ASTRONOMY PROGRAMME EVALUATION REPORT

JUNE 2019

EXECUTIVE SUMMARY

The UK astronomical community has been remarkably successful over the last decade. In most assessments of quality and productivity, the UK is ranked second only to the USA. This should be seen against a backdrop where ~60% of applicants to STFC exploitation grants receive no support and that, on average, an academic may expect to receive a 3-year post-doctoral assistant as support every decade. In contrast, the UK community has been remarkably successful in attracting European and especially ERC funding. In fact, the community has been far more successful than the rest of the Frontier Science disciplines *combined*. Consequently, >40% of university resources (post-docs/students) are funded through ERC grants. This quite remarkable success also represents the biggest threat to the continued success of the community, given the UK's impending departure from the EU and that these grants will likely no-longer be available to UK scientists. In this report we highlight this threat (and recommend continued support through indigenous schemes similar to those of the ERC). We do not assess wider implications beyond stating that the loss of these grants would have a *dramatic and negative effect* on the community and would at the very least affect the depth of excellence in the UK. In the longer term it seems inescapable that the community, or rather the employers, would contract the number of active astronomers.

One of the reasons for the astronomical community's success is the concentration on "excellence" as the main criteria for grant support (this is also similar to the ERC schemes). There is little strategic ring-fencing of resources but instead we expect the "best" science to be achievable from the newest facilities. One of the implications of this ethos is the broad range of science undertaken within the community. Several consultations with the community show that there is overwhelming support for continuing this model.

We have also looked at the relationship between STFC and UKSA. While there are some issues still to be resolved in this relationship we find the main factor limiting the ambition of our community is the limited funding available to the UKSA (and STFC). Since UKSA's inception, its programme has been closely aligned to that of ESA with few/no opportunities for bilateral missions. Despite this, the UK has achieved leadership roles in all the ESA Cosmic Vision and Exploration missions. However, there is a strong desire in the community to see an increased launch frequency and this may become achievable through a National Space Programme which is currently being discussed. While we expect this would be good for UK science leadership it would also enable UK scientists and engineers to gain valuable experience in advance of competing for roles in ESA missions.

The Panel recognised that membership of international organisations such as ESO and ESA has enabled UK industry to compete for lucrative contracts. Examples in recent years include the award of multi-million pound contracts to Teledyne e2v for the supply of detectors for the ELT, EUCLID, GAIA, PLATO, the Large Synoptic Survey Telescope (LSST) and NASA's Kepler space craft.

Enquiries to determine the first destination of their PhD students have found that some 25% of completing students move directly into the private sector, 30% of which are into software orientated positions. In terms of sectors, the

spread is broad with significant fractions going into manufacturing and finance; with around 10% in data analytics. This demonstrates that students are successfully being trained to positively enhance the UK skills base.

In addition to examining the health of the discipline the Panel has assessed the scientific and impact potential of a range of projects/facilities (~20) funded by STFC. While some are clearly of the highest priority (e.g. SKA, ELT, LSST) we find all produce top quality science and are worthy of continued support. This range of facilities is needed to support the scientific breadth of UK research. While we have ranked these projects we are aware that each is supported through agreements. If funding pressures require reducing the portfolio of projects this would at least partly depend on issues beyond the scope of our evaluation and would therefore need to be considered on a case by case basis when the funding situation was known.

We examine the impact on the STFC programme of a range (+10%, flat and -10%) of future funding scenarios. **In each case, and in common with previous reports, the community is overwhelmingly supportive of preserving the exploitation level.** In the case of a -10% cut then none of the options (exploitation/operations/withdraw from an international project) or their combinations are palatable and would lead to significant contraction and reputational damage. In the case of a flat cash budget, protecting the exploitation line would lead to increased stress on current operations and may well lead to a reconsideration of STFC's project portfolio. If any additional funds become available then the community would like to see this reflected in an enhanced grants line (exploitation). In all these scenarios the community view has been consistent over the last decade. In the event of a loss of ERC funding we expect a significant impact on the exploitation resources and our recommendations will need to be re-examined.

In summary, the UK hosts one of the leading astronomical communities, however, with our withdrawal from the EU its sustainability is entering a critical period. The breadth of the research, as stated above, is a key area of strength of the discipline which has enabled the community to establish a strong international status. The Panel makes 16 recommendations in this report.

This report demonstrates that the community has the flexibility, skills and reputation to continue to deliver excellent science, provided they continue to have sufficient availability of funding and opportunity.

1. Introduction

STFC is the prime supporter of research in astronomy in the UK, supporting a sizeable and diverse community. The latest Royal Astronomical Society figures (2016) report that this community encompasses some 1,476 staff in over 60 different university groups and research centres, as well as an additional 128 staff in STFC establishments. The UK has groups which are considered to be world leaders, contributing to all the key questions in Astronomy, from the origins of the universe, to the development of stars and galaxies, the solar system and the search for other worlds. The community uses the full range of available tools to address these questions, from theory and (computational) modelling to observation, ground and space-based facilities and at wavelengths from gamma rays and the UV to radio observations. It is this breadth and diversity of scientific and technical expertise that gives the UK Astronomy community its world-leading reputation and that allows it to be flexible and take full advantage of a range of world-wide opportunities.

The STFC programme is designed to enable this diverse approach to research, through access to the world's leading facilities (and planning for the next generation), provision of resources to exploit those capabilities, and lead development through novel technologies. It works closely with the UK Space Agency and with international agencies to foster the UK's influence and leadership, within a constrained budget. To date, STFC has not set priorities between sub-disciplines or science questions. Cosmology is as relevant as exoplanets, X-Ray as optical or radio. Decisions are made on the basis of scientific excellence, international competitiveness, and the quality of the UK team.

With regard to facilities, whilst having a leading role in developments such as the Square Kilometre Array (SKA) and the European Southern Observatory's Extremely Large Telescope (ELT), the scale of our investment has been tailored to enable significant roles in smaller, but high potential facilities such as DESI, MOONS and DKIST.

The Astronomy programme is supported by two Advisory Panels, namely the Astronomy Advisory Panel (AAP) and the Solar System Advisory Panel (SSAP), in recognition of its two active, but distinct, research components. The programme serves a large UK research community that plays pioneering, leading and innovative roles on the international stage, and has a long-standing heritage. Research in astronomy is conducted via a wide range of space-based and ground-based instrument development, and operation and exploitation projects. The UK's main observational and experimental interests in this area (excluding radio wavelengths) are covered by membership of the European Southern Observatory (ESO) and the European Space Agency (ESA). On the ground, ESO offers critical optical/infrared and sub-millimetre telescope access for UK astronomers, whilst in space the current ESA missions, together with bilaterals (e.g. Gaia, XMM-Newton, Bepi Colombo, Cluster, SWIFT, Hinode) support a number of key lines of UK space science research. STFC also supports a programme of astro-particle activities.

Funding for astronomy facilities is primarily partitioned between STFC and the UK Space Agency (UKSA), but there is also a small contribution from the University and private sectors. STFC funds the development and operation of ground-based astronomy projects, whilst UKSA funds the development and operation of space-based astronomy projects. However, all astronomy exploitation (other than some aspects of planetary research which are covered by UKSA for the ESA Mars exploration programme) and novel technology funding is in the remit of STFC along with private and European funding sources.

The current (FY19/20) STFC astronomy programme costs £52M, which breaks down as just under 60% for exploitation grants (£29.7M/year), and the rest for development (£12.7M/year) and operations (£9.4M/year). In the development area, funding for SKA (radio astronomy) and the ELT (optical/infrared) are the two major components, accounting for 32% and 39%, respectively. The operations element, the smallest part of the overall budget, reflects a

similar split with radio astronomy accounting for ~45% of the spend, while a spread of optical/IR facilities accounts for the rest.

The exploitation element of the astronomy budget services a huge range of astrophysical phenomena, encompassing the Solar System, exoplanets, stars, galaxies and cosmology. The overall size of the research community bidding into the Astronomy Grants Panel (AGP) for support has increased steadily in recent years, causing intense pressure on flat-cash, exploitation funding. This growth arises from three sources. These are growth in established departments (e.g. Portsmouth, Surrey, LJMU), growth in new groups (e.g. Northumbria, Dundee), and growth through research areas not previously seeking STFC support (such as in geophysics, particularly in lab astrophysics, planetary geology and astrobiology).

Evidence of the competitiveness of UK astronomy, and of the recognition of the need to seek funding from sources outside the highly stretched AGP line, can be derived from the high success rates in gaining European Research Council (ERC) grants in recent years (more applications are submitted from the UK and are awarded than for any other eligible nation in the general area of Astronomy), and in the continuing high standings in leading journal citations.

The astronomy programme serves a large and diverse UK research community of international standing that operates in a rapidly evolving landscape. To manage this diversity STFC has, in consultation with the community, identified key science drivers (last updated in November 2018) that are encompassed by three overarching questions:

A) How did the Universe begin and how is it evolving?

B) How do stars and planetary systems develop and how do they support the existence of life?

C) What are the basic constituents of matter and how do they interact?

These three fundamental questions are further broken down into a set of 23 research 'challenges' facing the community – the complete list of which can be found at https://stfc.ukri.org/research/science-challenges/. STFC's strategy is built around these questions, and this sets the future scientific direction and scope for opportunities in a clear, structured, and well-motivated manner.

Nonetheless, astronomy is a broad subject area and requires the study of the Universe across an expansive parameter space in terms of distance, density, temperature, and spatial scale. To enable delivery on these challenges, research efforts are necessarily married to a host of long-term large-scale facilities, from international ground-based and space-based observatories that span the electromagnetic spectrum, to high-performance and high-throughput computing facilities. Examples include membership of the ESO, ESA's programme, subscription to the Square Kilometre Array (SKA), and the DiRAC supercomputer amongst others. As a result, the astronomy budget has to serve scientists investigating a wide assortment of astrophysical phenomena often requiring access to a range of multi-purpose facilities, leading to a complex funding model.

Driven by the key science challenges, research conducted by the astronomy community also drives the growth of innovative new technology, which subsequently feeds excellent opportunities to the UK's high-tech industries. To this end, STFC also supports the UK's ability to maintain leadership in instrumentation through the blue skies development of low Technology Readiness Level (TRL) instruments and meta-materials relevant to astronomy applications, which is assessed by the AGP's Technology Expertise sub-panel.

2. Leadership

There is much evidence that demonstrates that the UK's astronomical research programme is amongst the best in the world. For example, in terms of the number of scientific peer-reviewed publications in astronomy, the UK has consistently ranked 2nd or 3rd globally since 2008, typically behind only the USA and vying with Germany for 2nd place. In terms of field-normalised citation impact, the UK oscillates between 1st and 4th, jostling with France, Germany and Italy, and outperforms the USA. UK authors are 2nd only to the USA in the Thomson-Reuters "highly cited researchers" list and, in addition, UK astronomy also delivers more highly cited papers than our competitor nations (USA, Germany, Italy, and France). As a result of its long-standing heritage, the UK astronomy community plays a number of leading roles on the international stage. Highlights include hosting the global headquarters for the SKA, as well as leading the development of the HARMONI instrument for the 1.1€billion Extremely Large Telescope (ELT). Our membership of international organisations such as ESO and ESA has enabled UK industry to compete for lucrative contracts. Examples in recent years include the award of multi-million pound contracts to Teledyne e2v for the supply of detectors for the ELT, EUCLID, GAIA, PLATO, the Large Synoptic Survey Telescope (LSST) and NASA's Kepler space craft. Andor Technology Belfast, PLC has also played a key role in the delivery of cameras for the Daniel K. Inouye Telescope (DKIST), the world's largest solar telescope. The wide-ranging international impact of UK astronomy is undisputable.

3. Breadth and Balance

A key strength of astronomy research in the UK is its tremendous breadth. Projects range from studies of mud in the Patagonian desert, as a proxy for conditions on other planets, to understanding the first fraction of a second after the Big Bang in the very early universe. Predicting important developments in science is difficult, but our support for "excellence" wherever it lies, is likely to result in the UK being in the vanguard and leading new exciting areas of research. This ethos has also led to a number of high profile international appointments over recent years.

The clearest demonstration of this is planetary exploration (including extrasolar systems) where scientists studying a range of subjects well beyond "normal" astronomy are needed to make progress.

3.1 Exploitation Grants

This diversity of science exploitation in UK universities is primarily supported through the STFC Consolidated Grant (CG) scheme where grants are reviewed and ranked by the Astronomy Grants Panel (AGP). The CG scheme, which replaced the previous rolling and standard grant scheme, is now in its third cycle[1] and is the subject of a separate STFC review.

The AGP does not set its own budget, but rather it provides a single ranked list of projects submitted for assessment each year in astronomy, solar system and planetary science, based on scientific excellence. A major challenge facing the scheme is that the UK astronomy community (reflected in the number of projects submitted) has steadily grown over this period, while resource has remained frozen in a flat-cash environment since 2015).

While the current CG scheme is by its nature scalable (a 10% cut would simply cut 10% from the number of projects that could be funded) it may come to a point where the present scheme becomes unsustainable. The AAP reported that "*the grants line is already stretched… Any further reduction will be very damaging to the international competitiveness of UK astronomy and astrophysics*"

[1] Departmental astronomy exploitation grants are distributed evenly over a three-year period and assessed every three years.

Table 1: AGP statistics derived from applications over a complete UK community grant cycle (2016, 2017, 2018).

Projects Funded				
	Number of projects	All projects	Male Project PI	Female Project PI
Projects Funded	247	38%	38%	39%
Projects Unfunded	407	62%	62%	61%

This is most evident in terms of the use of CG funds to support investigator time (fEC) on projects. fEC has steadily been reduced over the lifetime of the CG scheme with the maximum allocation to the lead investigator on a project falling from >30% to 15% FTE. This has been done to maintain as far as possible the overall number of postdoctoral research associates that can be funded in a flat cash environment i.e. attempting to keep the volume of research constant. Nonetheless only approximately 1 in 3 projects are funded (Table 1), and only around 40% of applicants get some funding for their time. That means that 60% of the academic staff in astronomy receive no direct support from CGs. They are not named on the CG awards, and cannot re-apply for CG support for a further 3 years. The Full Economic Costing model is failing to cover the cost of excellent research currently being done in university departments. This is a particular cause for concern in the community where lack of evidence of research grant success can have an adverse effect on individuals' careers and promotion. There is some anecdotal evidence that reductions in FTE allocations to staff have led to changes in workload allocations (e.g., increased teaching loads) and make appointments in astronomy less attractive to some universities. Cuts in university budgets from other external drivers, such as the Augar review of tuition fees, could further impact upon the willingness of universities to subsidise research by astronomy staff without any external research funding.

Conversely, if AGP funded a larger proportion of the community but at a lower level (say 10% FTE) then this could cause a significant reduction in the number of postdocs. This, in turn, would impact both the research outputs being delivered and the career pipeline needed to deliver future leaders in astronomy. The AAP report that the low-level of exploitation funding is already having a disproportionate effect on early career researchers.

As highlighted in the previous Balance of Programmes (BoP), the effects of this sustained real-terms cut may now be becoming apparent in publication statistics as well, with UK first-author rates having steadily declined from 26% in 2006/7, to 18% in 2014/15 – thereby evidencing a reducing capacity for international leadership. This data supplied by OUP/MNRAS (A. Leary) for the last decade show that UK researchers continue to co-author papers at a nearly constant frequency relative to international competitors.

A strength of the current system is that there is no minimum size for a group to be funded allowing for a flexible and responsive system based solely on the excellence of science. However, this has led to a growing number of groups submitting proposals, either from new appointments in astronomy or from groups previously funded by other research councils.

AGP reviews projects funding both scientific exploitation and early development of new technology (Technology Readiness Levels 1-4). While superficially it appears that overall technology groups have a similar success rate to scientific exploitation (about 1 in 3) this could result in some groups being shut out of funding schemes for long periods threatening their viability. This problem is further discussed in Section 3.5.1.

Recommendation 1: We encourage STFC to investigate the viability of technology groups within the current grant system and to find ways to stimulate this community.

Under the CG system, applicants can only submit projects once every three years, which does restrict the number of applications each year. But there are still many high-quality applications and for many applicants there is a fine line between success and failure. It is not clear that any system can accurately judge between large numbers of

applications of similar quality. Any alternative grant scheme would still have to find some way to limit demand which was one of the reasons for introducing the CG scheme originally.

AGP does not focus on or prioritise any particular areas or specific facilities. There is strong support for this approach from the community; **>90% of respondents to the Astronomy Advisory Panel wanted grants to continue to be funded solely on the basis of scientific excellence**. While exploitation grants linked to STFC- or UKSA-funded facilities are not explicitly prioritised they can and do succeed based on quality of science and UK leadership in these projects. They are held to the same standards as any other projects, which ensures the same high quality for all funded projects. This flexibility means that AGP can and does respond to emerging areas and "hot topics", such as gravitational wave astronomy, funding science exploitation in all areas of astronomy.

Figure 1 shows the breadth of applications and associated awards to the AGP. These results should be considered as indicative as the data underpinning this figure is based on titles of proposals and could be misleading.

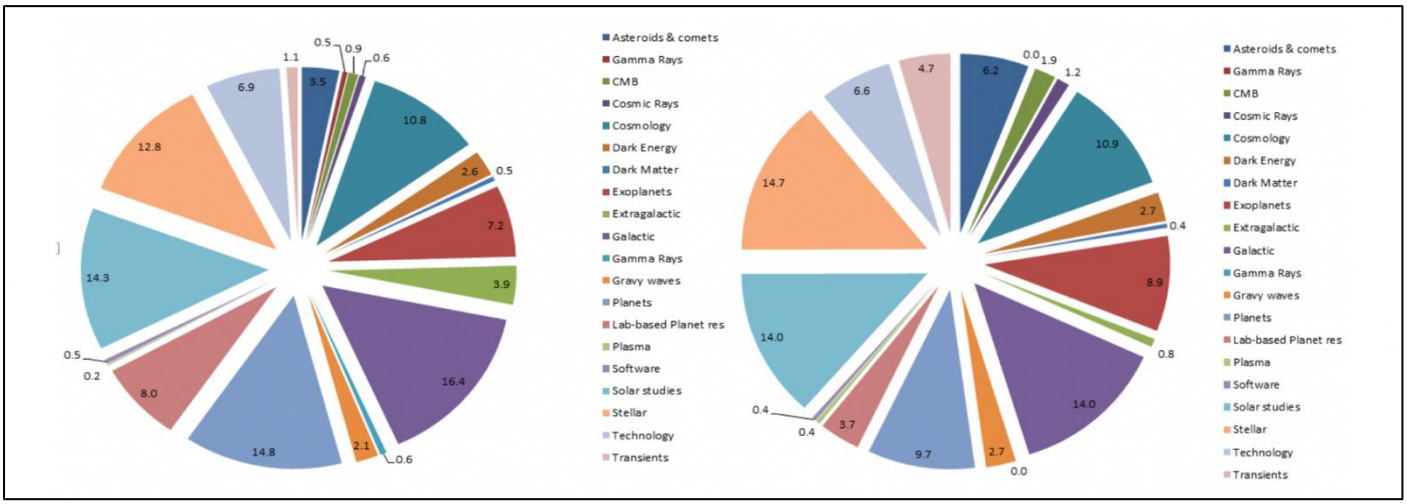

***Figure 1**: AGP applications (left panel) and awards (right panel) for 2015-18 by subject area as a percentage of total number of application or awards, respectfully. Due to the method of data collection these results should be considered indicative rather than accurate.*

The overwhelming majority of the upper tercile of unfunded projects reviewed and ranked by the AGP are highly competitive, either in terms of the "Importance of the proposed science" or "International competitiveness" criteria. In the 2018 round, the number of these very high quality but unfunded projects meant that 152% of the funded research could be considered world class - in other words, STFC is funding a smaller fraction of this category than in 2010 when the figure was 136%. With this in mind, the AGP frequently trims resource requests to maximise the impact of the available budget, but the scope to achieve significant savings has long since disappeared. Currently, just over 60% of applicants to AGP received no support at all and are locked out from re-applying for three years. An academic working on astronomy research has access on average to a third of an STFC-funded PDRA at any one time, or equally that they can expect to be awarded three-years of PDRA support once every decade.

3.1.1 European Funding

The astronomy community has been extremely successful in obtaining EU-funded grants from the 7th European Framework Programme, Horizon2020, and European Research Council (ERC). These grants service the community at all career stages, from early career researchers, to upcoming and well-established research leaders. UK astronomers have become extremely successful in winning these grants and currently some >40% of programme funding (postdocs and students but also significant PI time) originates in European sources. The potential loss of ERC grants, in particular, could have a devastating effect on UK astronomy, more so than other research fields within STFC's remit. This success, coupled with the flat-cash funding from STFC, has led astronomy research groups to become reliant on EU funding. For example, STFC funds less than a quarter of one UK department's research income, and STFC's Astronomy Advisory Panel reports that over 30% of astronomy postdoctoral researchers are funded by the

EU. The level of EU funding ranges from 0.2 to 15 Million GBP per department, and is used to cover capital costs, post-doctoral researchers and PhD studentships. In general, it is the largest UK astronomy groups that are most dependent on EU funding. But there will also be a knock-on effect on other groups as these teams turn back to STFC grants for support. The effects of an extended period of flat-cash support for exploitation grants has to some extent been mitigated by the success of UK researchers in winning EU funding. Those researchers with significant EU funding, such as ERC grants which typically support teams of multiple post-doctoral research associates, have been effectively excluded from CG support on the basis that STFC will not fund work that is already being supported. Although ERC grant holders can apply for CG funding, they need to be able to show that the proposed work is not already funded by the ERC, and yet is of the highest quality; few ERC-funded researchers can demonstrate science of the very highest quality that they did not already include in their ERC proposal, given the wide scope expected from ERC grant applications. As these ERC team leaders turn back to the already overstretched STFC exploitation budget, resources will be further stressed. There also exists the possibility that previous ERC team leaders become demoralized by the lack of support available from STFC and are lost to the UK. A modest increase in the AGP budget would not be sufficient to offset this impact and a more substantial increase would be required to maintain the current level of activity in the UK astronomy community.

Uncertainty over whether this source of funding will be replaced is currently a source of much angst amongst UK-based researchers. The loss of access to EU funding will have a major impact on the UK's ability to recruit and retain world-leading researchers. It is likely that this 'brain drain' will affect both well-established researchers, who will apply for ERC grants and take them to EU universities, current PDRAs, and the next generation of PhD students. UK-based PhD candidates will be enticed to the EU by the plethora of PhD funding, and it may be difficult to persuade these skilled people to return to the UK after their training. Furthermore, without EU-funded PhD studentships, most PhD studentship awards are limited to only people with UK residency, which severely impacts the UK's ability to recruit the best succeeding researchers. UK astronomy departments report that they have already felt the negative impact of Brexit uncertainty on staff recruitment and retention.

The ultimate consequence of the loss of the EU-funding stream will be a shift in the UK's standing in astronomical research. Whereas the UK currently ranks amongst the top three nations for astronomical research, the sudden lack of EU-funded postdoctoral researchers and PhD students will result in a drastic reduction in the UK's research output which can lead us to drop down the rankings. Some anecdotal evidence suggests this has already started. The brain drain of established researchers will immediately and irreversibly impact the UK's leadership of international projects, which is likely to have the knock-on effect of reducing contracts for UK-based technology companies.

At the time of writing UKRI is considering a replacement scheme for the Horizon 2020 EU funding scheme. We make the following recommendations for a replacement funding scheme to ensure that UK astronomical research can continue to be world-leading.

- The level of funding needs to be comparable to that currently relied on by the UK astronomical community.
- The scheme should be dedicated to blue-skies research with an allotted fraction of the funding for 'Universe Science' (the ERC definition of "universe science" spans everything within STFC's remit and is not specifically about the universe).
- The funding criteria should be based on scientific excellence and quality of the applicant, rather than impact. The impact of Universe Science is very long term, and therefore hard to judge.

Recommendation 2: STFC-UKRI is strongly encouraged to introduce a funding scheme with similar characteristics to those from the ERC to replace any lost income. The main criteria to receive the funding must be scientific excellence and could use the same criteria as the ERC Schemes. STFC should endeavor to establish this scheme as soon as possible.

3.2 Key Findings for the AGP and Exploitation Grants

- There is broad acceptance in the community that the AGP does as good a job as possible in the circumstances and with the budget available. Nonetheless the system is showing signs of significant strain. Any continuation of flat-cash (or a reduction) for exploitation grants coupled with the loss of EU funding and consequent increased demand on UK funding, threatens to undermine the current system for funding core research in UK astronomy groups. While recognizing the growth in government funding in new initiatives, e.g., supporting the industrial strategy or global challenges, without increased funding for core research based on scientific excellence, the UK astronomy community will not be in a position to respond to these new initiatives.
- A particular concern in the present CG system is that the majority of applicants receive no support and are locked out from re-applying for the next 3 years, which adversely affects careers and the ability of the community to respond to new opportunities.
- Intense competition for resources based on scientific excellence has led to a UK community that has had great success in winning EU, and in particular ERC, funding. The astronomy community is therefore particularly at risk from the loss of access to EU funding.
- The clear message from the AAP and SSAP consultations is that any uplift in STFC funding should be directed to exploitation grants, selected on the basis of scientific excellence. Indeed, almost every consultation over the last decade has given the same advice.

3.3 Gender Balance

Information learnt from AGP grants enables us to examine the gender balance in the process. These results are in line with that expected from the gender balance in UK Physics & Astronomy Departments. While beyond the scope of this report this demonstrates how much further Physics & Astronomy Departments need to travel to reach a more reasonable balance. These statistics are demonstrated in tables 2, 3 and 4. It was felt that STFC should make every effort to increase the diversity (gender/ethnicity) of the community. STFC is encouraging better Equality and Diversity balance and should be proactive in trying to improve the situation within this discipline. Improving gender balance on committees, active mentorship and encouraging females at an early age to be interested in the discipline could all help to encourage greater levels of female representation.

Table 2: AGP Gender Statistics [2016/17/18]. Applicants by gender

Gender of applicants (where known)*	**Individuals**	**Male**	**Female**
Grant PI	115	92 (80%)	23 (20%)
Project PI	654	536 (82%)	118 (18%)
All applicants	753	617 (82%)	136 (18%)

** Not all genders are known or declared as binary*

Table 3: AGP Gender Statistics [2016/17/18]. Project success rates by gender

Fraction of Projects funded	**Number of Projects**	**Male Project PI**	**Female Project PI**
% Projects Funded	247	204 (38%)	46 (39%)
% Projects Unfunded	407	332 (62%)	72 (61%)
Total	654	536 (100%)	118 (100%)

Non-AGP gender statistics

The below statistics are taken from the 35 instrumentation and development grants that are spread over the 20 facilities that are detailed later in the report.

Table 4: Gender statistics for current STFC instrumentation & development grants.

	Male	Female
Principle Investigators	31	4
Co-Investigators	20	3
Researcher Co Investigator	6	1
Researcher	6	2
Total	**63**	**10**

3.4 Synergy with Particle Astrophysics

There are several research areas within the Astronomy Programme that now have strong synergies and overlaps with the Particle Astrophysics Programme, which internationally includes the Cosmic Microwave Background (CMB), dark matter, gravitational waves and very high-energy particle astrophysics. This reflects major advances and discoveries in some of these fields that have transformed not only their specific disciplines but have also triggered flourishing activities that have become an integral part of research programmes in astronomy. CMB and cosmology are examples of synergies dating back decades whereas gravitational waves astronomy is a very recent one. Dark matter, or very high-energy astronomy, is a possible candidate in the coming years.

Particle Astrophysics currently supports the construction of the direct dark matter search experiment LUX-ZEPLIN (the project is essentially complete), gravitational-wave science (currently the LIGO A+ construction project, and instrument R&D and science exploitation through a dedicated non-competed "consolidated grant"), and the preparation for possible involvement in the Cherenkov Telescope Array (CTA), to study high energy events, construction at a lower level. CMB ground-based construction projects currently fall in the remit of Astronomy and there is an ambition to participate in the US-led, Simons Observatory[2].

STFC has made significant investments that have led to established UK leadership and reputation on the world-stage. STFC is also benefiting from significant university investments in these emerging areas (e.g. a new group in Portsmouth (+3 faculty), new faculties at Kings/Queen Mary, expansion at Cardiff & Birmingham), and it is essential that STFC can capitalise on this investment. CMB science exploitation is now firmly in the Astronomy programme and funded through AGP. It is understood that LUX-ZEPLIN exploitation will be funded through Particle Physics consolidated grants, though a detection will likely trigger significant interest and request for funding in AGP. When CTA comes to fruition, science exploitation will likely see requests both in the PP consolidated grants and in the AGP. Gravitational-wave astronomy is a very noticeable anomaly. There is potential for the same types of activities to be funded under different programmes using different criteria. It is imperative that a consistent funding approach is adopted to maximise the potential of the UK in this area.

Recommendation 3: STFC should review the scope of the different grant schemes and provide an appropriate structure to maximise the return enabled by the discoveries and the new expertise and capability in Particle Astrophysics.

[2] The Simons Observatory is a US-led, next-generation Cosmic Microwave Background (CMB) experiment to be sited on the Chajnantor Plateau in the Atacama desert in Chile. Its primary scientific goals are (i) to constrain the physics of the early Universe by searching for signatures of primordial gravitational waves, and (ii) to constrain neutrino physics and dark energy models through CMB lensing measurements and Sunyaev-Zel'dovich detections of galaxy clusters

3.5 STFC, UKSA and Space Science

The Astronomy funding environment remains complex due to the different responsibilities of STFC (funding the development and operations of ground-based astronomy projects; research exploitation of all astronomy and planetary themes, plus novel technology funding) and UKSA (funding the development and operations of space-based projects and mature technology funding). Indeed, there remains a grey area where the two funding agencies overlap, requiring both (i) strong collaboration and communication between the two agencies, and (ii) clear guidelines provided to the community as to which agency should be the logical home for project development, operations, and exploitation.

Historically there have been perceived issues in the relationship between STFC and UKSA but, by and large, these are due to lack of clarity about the UKSA mission and the mismatch of funding between that available and the ambition of the science community. UKSA, since formation, has funding that supported the ESA membership (subscription plus payload development). Science exploitation remains in STFC's remit and therefore the AGP. Given the competitive nature of the CG system it is possible that proposals to exploit data from missions that UKSA has invested in are not supported through the AGP. However, given the scoring criteria from the AGP this is unlikely. More likely is that the level of awarded resources is seen as low – reflecting the fierce competition within the AGP. However, there remains areas that could be made clearer to the community. For example, in recent years mission concepts have been proposed both to UKSA and STFC. While the lack of funding within UKSA beyond the ESA programme makes this discussion moot, the situation may change in the future and clarity is needed.

With the exception of Martian and Lunar exploration, which fall under the *Human and Robotic Exploration* arm of ESA, the majority of UK activity space-based missions fall under ESA's Science Programme and specifically its *Cosmic Vision* (and ultimately its successor, *Voyage 2050*)[3]. The UK joined ESA in order to pool resources and expertise and build missions that could not be afforded by a single country and hence tackle significant science problems. The geo-return requirements placed on ESA mean that UK industry also benefits from this arrangement.

All nations joining ESA are required to contribute to this Science Programme. But a natural consequence of the ESA selection process is that the UK may not always be funding *its* highest priority missions. So far in the Cosmic Vision programme this has not been the case as the UK has achieved science and engineering leadership positions in *all* these missions. However, the UKSA budget is under considerable strain and it is possible that in the future funding pressures may result in lower priority missions not being supported at all (beyond the ESA subscription). The ESA Science directorate is requesting an uplift in the budget of some 20% in the 2019 ministerial meeting in part to increase the cadence of missions. If this was successful and without a corresponding increase in UKSA support then it is almost certain that some missions could not be supported.

There is also strong support in the community for a new scheme enabling a *National Space Programme* to be established. This could take the form of relatively low-cost UK or bilateral missions that would benefit both academia and industry. Whilst UK only missions may focus on specific science (or technology) problems one of the main gains would be to enable the UK space community to obtain experience on relatively modest projects, placing UK teams at a competitive advantage when bidding for the larger ESA missions. Consequently, the national programme should not be seen as in competition with our ESA membership but rather to help fully capitalize on it. Bilateral missions with non-ESA partners such as NASA or JAXA, would further increase the number of missions and give significant science return at a modest cost.

While the ESA Voluntary Programmes have been used to encourage industrial participation, it was realized that this also needed Science leadership. In the case of the Mars exploration programme this has led to the development of the Aurora Science fellowship scheme. This is a small component of the wider planetary community, but raises the

[3] The UK science community exploits data from space missions irrespective of the funding agency.

question of whether funds as part of a *National Space Programme* might be allocated towards exploitation of space projects within ESA's Cosmic Vision programme, potentially taking pressure away from the blue-skies STFC exploitation grants line. This theme-specific grants line could be time-limited, in response to a particular mission lifecycle or other opportunity, following the model of UKSA's Aurora programme.

Recommendation 4: STFC and UKSA should partner together to accept mission concept proposals either through STFC's Science Board or through a joint STFC/UKSA panel. In either case the selection should be supported by assessment through STFC science advisory panels. In the latter case membership, selection, and the panel's terms and conditions should be published. Criteria for mission ranking should be made visible to the community. This panel could also examine ESA selections with a view to improving the likelihood of success of concept missions that the UK is particularly interested in.

Recommendation 5: If a National Space Programme comes into existence we would support the development of small targeted fellowship schemes to develop depth and leadership in science areas supporting our science programme.

3.5.1 Space orientated Hardware/Instrumentation Development

A key area for concern in the astronomy, planetary, and solar system communities is the lack of overlap and continuity in hardware development programmes. The advisory panels (AAP, SSAP) recognise that hardware development is an essential component of the astronomy programme – without new missions and ground-based astronomy projects, there is a risk of stagnation. Yet the current funding environment has seen a reduction in capacity of all astronomical instrumentation. In space science, part of this stems from the low cadence of ESA missions and the lack of funded bilaterals, from the time that UKSA was formed.

The hardware responsibilities between STFC and UKSA have been clear for some time. Initial technology developments (TRL 1-4) are within STFC's remit, while higher levels are supported by UKSA (presumably being implemented in space projects). AGP statistics show that proposals addressing low TRL developments have the same success rate as other proposals, but few appear to be submitted. The reason for this is not apparent but could be because of an overall lowering of activity due to the lack of Project Research & Development scheme (PRD) opportunities and spin off developments. One further consequence of this situation is that the small number of available mission slots means that most STFC space orientated technology developments are not brought to fruition and are affectively wasted. It is important that this situation is monitored in the future as this will eventually leave a lasting impact on our astronomical technological base and our ability to lead missions. In any case we would support the reintroduction of the PRD.

Recommendation 6: STFC should consider re-introduction of the PRD funding scheme, possibly with themed calls.

Recommendation 7: STFC should further investigate whether the perceived dearth of low TRL AGP grants is indeed genuine and, if real, ascertain the reason for it. STFC and UKSA should look at how instrumentation groups can be better supported from both sides, with greater clarity, as a central pillar of the UK's astronomy, planetary, and solar science.

3.5.2 Science Exploitation

The dual-key approach between UKSA and STFC to space-based missions, with the former supporting development and operations, and the latter supporting scientific exploitation, is seen as a risk by the community. Without specific ring fencing of resources, proposals for exploitation must compete with those in the usual AGP rounds. However,

given the competitive nature of mission selection we expect that the science underlying these experiments must be highly rated and would be extremely competitive in the AGP process. Despite this, the real danger is that science leadership may be put at risk through inadequate levels of resource. Until there is a significant uplift of the grants line this will remain a risk and we would encourage STFC to continue to monitor and report (as it now does to Science Board and UKSA's SPAC) awarded resources for space exploitation. We note that the astronomy programme within STFC holds a specific, albeit very small, budget line specifically to support science preparation for UKSA supported space missions, which is awarded subject to review via the AGP chairs. Awards are largely made to support community building and pre-launch exploitation preparation.

Recommendation 8: STFC grants should be allocated according to scientific excellence. STFC should continue to monitor the level of awards supporting UK space mission interests. Both UKSA and STFC should seek ways to maximise the scientific exploitation of space-based missions, potentially through new and separate grant lines (e.g., following the example of the Mars Aurora fellowships), dependent on new funding becoming available.

4. Skills pipeline

The STFC Astronomy Programme provides high quality training for young scientists in STEM subjects that are in high demand, not only for the STFC (and other research councils) research programmes, but also for the broader economy, in particular in areas such as high tech, big data, statistics, and numerical modelling. Given the government's target for economic growth these people will be essential.

STFC studentships are allocated to departments by guideline formula based partly on their CG performance or, rarely, through direct award on CG and/or instrumentation development projects. Since 2011 the total number of studentships has been flat at about 122-130 studentships/per year and have not reflected the increasing academic community (Table 5). The studentships are allocated to university departments and it is up to local management to decide how the quota filters down to individual STFC groups. As the academic community has grown over this period many astronomy groups have struggled with the relatively diminishing number of studentships (per academic) available. They provide only a fraction of the support that is needed for the projects that are being pursued across the UK. To partially compensate for this shortage of studentships, significant support has come from (primarily) ERC grants. In addition, recently as many as 17 astronomy groups have been able to use opportunities arising from competitions to establish Doctoral Training Schools (Centre's for Doctoral Training or CDT's). CDTs are focused on big data and industrial applications, and therefore can only be partially used to support the core programme.

Table 5: Historical STFC Studentship and Fellowship support levels. The table shows the breakdown of studentships between the astronomy programme and the other areas that STFC supports.

Year	Total No. of STFC Studentships awarded	No. of STFC Studentships awarded – *Astronomy only*	Total No. of STFC Fellowships awarded	No. of STFC Fellowships awarded – *Astronomy only*
2009	256	137	6	3
2010	235	134	12	5
2011	220	122	12	5
2012	220	128	12	6
2013	220	127	12	5
2014	220	127	12	9
2015	220	131	12	6

2016	220	130	12	6
2017	220	128	13	7
2018	220	129	12	6

At the postdoctoral research level, there is a lack of a clear career path that can bridge between the PhD and a de-facto tenure-track faculty position. Around ten years ago, the UK lost the opportunity for personal fellowships for early career researchers that are seen as an important stepping stone for prestigious fellowships (such as the STFC Ernest Rutherford Fellowships (ERF), and Royal Society University Research Fellowships) that can lead to faculty positions. This is, for example, in contrast to countries such as The Netherlands, where the VENI-VIDI-VICI scheme has provided a very successful and clear career path for high quality scientists at every stage: from post-PhD to established faculty. Although it is recognised that, under the current financial constraints, priority should be given to protect the ERF scheme, reinstating an early-career fellowship scheme should be seen as a requirement to maintain a healthy career structure for our early-career researchers. Overall, the present climate dissuades the best UK graduates to remain in this country and talent will frequently leak abroad.

A different consideration affects the skills specific to experimental physics applied to astronomy instrumentation. The funding opportunities for R&D, blue-sky research have shrunk in recent years, as flat budgets reduce the likeliness of funding and the PRD scheme has not been in operation. It is therefore increasingly difficult to maintain an active, healthy and diverse research programme in these areas, including the training of the next generation of scientists (both for academia and the industrial world). This adversely affects a wide number of sectors: it diminishes the UK's ability to bid for leading hardware roles in major astronomy projects, and as a consequence reduces down the line access to the best data for science exploitation, and limits the training opportunities for highly skilled experimental physicists who then transfer their skills to the broader high-tech industry and economy.

Recommendation 9: 3-year fellowships should be put in place as demonstration of independence at an early career stage. This is additional to, not replacing, the ERF scheme.

4.1 Student and Fellow destinations

STFC have made enquiries to determine the first destination of their PhD students during the period 2012-15 (https://stfc.ukri.org/files/first-destinations/). This shows that some 25% of completing students move directly into the private sector, 30% of which are into software orientated positions. See figure 2 below. In terms of sectors, the spread is broad with significant fractions going into manufacturing and finance; with around 10% in data analytics. This demonstrates that students are successfully being trained to positively enhance the UK skills base.

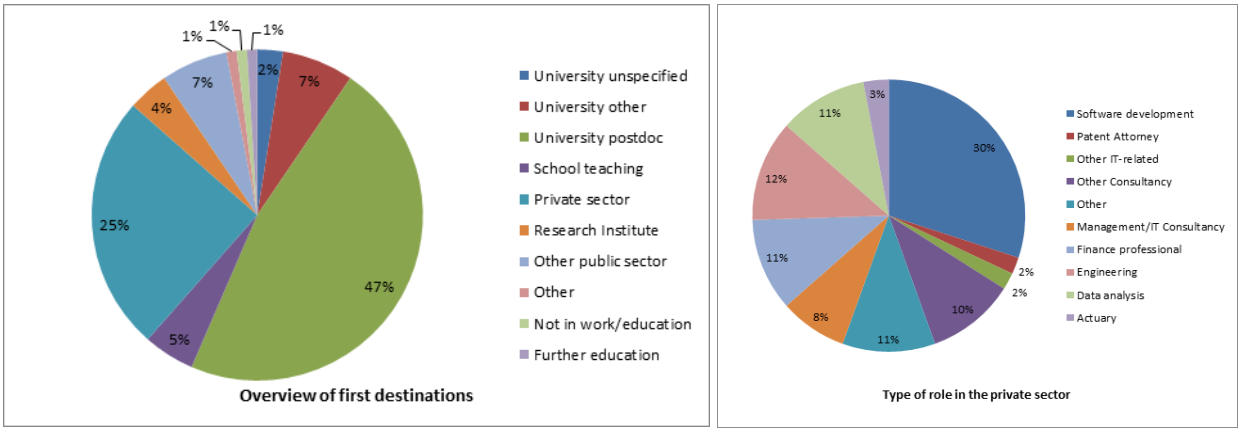

Figure 2: The left hand pie chart shows the first destination by subject area for of astronomy students. The right hand pie chart shows the type of role undertaken in the private sector

About 60% of the students stay in research (postdoc/university/research institute), with around half of postdocs remaining in the UK & 10% going elsewhere in the EU. Many will be working in countries such as Australia, the USA and Canada.

In terms of public sector, about half (~5%) end up in teaching and the rest (~6%) are split over various public bodies, but the civil service and health sector account for half of the rest.

These figures demonstrate a high level of diversity; the UK is both training the next generation of astronomers and supplying a wide range of public and private sectors with highly skilled and highly numerate staff. All key sectors (both private & public) strongly benefit – demonstrating that training in astronomy is an excellent all-round training for the most complex roles in the modern economy. It is important to remember that these are the first destinations; eventually a large fraction of those continuing in astronomy will leave, presumably into a comparable spread of destinations, so it should not be underestimated that a high fraction of astronomers eventually end up in the wider economy. Even the destinations receiving a comparatively small percentage of our output are receiving significant numbers of highly trained individuals.

5. Current Programme

5.1 Current Facilities receiving STFC funding

The breadth of the astronomy programme requires a broad range of facilities to deliver on the science drivers. Smaller facilities tend to be more focused on specific science goals, while larger facilities service a larger fraction of the community.

Some of the projects listed below have international agreements that last beyond the BoP2 horizon, whilst other projects have already had their final installment of STFC costs and will not seek further funding. We therefore do not provide prioritised rankings for all currently funded projects, but instead give broad recommendations. The broad science portfolio of UK astronomy requires a broad project base. We recommend that each project be considered on its scientific excellence rather than make recommendations of scientific priority based on research topic. In a flat-cash or decreasing funding scenario it is unsustainable to continue all of these projects or start new ones.

Involvement in broad-goal, large, international projects, such as LSST, is deemed essential to ensure the UK remains a leader in multiple aspects of astronomy. However, funding smaller scale projects, such as WEAVE, gives the UK the competitive edge to exploit and capitalise on big investments (e.g. GAIA through the ESA subscription).

We have assessed the projects using the standard scheme (given in Appendix 1), rounded to the nearest half integer. For ease of presentation we divide the project along broad wavelength lines: optical/IR and mm/radio facilities.

5.1.1 Optical/IR orientated facilities

DESI

The Dark Energy Spectroscopic Instrument (DESI) is a 5000-fibre spectrograph with an 8-square degree field of view on the 4m Mayall Telescope at Kitt Peak National Observatory. A 5-year survey, starting in 2020, will determine the spectroscopic redshift of over 30 million galaxies and quasars, an order of magnitude improvement on the previous generation of spectroscopic redshift surveys such as BOSS. It will use the three-dimensional clustering of galaxies to constrain theories of modified gravity and cosmic inflation, and measure the sum of the neutrino masses with an uncertainty of 0.020eV, sufficient to determine the nature of the neutrino mass hierarchy. DESI is an international collaboration of over 600 scientists world-wide in a field in which UK astronomers have a strong record. STFC funding

for instrumentation development in Durham and UCL has enabled more than 50 scientists from the UK to participate, including UK leadership in 6 science working groups. DESI:UK consortium membership is restricted to a fixed number of UK academic staff and their postdocs and students at 6 UK institutions. **For scientific excellence this was rated Alpha 3.5. For impact this was rated 3.0.**

DKIST

The 4-metre Daniel K Inouye Telescope (DKIST) currently under construction in Maui will represent the state-of-the-art for ground-based solar observations. DKIST will have a range of imaging, spectroscopic and spectropolarimetric instrumentation, permitting diffraction limited imaging down to a resolution of 20 km in the photosphere and chromosphere. DKIST will resolve, with unprecedented sensitivity, individual magnetic flux concentrations, observing their emergence, structure and dynamics, measuring their field strengths and direction in the solar photosphere, chromosphere and corona. DKIST's primary design (off-axis) will enable the first routine measurements of the coronal magnetic field.

Driven by recent developments in instrumentation and adaptive optics, DKIST represents a step-change in the field that will lead to fundamental advancements in solar physics. DKIST will provide important complementary observations to space-based missions and ground-based facilities.

STFC/PPRP provided total funding of £2.4M for the DKIST project. All of the STFC funding was invested in the UK. Approximately 90% of the STFC funding was invested on detector R&D with the remaining funds directed to the UK academic partners for the development of software tools. The industrial partner invested an additional £1.2M and UK academic partners provided additional funding of £0.9M as a cash contribution for camera equipment. **For scientific excellence this was rated Alpha 4.0. For impact this was rated 4.5.**

ELT

The Extremely Large Telescope (ELT), when construction is completed in the mid-2020s, will be the world's largest and most sensitive ground-based optical/near-IR telescope. Built by ESO, it will have a ~40m diameter segmented mirror and benefit from adaptive correction using both natural and laser guide-stars, giving it a light gathering power some ~40 times that of JWST and a diffraction-limited angular resolution 6 times better. Its science goals cover the main drivers of astrophysics and cosmology for the foreseeable future, from characterising how planetary systems form (including discovering and imaging Earth-like extrasolar planets) to carrying out detailed studies of the earliest galaxies and their subsequent evolution, and to potentially directly detecting the accelerated expansion of the Universe. Once operational, the telescope will be crucial to the research plans of a large fraction of UK astronomers whose work requires optical and near/mid-IR observations.

A suite of instruments is being developed contemporaneously with the construction of the telescope. STFC funds the UK groups (ATC, Cambridge, Durham, Oxford, Heriot-Watt) involved in the development of several of these through a ~£5M p.a. grant. The UK leads one of the two high-profile first light instruments, HARMONI (a single-field near-IR IFU spectrograph), is a minor partner in METIS (a mid-IR imager/spectrograph) and is a partner in the consortia developing HIRES (a high-resolution spectrograph) and MOSAIC (a multi-object spectrograph). The balance of leadership/membership is in-line with the policy towards ESO/ELT developed by Science Board. HARMONI will likely be the main workhorse instrument for most of the user community during the first years of ELT operation, and so has an extremely high profile across the ESO member states.

In addition to open time available to the UK community through the ELT component of ESO membership, instrument development brings significant GTO to the UK. This will be deployed by the builders as part of the international science teams developing key structured science cases to exploit the instruments. Consequently, this directly benefits astronomers at the builders' institutions. The rest of the UK community should subsequently benefit from

operational knowledge developed via GTO time being communicated to them and feeding into their open time programmes, this being the main benefit to them of UK involvement in building the instruments. **For scientific excellence this was rated Alpha 5.0. For impact this was rated 4.5.**

GAIA – Additional Computing DPAC CU9

The GAIA mission has already proved a great success for ESA by enhancing our knowledge of stars and structures in our galaxy. It is transforming our knowledge of the fundamental parameters of stars and therefore allowing the theory of stellar evolution and models of the galaxy and its formation and evolution to be placed on a firm footing. GAIA results will impact on many aspects of contemporary astrophysics for decades to come.

Production of most GAIA data products are official ESA deliverables and are funded through UKSA. STFC is funding extra computational work related to these products. Despite several attempts the panel was unable to gain a detailed understanding from the grant holders of the full purpose of this work and usefulness to the UK Community. Hence the panel was unable to form a view of the value of this work beyond the official data products. This is despite this project being recently assessed by PPRP.

HARPS3

The High Accuracy Radial Velocity Planet Searcher 3 (HARPS3) is a UK-led international project to build an instrument that will search for Earth-mass planets around other stars. It will be placed on the 2.5m Isaac Newton Telescope (INT) in 2021. This instrument is similar to HARPS-N on the 3.6m Galileo National Telescope on La Palma but the HARPS3 science case requires extended observations (initially >50% of the total available telescope time). The data itself will be useful for a range of other projects such as stellar activity studies where the long observation periods could make a major impact (and be useful in other exoplanet projects). From 2026 the instrument will contribute towards PLATO follow-ups of terrestrial planets. Most of the major project roles are held by UK researchers, and the instrument will be accessible by the entire UK community through open competition. STFC has contributed ~£0.7M towards the project with the rest raised from UK universities and international partners. All current funding has been used on manufacturing, assembly and integration of the instrument, which will continue until 2021. After that time the operation costs will be primarily met by the ING, but the HARPS3 team plan to seek funding for the instrument and data archive maintenance costs and scientific exploitation costs. **For scientific excellence this was rated Alpha 3.5. For impact this was rated 3.0.**

ING

The Isaac Newton Group manages the 2.5m Isaac Newton Telescope (INT), and the 4.2m William Herschel Telescope (WHT) on La Palma, in the Canary Islands. There is strong consensus within the astronomical community that membership of the ING should not be lost from the UK portfolio as Northern facilities are needed to ensure the community can operate at the top research level. With the dominance of 8m-class telescopes in recent times, the ING have responded by carving a niche: single instrument observing modes (with the new instruments WEAVE and HARPS3) that will complement and provide added value to the surveys that form the core of the current UK astronomy research programme. In 2017, the UK entered into a 10-year tripartite agreement with the Netherlands and Spain to continue funding the operation of ING until February 2027. In addition to the scientific impact brought by WEAVE and HARPS3, the ING offers the UK significant opportunities in technological and instrumentation research and development. However, it's worth remembering that these developments come with vastly reduced access to open time for the general UK astronomical community.

The UK use of the WHT for the ELT adaptive optics pathfinder, CANARY, has resulted in leading roles for the Durham-based instrumentation group, contracts with ESO and other observatories, and partnering industry. Going forward the ING telescopes support WEAVE (WHT) and HARPS3 (INT) which are assessed separately. In the post WEAVE era

the position of ING will need to be reassessed. We have not rated ING but have rated WEAVE and HARPS3 individually.

Liverpool Telescope

The Liverpool Telescope (LT), with a mirror diameter of 2-m, is the world's largest multi-instrument, fully-robotic telescope. Specialising in time-domain astrophysics and transient follow-up, the UK PATT community receives 28% of the time on the LT, with LJMU staff receiving a further 28%. With both the WHT and INT becoming (essentially) single-instrument telescopes, the LT will soon become the UK's only telescope with multi-instrument capability accessible in the northern hemisphere to the UK community. The LT is well placed to exploit new international projects and surveys with other facilities expected over the next decade. This includes the developing field of electromagnetic counterparts to gravitational wave sources. The LT will provide the UK with a key facility for rapid photometric, spectroscopic, and polarimetric follow-up of newly discovered transients.

While the Liverpool Telescope is mainly used for professional astronomical research, part (~10%) of its available time is devoted to educational projects run by the National Schools' Observatory (NSO) at LJMU. This offers school pupils near-immediate access to a world-class observatory and, since its launch in 2004, has led to over 120,000 observing requests from schools. Working with over 4000 teachers throughout the UK and Ireland, the scheme is wide-reaching, with the NSO website attracting over 1.5 million visits per year. **For scientific excellence LT was rated Alpha 3.0. For impact this was rated 4.0.**

LSST

The Large Synoptic Survey Telescope (LSST) will conduct the most ambitious optical sky survey yet planned, imaging the whole visible portion of the southern sky twice a week for 10 years from late 2022. The resulting survey will constitute an unprecedented multi-colour movie of the Universe that will be used to study a broad range of astrophysical phenomena, from the closest asteroids to the nature of the dark energy. Access to data during the two-year proprietary period will be determined by in-kind contributions, such as the Data Access Centre (DAC) and development data products (DEV) planned by the LSST:UK consortium.

LSST has strong synergies with the other facilities that form the core of the UK's future astronomy programme: Euclid, SKA and ESO ELT, so UK astronomers have the potential to make a significant contribution to the survey exploitation. The UK community has not been lax about getting involved. Every astronomy research group in the UK already has at least one researcher involved in the LSST:UK consortium, which is taking a leading role in a number of LSST science areas within the wider international consortium. The greatest scientific impact will not be realised until the first data release in 2023, but economic and societal impact in the UK is already starting to materialise. The survey comprises a "Big Data" challenge and the LSST researchers will exchange knowledge and skills with enterprises working on such issues through their interaction within the STFC Higgs Centre of Innovation. Losing access to LSST data would significantly weaken the UK's position in the international astronomical community, especially in terms of the multi-messenger global astronomy programme. **For scientific excellence this was rated Alpha 5.0. For impact this was rated 3.0.**

MOONS

The Multi-Object Optical and Near-infrared Spectrograph (MOONS) is a 3rd generation high-multiplex optical/near-IR spectrograph with a wavelength-dependent resolution of 4000-18000 which should be mounted on the VLT from 2022. UKATC and Cambridge are part (~42% by effort) of an international consortium building the instrument. They have been funded by an STFC grant totaling ~£5.8M which should end when all UK work-packages are complete in 2022.

The main science drivers include studying the resolved stellar populations of the Milky Way and the Local Group, carrying out an SDSS-like galaxy survey of ~1 million galaxies at z>1 to explore the growth of galaxies and structure at these redshifts and to spectroscopically characterise the first galaxies at z>7. The instrument will be the ESO community's workhorse spectroscopic follow-up instrument for, and consequently synergistic with, a wide variety of existing and future multi-wavelength imaging surveys (LSST, Euclid etc.). Given this, the instrument should be central to the future research plans of a large fraction of the UK observational community. As well as open time on the instrument, the international consortium has ~300 GTO nights which will be used in a coordinated way by the Galactic and Extragalactic Science Working Groups.

There are few 8m-class high multiplex spectrographs that will compete for science impact with MOONS. The clearest competition will come from Subaru's Prime Focus Spectrograph which has 2400 fibres and a 1.25 deg^2 field operating in the northern hemisphere between 0.4 and 1.3 microns. It has a core science programme similar to that of MOONS. That programme will last 300 nights over 5 years as Prime Focus Spectrograph (PFS) shares Subaru with a significant number of other instruments. This comparatively slow observing rate allows MOONS time to deliver its scientific impact despite its smaller field-of-view and multiplex. **For scientific excellence this was rated Alpha 3.5. For impact this was rated 3.5.**

NGTS

The Next-Generation Transit Survey (NGTS), is a robotic array of 12 telescopes located at ESO's Paranal Observatory, providing continuous monitoring with high photometric precision for bright southern stars. The survey seeks to detect transiting exoplanets in the super-Earth to Neptune size range over a wide (100 square-degrees) field of view. NGTS is led from the UK, and is considered to be world-leading, with four confirmed detections published to date from the first two years of the survey. By focusing on bright stars, NGTS detects exoplanets that are well suited to atmospheric characterisation follow-up from other facilities (e.g., VLT, ELT, JWST, etc.), and the fine spatial resolution provides confirmation/vetting of candidates identified by space observatories at lower resolution (e.g., TESS, CHEOPS). The facility was constructed in 2014-15, and a proposal for continued STFC funding until 2022 (£177k/yr) was recently authorised. A role for NGTS is foreseen until at least 2030, particularly in collaboration with PLATO (launch in 2026). Reductions in NGTS operations would be a detriment to the young exoplanet community that are ultimately being trained to take on leading roles in the 2020s, particularly with PLATO and ARIEL. However, NGTS could investigate options for opening up the facility to the wider UK community, and potentially international partners, for some percentage. Reduced funding would also remove the UK leadership that NGTS provides; lessening the UK's potential to participate in future projects. Nevertheless, funding beyond the present BOP would require continued renewal proposals from the NGTS team. **For scientific excellence this was rated Alpha 3.5. For impact this was rated 3.5.**

SOXS

SOXS ("Son of Xshooter") and is a near UV-Optical-Near Infrared, single shot spectrometer which will be permanently mounted on ESO's New Technology Telescope in La Silla, from 2020 onwards. In the next decade LSST will be in operation with a host of smaller but wider field survey telescopes, in addition to gamma- and X-ray telescopes (Swift, SVOM, eROSITA), CTA, radio telescopes (e.g. Meerkat/SKA) and gravitational-wave observatories (LIGO, Virgo and later KAGRA and LIGO India). The need for optical-NIR spectroscopy follow-ups with minimal time delay is therefore critical for multi-messenger science and the new large discovery space that will open up; SOXS delivers this capability. SOXS is operated by an international consortium (UK, Italy, Denmark, Chile and Finland) and has a well-established UK leadership. In the UK, construction - hardware and data architecture - has been funded through PPRP and by Queen's University Belfast. Operation (currently envisaged to start in 2021) will be supported through bids to AGP. **For scientific excellence this was rated Alpha 3.0. For impact this was rated 2.0.**

WEAVE

The William Herschel Telescope Enhanced Area Velocity Explorer (WEAVE) is a cutting-edge multiplexed fibre system that will be placed on the WHT in 2019. It offers the UK community observing capabilities that are not available on any other telescope in the Northern hemisphere. Approximately 70% of the available time over the first 5 years will be spent on large surveys that build upon the UK's strategic research focus, such as the exploitation of GAIA and the Northern SKA pathfinders. It thus provides UK astronomers with a major opportunity for producing impact above their relative weight. Four out of eight of the core observing programmes are led or co-led by UK researchers, and the vast level of scientific interest in this project is reflected by the involvement of over 120 UK-based researchers in WEAVE science projects. To date, the costs for this UK-led international consortium project have been primarily for construction, which has strongly supported UK instrumentation-building research groups in universities and research institutes, as well as contracts awarded to UK technology industries. Future costs for this project will be operational costs for the ING (see above), and exploitation costs of the science through grants to UK-based researchers. **For scientific excellence this was rated Alpha 3.5. For impact this was rated 3.0.**

Wide Field Astronomy - CASU

The Cambridge Astronomical Survey Unit (CASU) develops and operates world-class astronomical pipelines, supporting the analysis of astronomical surveys in optical and infra-red wavebands, and allowing users interactive and automatic access to the associated repositories hosted by CASU. Its strength is a core of expert staff with a history of providing solutions to unique challenges posed by surveys or facilities, such as the VST and VISTA imaging surveys. CASU also developed and operates the core analysis pipelines for the GAIA-ESO spectroscopic survey, and is currently developing spectroscopic pipelines for WEAVE and 4MOST. Continued STFC funding should be dependent on CASU continuing to demonstrate added value to UK science, closely aligned with STFC projects. There will be a continuing need for access to repositories such as the ING-INT archive. CASU expertise in image analysis is now being applied in the medical sciences, to improve understanding of cancer pathways, with funding from Cancer Research UK. **For scientific excellence this was rated Alpha 3.5. For impact this was rated 3.5.**

Wide Field Astronomy - WFAU

Since 1999 the Wide-Field Astronomy Unit (WFAU) at Edinburgh has operated a number of the largest sky survey archives in the world, including those from the ESO public surveys programme. WFAU curates and publishes data products within the WFAU archive and through the global Virtual Observatory. Most of this programme is in collaboration with the Cambridge Astronomical Survey Unit (CASU) who operates the data pipelines, and WFAU archive and publish the data products. Current VISTA, VST and GAIA-ESO Spectroscopic Survey data handling will finish in the coming years, leaving the question of STFC bridging for WFAU until it is due to become home to the UK's Euclid Science Data Centre and LSST Data Access Centre. There will be a continuing need for national archiving of astronomical survey data in the future. **For scientific excellence this was rated Alpha 2.5. For impact this was rated 2.5.**

5.1.2 Radio/mm orientated facilities

ALMA Regional Centre

The ALMA Region Centre (ARC) is based at the Jodrell Bank Centre for Astrophysics and it delivers quality assured, pipeline reduced ALMA data products to UK users. ALMA is the world's premier telescope operating at millimetre wavelengths. Its combination of sensitivity and resolution has transformed the study of star and planet formation, galaxy formation and evolution and the buildup of complex molecules. In addition to the delivery of data products to the users the ARC nodes also provide support for proposal preparation, community workshops, software development, advanced data reduction and archiving of ALMA data as well as providing observing support at the

ALMA observatory in Chile. The UK has a vibrant ALMA community and the UK ARC is one of the busiest out of the seven European nodes. The ARC makes a significant contribution to the delivery of ALMA science by the UK community and a cut in funding would slow down and compromise the delivery of results from this top ESO facility. **For scientific excellence this was rated Alpha 4.0. For impact this was rated 3.5.**

e-MERLIN

e-MERLIN (Multi-Element Radio Linked Interferometer Network) is the UK-based radio interferometric array of seven telescopes operated by the Jodrell Bank Centre for Astrophysics delivering high spatial resolution cm-wave continuum and spectral line observations (1-25 GHz). Its 200 km maximum baseline means that its spatial resolution is seven times higher than the EVLA at the same frequency. This resolution matches those of other key facilities for multi-wavelength studies such as HST/JWST, Chandra and ALMA. The 76 m Lovell Telescope is regularly included in the array and this results in a collecting area that is 25% that of the SKA mid-frequency array (SKA-Mid). The combination of resolution and sensitivity allows the array to address a wide range of science from star and planet formation, galaxy evolution, AGN, extreme environments around compact objects and gravitational wave sources, dark matter and fundamental physics. The instigation of several large Legacy Survey projects has greatly expanded the UK and international user base of the facility. Recent developments in pipeline software are speeding up the delivery of data products to users. The science, techniques and technology that e-MERLIN delivers are seen as key pathfinders in the run up to SKA-Mid and strategically important in preparing a large UK community for exploiting that flagship facility. Future upgrades will see the early adoption of the SKA Science Data Processor (SDP) software to further aid UK preparation. At a cost of £2.5M per year, e-MERLIN is a major facility for STFC. As concluded in the recent Radio Astronomy Strategic Review conducted by STFC, e-MERLIN is delivering excellent science and is a high priority for at least the next 5 years and will be reviewed again in 2021. A reduction in funding below that required to run this UK-based facility would result in its closure and cut off access of the UK community to high resolution cm-wave science and important pathfinder for SKA-Mid. **For scientific excellence this was rated Alpha 3.5. For impact this was rated 3.5.**

LOFAR

The Low Frequency Array (LOFAR) is the European low radio frequency (30-240 MHz) telescope based mainly in, and led by, the Netherlands. It has international stations is several European countries including the UK station at Chilbolton providing long baselines (1000 km) and sub-arcsecond resolution. A large consortium of UK universities (LOFAR-UK) provided the capital costs for the Chilbolton station, whilst STFC contributes the running costs of the station at £260k per year. The UK has good leadership in Key Science Projects (KSP) in the areas of surveys, transients/pulsars, magnetism and solar observations. The sky survey KSP addresses areas such as AGN, galaxy evolution and cosmology and there is synergy with complementary WEAVE-LOFAR survey for optical spectroscopy. The KSPs have also brought in a large user base in the UK. The UK has contributed to the calibration of the international baselines. With its all-digital operation, LOFAR, along with the Murchison Widefield Array (MWA) in Australia, is a key pathfinder for SKA low frequency array (SKA-Low) both in terms of science, technology and data processing. LOFAR has a phased programme of upgrades (LOFAR2.0) with funding already secured in the Netherlands that will initially improve the correlator and electronics and enable greater efficiency and sensitivity. LOFAR-UK will bid for a one-off injection of around £350k in 2020. The recent Radio Astronomy Strategic Review concluded that the UK's involvement in LOFAR represented excellent value for money and was its highest priority in the run up to the SKA, including the LOFAR2.0 upgrade. A reduction in funding below that required to run the Chilbolton international station would cut-off access of the UK community to high resolution low frequency science and this important pathfinder for SKA-Low. **For scientific excellence this was rated Alpha 3.5. For impact this was rated 3.0.**

JCMT

After the STFC withdrew its major role on the Hawaiian island site a consortium of 18 UK universities contributed to the continued operations of the 15 m sub-millimetre observatory, which is now owned and mainly operated by the East Asian Observatories collaboration. The James Clerk Maxwell Telescope (JCMT) is primarily used for surveys addressing problems in star formation, galaxy evolution and cosmology. There continues to be a significant UK user base and UK astronomers continue to play leading roles in the new generation of surveys being conducted with East Asian partners and in bidding for open time enabled by the STFC's matched contribution of £250k per year. A bid is expected in the range £0.5-1M for a UK group to develop a new camera based on KIDS technology for the JCMT. These cameras are already operating at millimetre wavelengths on the 30 m IRAM telescope and will soon be installed on the 50 m LMT. A reduction in funding would reduce access for the UK community to the single-dish sub-millimetre capability that the JCMT provides. **For scientific excellence this was rated Alpha 3.0. For impact this was rated 3.5.**

JIVE

JIVE is the Joint Institute for VLBI (Very Long Baseline Interferometry) ERIC (European Research Infrastructure Consortium). It is an international organisation hosted in the Netherlands that runs the European VLBI Network (EVN) of telescopes and runs the data processing. The UK has always been a member of JIVE and contributes some of the e-MERLIN telescopes to the EVN network, which mainly operates from 1-25 GHz over 1000 km (European) and 10 000 km (to Asia and Africa) baselines. The milli-arcsecond resolution delivered enables kinematic and parallax studies as well as imaging and is used to address questions in star formation and evolution, AGN, and with the development of real-time VLBI, energetic transient events. The routine integration of the full array of e-MERLIN telescopes in to the ~45 days of EVN operations per year is currently being implemented. This greatly improves the imaging fidelity of the array that was already the most sensitive VLBI array in the world. STFC currently contributes £175k per year to JIVE. Although the UK VLBI community is small, JIVE makes an important contribution and is seen as good value for money as also concluded by the Radio Astronomy Strategic Review. A reduction in funding below the required international subscription would reduce the UK's access to the milli-arcsecond resolution astronomy enabled by VLBI. Given the common longitudes of the EVN telescopes with SKA-Mid, cases are being developed to make use of the large sensitivity gain for VLBI when SKA-Mid operates in simultaneous VLBI-mode. **For scientific excellence this was rated Alpha 3.0. For impact this was rated 2.5.**

SKA

The Square Kilometre Array (SKA) is the world's next generation radio observatory and a flagship project for STFC. It will consist of two telescopes: SKA-Low in Australia operating at 50-350 MHz over 65 km baselines and SKA-Mid in South Africa covering 350 MHz to 15 GHz over 150 km baselines. It will address the full range of astrophysical questions including cosmology, galaxy evolution, extreme environments, planet formation and fundamental physics. The high resolution of SKA-Mid has good synergy with ALMA and the ELT. The UK plays a major role in the SKA with the STFC currently contributing £4M per year to UK design work on both SKA-Low and SKA-Mid and another £2.4M per year to running the global HQ at Jodrell Bank. The UK has leading roles in many of the international design consortia as well as a high proportion of chairs and active members in the Science Working Groups that are preparing for SKA Key Science Projects (KSPs). Early science will focus on large surveys via KSPs and preparation for those is a high priority as highlighted by the Radio Astronomy Strategic Review. It is anticipated that a large fraction of UK groups will utilize SKA data once fully operational. Familiarization of the community with the techniques and SKA SDP software will be important in this regard. UK contributions from within the approved BEIS funding will increase as construction begins and level off at around £11M per year during operations around 2027. Funding is also likely to be required for an SKA Regional Data Centre in the UK along similar lines to the ALMA Regional Centre. **For scientific excellence this was rated Alpha 5.0. For impact this was rated 4.0.**

Where we have been able to gain sufficient information we can confirm that all of STFC's projects are world leading and of high scientific value.

5.2 Additional areas of relevance

The panel has also been asked to examine two areas of relevance to both the Astronomy and the Particle Astrophysics areas:

The CMB area

Research in the Cosmic Microwave Background (CMB) has a long tradition in the UK. The continued development of THz detectors is thought world leading and attracted significant grant funding over recent years. The CMB community has had significant roles in some of the highest profile projects e.g. ESA's Planck. Investment in the US-led Simon's Observatory has been proposed as a priority project to STFC and was submitted to the BEIS Fund for International Collaboration (FIC) and more recently to Science Board.

Ground-based gamma ray astronomy

UK interest in this area has diminished over recent years – which could be due to a lack of access to a competitive instrument and loss of key academics. However, STFC has been part funding a study of the Cherenkov Telescope Array (CTA) and a consortium is proposing to supply instrumentation to the project enabling UK entry to the project. We are unable to comment as to whether this strategy will stimulate a community as we are not aware of any STFC funded research activity in this area beyond the small level of investment provided under Particle Astrophysics.

This examination was by no means complete but served to identify the historical impact of these areas within the AGP.

5.3 The STFC Priority Projects - Emerging opportunities

In response to a number of new capital funding opportunities, STFC advisory panels were requested to put forward a number of concepts as part of the Priority Projects exercise. In total 76 'projects' were submitted to the AAP (x47) and SSAP (x29) of which 10 were shortlisted for further investigation within STFC and potential UKRI sources of funding. The panel noted that the exercise showed that the community was still very vibrant and brimming with good ideas for new projects. In uncertain times there may well be a good opportunity to obtain additional capital funds for the community and that was welcomed by the panel.

We would endorse the shortlisted priority projects given that they have been studied and recommended by the advisory panels. However, we note that these projects have not been tensioned against the rest of the programme and would advise against their adoption unless new (and full) funding becomes available. Most of the priority projects are indeed actively seeking sources of funding other than the core STFC budget. For example, the Simons Observatory has been submitted to the UKRI Fund for International Collaboration.

The panel noted that this particular process of selecting these priority projects was a one off, connected with the desire of the newly appointed CEO of STFC to have a set of project ideas ready to exploit any sources of new capital funding which may become available. This meant that the application and review process was compressed and not subject to the usual levels of scrutiny that would be expected. However, if funding for any of these projects does materialise, then the applicants will be invited to submit a full proposal for detailed technical examination by the Project Peer Review Panel (PPRP). We emphasize that although these projects were mainly for capital programmes, they will of course have associated operation and exploitation costs. These costs must be spelled out and either provided by the new source of funding or tensioned with the rest of the programme.

The Panel noted that it is the role of AAP and SSAP to carry out horizon scanning and that this should be a continuous process. This means that the list of current STFC Priority Projects should be a live document. The actual process to solicit, review and tension new projects needs to be looked at by STFC with input from the advisory panels and the community.

Recommendation 10: Advisory Panels cannot carry out this exercise in such a short timeframe. This should be an ongoing exercise with projects on the list reviewed as new ones are considered. Process for horizon scanning and associated review processes should be discussed with the community, possibly at NAM. We encourage the advisory panels to be more fully engaged with the community.

5.4 Funding the STFC Programme

Figures 3 and 4 show the planned 6-year projection of the STFC Astronomy Budget. The drop in budget from 18/19 to 19/20 is due to a number of long term instrument development commitments coming to an end (WEAVE, DKIST, HARPS3) and the reduction of the SKA pre-construction allocation from £8M p.a. to £4M p.a. Within this funding envelope, approximately £30M is earmarked for science exploitation via the grants line, with the rest for operations and development. It is worth noting that beyond the current year, funding levels are within a flat cash model.

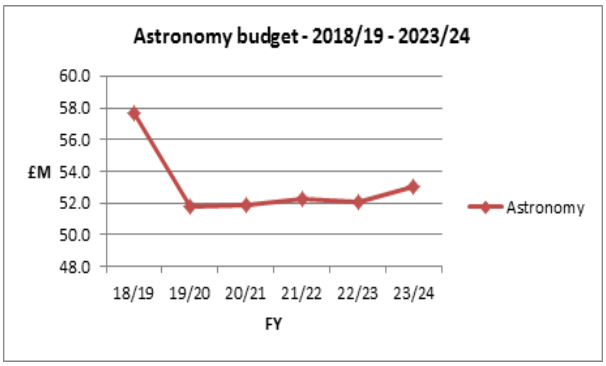

Figure 3: Six-year projection of the STFC Astronomy Programme budget. Post 2019/20 is indicative and dependent on outcome of the CSR.

Note: funds for the construction and operation of the SKA are provided separately by BEIS and not included in the above plan. Funds for the ELT subscription and development all derive from within the STFC core.

Figure 4 shows the breakdown of the budget into exploitation, developments and operations.

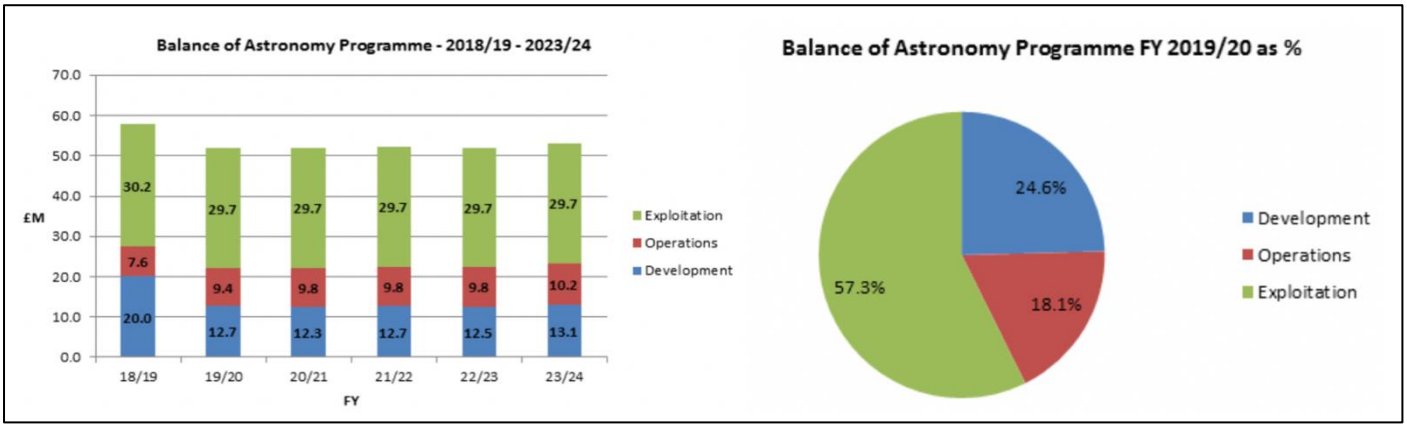

Figure 4: The left panel shows the breakdown of the astronomy budget into exploitation/development/operations and indicative projection over the next 5-year period (note this assumes a flat cash settlement in the 2019 comprehensive spending review). The right panel shows a different visualization of the spend in this financial year.

The breakdown of project funding from the development budget over the next five years is shown in Figure 55 below. The budget is dominated by the ELT and SKA lines which stretch beyond this period. Due to a number of programmes coming to an end, there is headroom for new developments starting at a low level in the current year. The allocation of such funds would need to be carefully considered in light of the squeezed AGP.

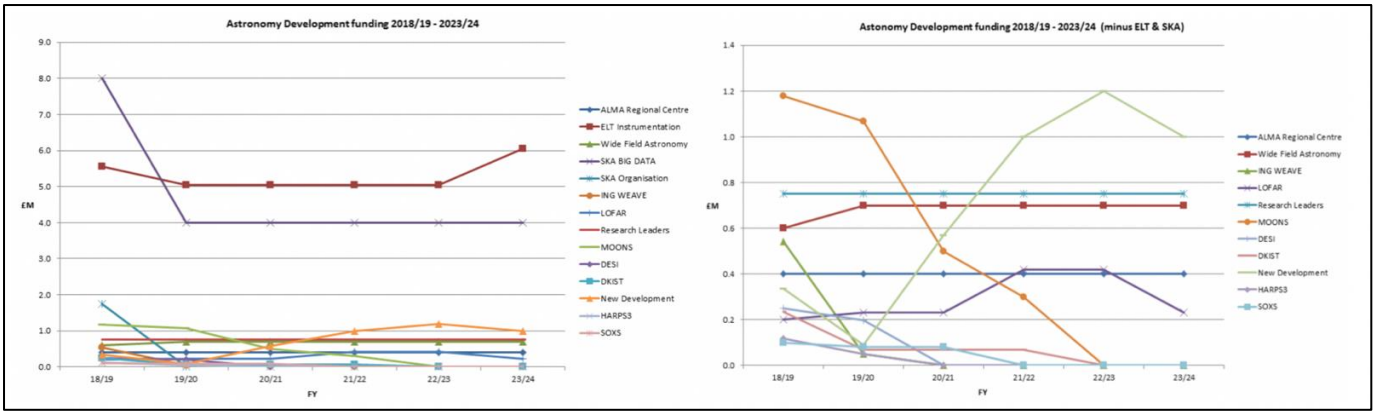

Figure 5: Breakdown of the development budget and its projected changes over the next 5-years. The left panel shows all projects while that on the right is the same but with the ELT and SKA lines removed for clarity. The projection assumes a flat cash settlement during this period.

Figure 6 shows the breakdown in operations funding over the next 5-years. The largest contribution during this period is the e-MERLIN facility.

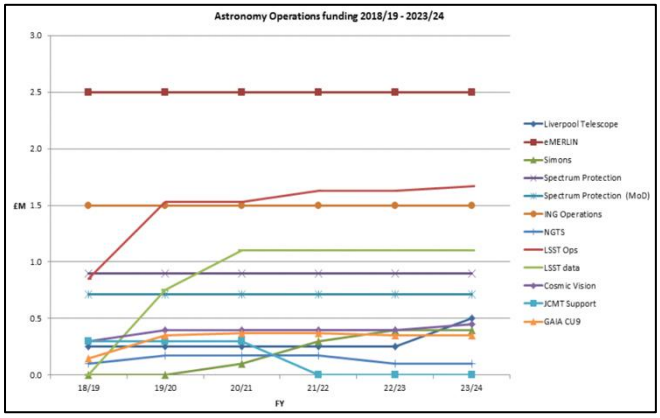

Figure 6: Expected breakdown of the Operations budget over the next 5-year period. During this period neither the ELT or SKA are operational.

6. Future funding scenarios

Within this exercise, we have been asked to make recommendations for the next five years based on flat cash or ±10% funding scenarios. The following does not take into account the potential impact that leaving the EU would have on the funding envelope, other than to note that it would *dramatically change* our assessment. The contribution of EU/ERC funding to the current programme is discussed in Section 3.1.1.

6.1 Flat cash

If faced with a continued flat-cash scenario for the next 5-years, protecting the grants-line is the highest priority – a view further echoed by both advisory panels (and by most reviews over the last decade). This is needed in order to preserve the breadth of the current programme, while still enabling a meaningful level of involvement in large projects. Naturally, this, along with increases in university overheads, FTE and FEC, would continue to squeeze the grants line further in real-terms. Given that a significant fraction of grants graded as internationally leading have been unfunded over recent years in the flat cash regime, its continuation would surely lead to a further erosion in the number of such projects that could be funded.

As noted in 3.3, in the AAP's community consultation exercise, 36% of the 293 respondents replied that, under continued flat cash, the exploitation line should be increased at the expense of either the development or operations line (or both). One potential way of mitigating against the continuing pressure on the grants line would be to tap into the funds becoming available as small projects come to a natural end over the next few years.

However, while this would enable the grants line to run above flat cash this amounts to a freeze on development and is only sustainable over a short term before future opportunities become limited/compromised.

6.2 A 10% cut in budget

A 10% cut would lead to a ~£5.1M cut across the astronomy programme per annum relative to current levels. Under such a funding scenario, the equivalent impact on the community and UK-standing can be illustrated by 3 broad 'boundary-conditions' dependent on where the cut falls:

1) Cut the grants line. A £5.1M annual cut represents a ~19% cut to science exploitation. Taking the last AGP round as a baseline and distributing this percentage cut uniformly, this would be the equivalent of cutting 13.2 FTE of the 76 FTE of PDRA/technical time awarded and reducing the number of academic applicants receiving investigator time to 88 (from 104 out of 256 applicants), or to only 1/3 of applicants. This would further limit the ability of the AGP to support the best research in the UK and, over the 3-year funding cycle, would lead to the loss of some ~40 PDRA/technicians plus FEC support to ~50 academic staff across the programme. This is the equivalent of closing a major Physics department within the UK and, alone, such an action would send a significant negative message about the UK's future capability to compete in STEM related subject areas. Further internationally leading research would be lost.

2) Cut the development and operations line, adopting a bottom-up approach. Under this scenario, activities supporting large facilities such as the ELT and SKA would be protected, at the expense of 'smaller' facilities that often involve a relatively small consortia of UK Institutes but are focused on problems not addressable by large facilities. Adopting such an approach, however, would mean decimating a large number of projects, since almost all but the most major facilities would be impacted to make the required savings[4]. While some UK institutes may step in to maintain some level of operational support to some of these facilities, the reputational damage to the UK and STFC would likely lead to future lowered levels of leverage from universities due to lack of trust. This would also severely damage the breadth of the Astronomy programme, as well as the technological development and building capabilities within the UK. It should be noted that even if a cut was subsequently reversed, the loss of capacity and expertise within the community would impact the ability of the UK to take meaningful roles in future projects and facilities for a significant time thereafter.

3) Cut the UK contribution to a significant international project completely. This would cause significant and immediate reputational damage to the UK, and again adversely impact on the UK technology and instrumentation sector. Ultimately, the confidence of international partners in the UK community's ability to deliver would suffer long-term damage.

***Recommendation 11: Given the potential impact a 10% cut would have on the programme and/or the UK's international standing at such a crucial period of time, STFC would need to set up a specific panel tasked with its implementation and it will need to be given a clear remit. Matters such as the timings of programmes/projects, decision points, as well as the potential loss of geo-returns and the impact on the UK technology sector, would have to be analysed and informed by relevant information at the time*.**

6.3 A 10% increase in budget

In the event that there is an uplift, this should be re-invested into the science exploitation line. Given the large number of highly rated projects that are currently unfunded, this would result in no reduction in the quality of the funded projects. This is also the resounding message that came from the AAP/SSAP community consultations. The

[4] Depending on when savings are required to take affect we note that in the development budget, a number of projects are naturally coming to an end over the next few years and that as much as £1M/yr will be uncommitted (see Figure 5).

UK community feels that they are not able to capitalise on the investment in ESO, ESA and other major facilities due to the lack of funding for exploitation.

One aspect that was raised in that consultation is the problem where, after the capital phase, UK scientists do not have the resources needed to lead exploitation of major international projects. Addressing this issue would imply prioritising funding of particular areas linked to these major facilities – a proposal that is strongly resisted by the community (which decisively favours the current model of funding based on scientific excellence only). In the event of an uplift to the grants line, one approach could be to adopt a hybrid model where a proportion of the new resource could be flexibly called on to support pump-priming the exploitation of such high-priority facilities and the planetary and space science themes of UKSA and STFC for a time-limited duration. Whether this new resource would be sufficient to make a meaningful contribution to solving this issue, and could be implemented in a way that would benefit the community, would need to be more closely scrutinised.

7. Computing Resources

In addition to ground and space based facilities, high performance computing is an essential resource for much of the Astronomy community for both computational modelling and the processing/analysing of large (observational) datasets. This panel was not tasked with a full review of computing facilities but given the essential nature of HPC to modern-day astronomy, the panel wishes to highlight some issues related both to infrastructure and skills pipeline/career structure for e.g. data scientists.

7.1 DiRAC

STFC high-performance computing (HPC) infrastructure has been provided in the form of DiRAC. The current incarnation (DiRAC2.5) is an interim upgrade of DiRAC2 rather than a full uplift to DiRAC3. In fact, given the long delay to the required upgrade to DiRAC3, this potential upgrade would now fall substantially short of the community's requirements and comparable facilities available to our international competitors.

DiRAC time allocation falls far short (less than half) of what is applied for. This risks that projects funded by e.g. AGP will not run in a timely manner (or at all) if the necessary computing time cannot be obtained. In addition, at least 2-3 times as much (as being run on DiRAC) is being run on non-DiRAC HPC facilities (either local facilities or abroad, as in-kind support or favours). Hence, there is considerably more science relying on HPC than that being supported by DiRAC. However, this support is ad hoc and cannot be relied upon by STFC.

7.2 Hardware Infrastructure

In addition to the traditional HPC used for computational modelling, data processing for astronomical experiments is moving towards much larger data sets, requiring facilities which are no longer sustainable at a local, institutional level or what can be funded from a single astronomy group's CG support.

Recommendation 12: Large-scale computing is an integral part of modern-day astronomy, both for modelling and data analysis and should be funded as such. Large-scale computing needs a substantial uplift if we are to retain (or regain!) our international competitiveness as current provision is a long way below requirement. Support would have to be multi-tiered with local, regional and national facilities. Such a multi-scale structure would allow the most efficient use of computing facilities at each level. Hardware infrastructure needs to be accompanied by sufficient staff provision to give local support e.g. for data access issues, software compatibility etc. In addition, the Panel strongly recommends that STFC continues and preferably increases its support for DIRAC.

7.3 Skills Pipeline/Career development

Issues with computing provision go significantly beyond the availability of national hardware infrastructure. There is little or no career structure for academic computing. Those specialising in creating and, crucially, supporting the software that is used widely within the community are usually funded on grants as research assistants, rather than having permanent (academic) positions because these positions do not generally lead to a publication profile appropriate for a permanent university position in the UK. Even then, there are very few such research assistants that have remained in the field for a sufficient length of time that any key software can be supported by them in the long-term.

As an example, TOPCAT is a widely used astronomy software package with a worldwide user base. It is the de-facto standard interface used to explore, manipulate and portray large astronomical catalogues across most or all observational subfields in the discipline. It is written and supported by a single PDRA. All development history and understanding of its architecture are embodied in this individual - there is no-one to straightforwardly take over the development and support of the software in their absence. Its development and the PDRA are funded mainly by the consolidated grant of a single research group. Its vital nature to the wide community is illustrated by its adoption by the GAIA mission as the standard interface to manipulate its catalogues. A specific adaptation to maximally exploit the GAIA data set has been funded through part of a recent project grant to the UK GAIA project (work that was seen as crucial by the PPRP). Had the general TOPCAT work not been continuously funded though previous consolidated and other grants (only one failure could have brought about the end of its support), there would have been no supported software for GAIA to adapt and use.

With the advent of key projects and facilities such as LSST, Euclid, PLATO, SKA and others, astronomy has truly entered the era of "Big Data" and the community's need for well-supported analysis tools will significantly increase. The dawning of this era is reflected in STFC policy through the recently funded Doctoral Training Centres which will generate a cohort of astronomers with the required software skills to exploit the data sets. However, without a subsequent coherent career path for those that are needed to specialise in astronomical software design and support, the investment in DTCs will not result in the creation of long-term supported software tools that will facilitate the optimal (and cost-effective) exploitation of these expensive facilities. Without adequate funding for the development of these tools, creating and supporting them will not appear to be an attractive career option for those with the skills to do so.

The funded DTCs have fostered the beginning of a mutually beneficial relationship between the astronomy community and industry in training and exploitation of Big Data expertise. However, without this DTC training being seen as part of a larger picture within the discipline, it is unlikely that this kind of relationship can be leveraged into something that can bring larger long-term academic and economic benefits to both sides.

Recommendation 13: There is a growing need for more money to fund data and analysis needs that go hand in hand with being part of "Big Data" facilities such as LSST and SKA. This plan needs to be put in place early.

Recommendation 14: A clear career structure for astronomical software engineers should be established.

Recommendation 15: STFC should look at ways to increase training and interaction with industry.

8. Other Funding streams

GCRF:

Astronomy projects have obtained 59% of the awards funded under the STFC GCRF foundation awards. These projects accounted for 67% of the allocated funding. The projects funded include “Astro-ecology: the solution from the skies to save Earth's biodiversity”, “The Development through Radio Astronomy Global Network” and “Applying Astronomy Capability to Map an Invasive Weed: Leveraging Satellite Surveys to Inform "Famine Weed" Policy in Pakistan”.

NEWTON:

Whilst there is no cross-discipline analysis of the Newton fund, there have been a number of Newton programmes/projects funded that are astronomy-related that have resulted in receiving significant funding e.g. DARA (Radio astronomy). Two funding calls with NARIT in Thailand on Capacity Building in Software and Hardware Infrastructures and Data Handling through Astronomy led to the funding of a further 12 projects. There are also astronomy projects in Mexico, Chile and Timor that are currently active and it is likely that there will be one astronomy-related project with Malaysia announced soon.

Recommendation 16: STFC should ensure that for all non-standard funding schemes a transparent list of funding routes/schemes with dates, criteria, funding limits should be produced for the community.

Appendix 1

Ranking Scoresheet for Programme Evaluations 2018/19

During the 2017/18 Programme Evaluations, projects/experiments/facilities within each discipline will be ranked. The ranking criteria will cover scientific excellence, exploitation within grants, and impact/industrial engagement. The exercise will look at all funded projects/experiments/facilities and ensure each is considered at whatever its stage of the exploitation cycle.

The panels will consider the merits or otherwise of supporting areas currently receiving STFC investment. This will include consideration of international engagement and subscriptions.

The ranking criteria will be largely based on that previously used by STFC, namely **α** rankings for projects/experiments and "g" rankings for science exploitation themes within grants as used in the last Programmatic Review. In addition a new "i" ranking will be introduced to cover evaluation of impact for the economy and society.

The Panel will be asked to consider the strategic value of the projects/experiments/ facilities that submitted proformas and how highly aligned they are to the mission of STFC. Consideration should also be given to the international standing and the potential for leadership of the area under review. Additional value, such as synergies within the STFC frontier science disciplines (Particle Physics, Astronomy, Nuclear Physics, Particle Astrophysics, Computing, Accelerators) programme should also be taken into account.
The Panel will be asked to score each of the projects/experiments/facilities on the following criteria and submitted 2 days before the meeting.

The Panel member should complete section 1 and 4 below for each proforma. A marking should be given for either section 2 or 3 dependent on which is most appropriate.

The below wording is generic for the six evaluations and may be slightly modified to suit the specific requirements of the individual reviews.

1. **What is the life cycle stage of the Project/Experiment/Facility?**

Early / Developing / Mature

2. **Scientific Excellence of Project/Proposal**

α5 - Highly innovative and very likely to result in seminal changes in knowledge.
α4 - Likely to substantially advance the subject.
α3 - Likely to make an important contribution to the subject.
α2 - Competent, worthy science.
α1 - Interesting science but outcomes considered doubtful.
β - Poor quality, flawed or unlikely to deliver meaningful or interesting results.

3. **Exploitation**

Projects in the science exploitation phase are funded via grant panels. Three categories are defined, intended as strategic guidance to the peer review carried out by grant panels. Please consider the value of exploitation when the area under evaluation reaches maturity.

g3 - A project with high strategic importance in the STFC programme, which has received substantial investment. We would expect to see it adequately funded via grants after peer review
g2 - A project with high potential for excellent science which should be considered via peer review
g1 - A project which is not well matched to the STFC programme, we would be surprised if it were to receive funding via the grants panel.

4. **Impact and Engagement**

Please consider if there is important impact within industry and/or wider society that STFC should be looking to exploit and that will otherwise not happen elsewhere.

i5 - Very exciting impact already under IP management or a close working partnership or exchange with non-academic partners is already in place.
i4 - Very exciting opportunities proposed, with some first connections made.
i3 - Interesting opportunities suggested but needs significant further work.
i2 - Little opportunity, although some could evolve in near future.
i1 - Little opportunity and unlikely to develop significantly in near future.
i0 - No apparent opportunities at all.