to the development of **sought-after skills in algorithm and database development, data science, and data analysis**, both across those directly involved in Gaia data work, and more broadly through training for the scientific community in how to use and analyse Gaia data, and the development of software tools to enable wider use of Gaia data.

While not directly funded by UKSA, outreach activities have covered everything from TV interviews to news appearances, keynote speeches, and art exhibitions. While impact is not something we are able to measure at this time, these activities may have impacts through **inspiring the next generation** and **boosting STEM** uptake.

The UK national funding was required to invent many of the techniques to get the accuracy needed from Gaia. This has led to the **development of new advanced statistical methods, algorithms, and capabilities**. Our assessment is that UK investment in Gaia has directly stimulated significant innovation in the field of 'big data' management and processing – a field that is, and will become increasingly, important in both the scientific and commercial domains. In the scientific domain, Gaia's innovations are being applied within current space science missions, and are planned for future missions. The innovations are also advancing medical science, with application to cancer tumour visualisation and detection that has the potential to save many lives.

In any impact evaluation, we need to consider the **counterfactual**, i.e. what would have happened in the absence of UKSA investment. In this scenario, our view is that the UK scientific return would have been significantly lower. Many of the benefits come from *"being close to the data"* and UK institutions and individuals would have been far less involved in the mission. Similarly, the UK would have lost the reputational benefits from

involvement in the data elements of a highly successful mission, would likely not have secured all the follow-on roles in other missions and activities, and skills benefits would have been lost as 'hands-on' complex work to develop new tools and solutions would have happened elsewhere and fewer training activities for the wider UK scientific community would have taken place. The UKSA national investments have been critical for the development of innovative big data techniques, and has this activity happened elsewhere, the spillover benefits to other UK activities would likely have been significantly lower.

Several interviewees and stakeholders spoke of the impact that Gaia has had on the astronomy and astrophysics community's self-belief, and the confidence it has instilled that the UK can perform the sort of leading roles on these big missions effectively. In this way, it is seen to have **positively affected UK space science strategy and direction**, though these impacts are inevitably difficult to measure.

In terms of lessons learned, Gaia – and the UK's national investments into the mission – has clearly been a success story. While there are good examples of knowledge flows and spillover benefits, we did hear suggestions that there could have been a more active focus on **cross-discipline synergies** (e.g. more actively seeking the transfer of techniques to Earth Observation or other areas). This was not an objective of the original funding, but could be brought in for other, similar missions in future to target and focus efforts more directly.

The scope of this study did not include a process evaluation, so we did not seek to assess factors such as what could have been done differently or what barrier / enablers to impact there were. Similarly, we do not conduct an economic evaluation that seeks to answer questions such as 'was it worth it'. However, given the substantial impacts in terms of science, skills, innovation and strong follow-on activities, all underpinned by the UK national investments that helped enable data to be high quality and well understood, we view that **the return on the UK funding has been considerable**.

… now you **know.**