The background of the cover is a vibrant, multi-colored astronomical image. It features a central bright region with a rainbow-like gradient from red to green. From this center, numerous thin, parallel lines radiate outwards, creating a fan-like effect. The lines are colored in a spectrum from red to green. The background is filled with various celestial objects, including galaxies, star clusters, and individual stars, all set against a dark, starry sky.

# Astronomy Advisory Panel Report for STFC Programmatic Review October 2012

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# STFC Astronomy Advisory Panel

## 2012 Programmatic Review report to PPAN (October 2012)

### Executive summary

This document provides a roadmap for UK astronomy and provides advice for future science and facility prioritisation as requested for the 2012–13 STFC programmatic review. In formulating our advice we have consulted the UK astronomical community, considered the current plans for UK expenditure on astronomy by both STFC and the UK Space Agency (UKSA) and have examined how UK astronomy fits into an international context.

Following the 2009–10 prioritisation exercise STFC faced some very difficult choices given a highly constrained budget combined with on-going commitments. Based on the community's stated desire to maintain the exploitation grant line and to enable investment in the 40-m class ESO E-ELT optical/IR telescope and the SKA radio telescope, the current astronomy spending plan could effectively lead to withdrawal from virtually all non-ESO or SKA facilities and prevent any major non-E-ELT/SKA technology development. Such an outcome would result in a dramatic reduction in the diversity of astronomy facilities historically available to UK astronomers and hence a corresponding loss of science leadership. The current STFC astronomy plan was formulated while another key restructuring was taking place, namely the formation of the UKSA which has taken over responsibility for the construction and operation of space-based astronomy facilities. The UK astronomy community was unable to respond adequately to these changes until the provision of the recently reformed advisory panels and now welcomes the opportunity to submit advice to the 2012–13 STFC programmatic review. The advice we present also contains comments relevant to UKSA; an organization facing similar budgetary constraints.

UK astronomy is currently the most successful area of UK physics, a success due to past investment and a desire to enable excellence to flourish whatever the scale of the facility. Indeed the UK astronomy success has been due in large part to diversity in facilities coupled with innovative technology. Our primary conclusion is that the current plan for a reduction in STFC astronomy expenditure will not maintain this success as it will lead to a harmful imbalance in the diversity of astronomy facilities available to UK astronomers, which in turn will result in the UK falling behind our international partners. These partners are seeking to maintain diversity so as to maximize their scientific return from E-ELT and SKA. Without action we will:

- a) dramatically increase the risk that we will fail to answer the key questions in astronomy using both current and future investments;
- b) reduce our ability to be technologically innovative and hence gain PI instrument status;
- c) provide reduced training opportunities and demotivate the next generation of scientists; and
- d) weaken our ability to attract young people into STEM subjects.

We identify seven science themes that are critical for the future of UK astronomy. We explain how these science priorities drive facility choices in the event of an increased budget, the current plan and an even more reduced budget. **We stress that if the current budget plan (or even less) is carried through, UK astronomy will be unable to carry out all of its science priorities. We could find ourselves unable to maintain our leadership in many areas, including sub-mm astronomy, radio astronomy, time-domain astronomy, large spectroscopic surveys and exoplanet research. We therefore argue strongly for a modest increase in funding in order to deliver what we consider to be a world-class science programme.**

The UK astronomy community is well aware that change is both inevitable and required; there must be an evolution from current facilities to new, but we request that these changes be better planned during a transition period so as to maintain a diverse set of facilities and enable future innovation to leverage a better science

return. In these difficult economic times, planned change while continuing diversity will enable UK astronomy to achieve its science priorities, maintain its international competitiveness and continue to support the scientific goals of STFC.

## 1. Overview of UK astronomy

For the 2012–13 STFC programmatic review the AAP were tasked with identifying the top scientific challenges for the future, reaching out 20–30 years, and to match the current/future programme to the STFC science roadmap. Any advice we provide should take into account the likely level of investment required and the available UK technological expertise. In order to achieve these lofty aims, the AAP began by considering the current state of UK astronomy and its place in an international context. The panel looked at past reports from the UK and elsewhere and the current plans for the STFC and UKSA astronomy programmes. We also considered the impact of UK astronomy and how it affects technology, education and the general standing of science in the UK – all core parts of the STFC remit.

The UK astronomy community is both large and internationally successful. It encompasses almost all areas of modern astronomy and astrophysics ranging from the study of the Sun and its interaction with the Earth to understanding the origin of the Universe. The study of such exotic phenomena lie at the heart of the STFC science vision and are among the most compelling areas of science for the general population. Astronomy is a vital area for attracting children into science, one of the major goals set by the government to ensure STEM subjects are popular at school and university to enable the knowledge economy. Even with the wealth of alternative sources of entertainment available, nearly four million people watched the 2012 “Stargazing Live” broadcasts from Jodrell Bank, while the National Space Centre in Leicester attracts 250,000 visitors a year, an extraordinary number for a specialist visitor attraction. Astronomy also drives technology and computing developments, as we seek to study the faintest sources of light known while dealing with enormous data rates from sky survey facilities.

To quote the International Astronomical Union strategic plan<sup>1</sup>, “Because astronomy combines science and technology with inspiration and excitement, it can play a unique role in facilitating education and capacity building and in furthering sustainable development throughout the world...A challenging science in itself, astronomy provides an exciting gateway into physics, chemistry, biology and mathematics. The need to study the faintest celestial objects has driven advanced developments in electronics, optics and information technology.” Such sentiments explain why developing countries such as China, India and South Africa are expanding their astronomy and space science activities, and our major European partners plan to maintain diversity while investing in future facilities. This is all happening while the UK is planning to reduce funding which will diminish our science leadership role and our ability to lead new instrument development.

Most of the UK astronomy community is based in university research groups who work closely with colleagues at STFC centres, overseas observational facilities and with various international space agencies. The current wide diversity in observational facilities is not an accident or a wasteful duplication but rather a requirement as no single organisation can provide access to the entire electromagnetic spectrum. Astronomy is a research field where both small and large facilities can be cutting-edge in terms of their impact on the subject<sup>2</sup>. Small groups or individuals can provide a facility which acts as a game-changer for a particular area. The recognition of this is why the UK has historically been a world leader by investing in observational facilities around the world whilst maintaining cutting-edge technology development programmes which have led to some of the most innovative instrumentation available. We have constructed observing facilities on the ground and in space which provide sensitive access to almost the entire electromagnetic spectrum and we are entering an era of non-photonic astronomy via gravitational waves and neutrinos – the multi-messenger era.

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<sup>1</sup> IAU report “Astronomy for the developing world, Strategic plan 2010-2020”

<sup>2</sup> Abt, H, 2012, ApJ, 144, 91 “Scientific efficiency of ground-based telescopes”

Past investment in astronomy has paid handsome dividends for the UK and we can truly claim to punch far above our weight.

To illustrate the success of astronomy in the UK we use the recent report by the Institute of Physics which benchmarked UK physics research using a bibliometric evaluation process<sup>3</sup>. The report includes a comparison (Figure 1) of how UK Physics compares to other comparator fields including what they call “Space Science”, which is equivalent in this context to UK astronomy as the 40 journals examined (taken from the Thomson Essential Science Indicators list) include all of the main astronomy and astrophysics journals. As can be seen from Figure 1, Space Science outperforms the rest of UK physics by a large (and increasing) margin in terms of share of research output. The normalized citation impact for Space Science tracks that of physics and both lie above the other research areas.

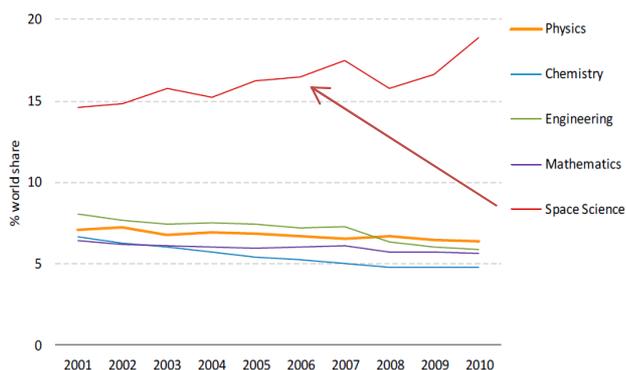


Figure 1: UK share of world papers in physics and comparator fields (2001-2010).

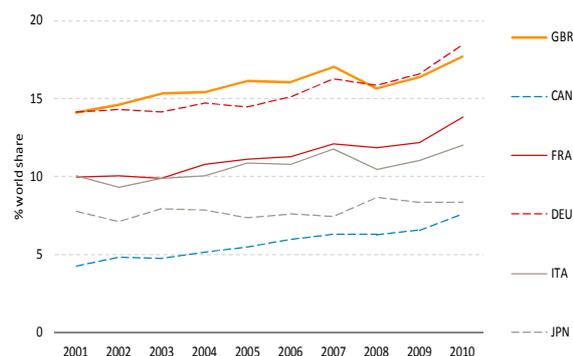


Figure 2: National share of world astronomy and astrophysics papers (2001-2010; USA not plotted).

The IoP report also considers “Astronomy and Astrophysics” (using almost the same list of astronomy journals as above) and compares the UK to the rest of the world (Figure 2). The USA (not shown) leads with 45.9% in 2010, closely followed by Germany (18.4%) and the UK (17.7%). The UK is ahead of both in normalized citation impact. These data and similar indicators, coupled with our current access to diverse observing facilities, show that the UK has maintained its role as the world’s second-ranked astronomy power despite growing competition from the BRIC countries. The UK community uses this success to leverage support from other sources, such as the EU (for 2008–12 the UK was the most successful country in obtaining astronomy ERC advanced grants), the Leverhulme Trust and the Royal Society. The EU success has helped partially to mitigate reductions in PDRA/studentship numbers but the success depends on UK access to facilities.

**We conclude that UK astronomy is the most successful area of UK physical science. This success is thanks to past investment by UK funding agencies, the efficient use of innovative facilities and the concerted efforts of generations of UK astronomers. The aim of this report is to recommend a strategy for UK astronomy to maintain that reputation and achieve its science priorities within the available budget constraints.**

In the rest of this report we give details of the community consultation process (Section 2), the current and future UK facilities and how they are matched to the highest priority science themes (Section 3), the need for technology development and high-performance computing (Section 4) and provide recommendations for various funding scenarios (Section 5).

<sup>3</sup> Bibliometric evaluation and international benchmarking of the UK’s physics research, IoP, January 2012; prepared for the IoP by Evidence, Thomson Reuters

## 2. Consultation process

The AAP consulted the UK astronomy community via a web-based form, a town meeting, by allowing submissions of cases for facility/technology support and by comments on the draft version of this report. Over 400 astronomers participated in this process nearly half of whom were not academics. We therefore believe we have received the views of a representative sample of the community. Here we only provide a brief summary of any key issues raised by the community in response to the specific questions set by the AAP on science, programmatics, facilities and technology.

*Science:* Overall the community appeared content with the general themes listed by the previous STFC advisory panels (NUAP and FUAP), although there were some comments on including more recent results and on overlap between themes. The ranking of individual questions within themes appeared to the AAP largely to reflect current interests so we have moderated that input to ensure a more forward-looking science portfolio. Many of the respondents noted the importance of high-performance computing (HPC) to the different science areas and the requirement for better coordination and communication between STFC and UKSA. The strongest comments were about the need to maintain diversity in facilities if the science goals are to be achieved. This is related to a more general feeling that some of the ‘newest’ areas are underfunded in UK (e.g. exoplanets) compared to the rest of the world.

*Programmatics:* The question of how the community views the balance of expenditure provided a mixed response. The strongest feeling was to increase or at least protect the (exploitation) grant line. There were also comments expressing dismay at the abolition of the postdoctoral fellowships, while the Rutherford fellowships were, if anything, thought to be too generously funded. There was a division of opinion on the relative spend between E-ELT and SKA versus the rest. As with the science responses, maintaining the exploitation grants, maintaining diversity and supporting HPC all ranked highly.

*Facilities:* The comments illustrated the strong, diverse community (a clear UK strength) as just about every facility that could be mentioned was! There was very strong support for remaining members of ESO but with some comments as regards the costs of various elements. Likewise good support exists for access to radio facilities, small telescopes, gravitational wave observatories, LSST and access to both hemispheres. Support for specialist facilities, e.g., MROI, SuperWASP/NGTS, and laboratory work also featured. Respondents noted the synergies between ground and space facilities with Swift, HST, JWST, Gaia, Herschel and Euclid all strongly supported together with a desire for a future exoplanet mission and a future X-ray mission. It was noted that the UKSA funding for bi-lateral missions is insufficient to provide a balanced portfolio.

*Technology:* The clear message was that UK technology is important as leading new technology results in the UK leading science projects. We need to look where the UK is strong and exploit that capability, e.g. E-ELT, SKA, multi-object spectrographs (MOS), detectors, X-ray, sub-mm, gravitational waves and HPC. Several comments were provided on the need to balance big, medium and blue-sky projects (i.e., diversity). It was recognized that we must ensure that our astronomy technology be used to encourage spin-off to industry and training and methodology in order to improve the funding case for astronomy and STFC in general.

The science themes outlined below and the facility recommendations given in this report reflect the views of the community moderated by the AAP’s knowledge of the STFC funding envelope.

## 3. Science priorities and facility requirements

In this section we summarize the key science priorities for UK astronomy under the following seven themes (which are not listed in priority order).

- Life in the Universe (Section 3.1)
- The formation of stars and planets in the Milky Way and other galaxies (Section 3.2)
- Stellar evolution and stellar populations (Section 3.3)
- The formation and evolution of galaxies (Section 3.4)
- The dark ages and first light (Section 3.5)

- Precision cosmology (Section 3.6)
- Extreme astrophysics (Section 3.7)

Within each theme we list the major open questions and provide a brief commentary. The key facilities and observational requirements are summarised at the end of each theme.

### 3.1 Life in the Universe

- What are the physical characteristics of exoplanet systems and how do they evolve?
- How did the solar system form and what can it tell us about other planetary systems?
- What are biomarkers and how can we detect them in planetary atmospheres?
- What is the frequency of habitable planets in the Universe?

It is less than 20 years since the discovery of a planet around a main sequence star. Since then the subject has undergone rapid development. The UK community was slow to engage with this new field, but initially through radial velocity surveys and dynamical simulations, and more recently through transit surveys and atmospheric modeling, the UK has developed world-leading programmes. The immediate goal of exoplanet research is an understanding of the formation and evolution of exoplanet systems, including full characterization of the host stars. This includes the search for biomarkers in the atmospheres of exoplanets. Ultimately, of course, the goal is to find and study Earth-like planets in the habitable zones of their stars – environments where life is possible. To reach our goals there are several milestones:

- a) Obtaining the planet population properties (both internal and atmospheric composition) and statistics in order to provide a powerful test of models of planet formation and evolution, required to understand their origin in general, that of habitable planets more particularly, and that of planet Earth especially. We are entering a time where comparative planetology is becoming possible.
- b) The detection and confirmation of habitable zone (HZ) transiting planets, including, in particular, terrestrial planets and Super-Earths with bright host stars. While difficult, the atmospheres of these planets could be studied via transmission spectroscopy.
- c) Direct imaging of nearby, young and bright, and then old and faint giant exoplanets and their spectroscopic examination. Eventually, imaging and spectroscopy of terrestrial planets.
- d) Studies of phenomena that lead to habitability and in particular examples of biomarkers. The examination of planetary spectra for biomarkers. Relevant to this topic is the sun-earth interaction (see the SSAP report).

While NASA's Kepler mission has had a major impact in some areas of exoplanets research, Kepler targets are usually too faint for detailed characterization or in most cases, even, confirmation. Consequently, while statistically we know the likely size distribution of planets (at least for those larger than Neptune), Kepler candidates cannot be used to derive a mass distribution. However, Kepler has shown us that multiple planet systems are relatively common and that Neptune sized objects (which could be ice-giants or large rocky planets or Super-Earths) are the most common types. Without accurate mass estimates we are still unable to say too much about the different composition types and their frequencies, but we do have tantalizing evidence of water/ice planets as well as Mercury-like bodies. While the UK is involved in Kepler candidate confirmation through the university funded HARPS-N collaboration, it is clear to further our aims of understanding planet composition and atmospheric structure/analysis much brighter host stars will be needed i.e. the CoRoT and Kepler stellar populations are too faint for the detailed examination necessary.

As we move towards the detection of HZ planets, understanding what influences habitability and signs of life (biomarkers) become pertinent topics. Simplistic arguments of habitability based on equilibrium temperature will need to be replaced by detailed understanding of planetary atmospheres, stellar activity cycles, planetary

system architectures and their interaction and biological processes. We may then begin to understand the uniqueness of our solar system and the prospects for ubiquity of life in the Universe.

The UK exoplanet community has developed rapidly over the last decade and has world leading projects in transit discovery and characterization (both optical and IR; SuperWASP, WFCAM), radial velocity (AAPS, HARPS-N), microlensing (the most efficient way to gather statistics on cool and low mass planets), planetary atmospheres and theoretical studies of atmospheres, composition, formation, dynamics and evolution. However, the relative youth of the community has meant that for projects that have a long lead time (eg space-based or VLT instrumentation) we have little penetration. For example, there was little UK involvement in CoRoT or Kepler planetary science, instead we have become involved through the follow-up of these surveys.

In addition the UK has a small, but leading asteroseismology community. One of the highlights from the Kepler mission has been the application of seismology techniques by UK groups to planet host stars which has allowed significantly improved accuracy in planetary physical parameters. Exoplanets, habitability and the search for life is perceived as one of the most exciting areas of modern science and is truly cross-disciplinary. Maybe this helps explain the insatiable public interest in this subject and astronomy in general<sup>4</sup>.

Key facilities and observational requirements:

- Access to current and planned instrumentation being used for confirmation and characterization eg ESO 3.6m/HARPS, HARPS-N, WHT, HST, VLT/ESPRESSO and microlens surveys.
- Survey capable of discovering small planets around bright stars. The Next Generation Transit Survey (NGTS) is a UK led, European collaboration (including ESO) under construction at Paranal. NGTS builds on the success of the world leading UK led SuperWASP experiment. This has levered participation in the ESA S-Mission CHEOPS needed for bulk composition analysis.
- Atmospheric characterization with VLT/E-ELT (HIRES), JWST, and other space missions (eg the ESA M3 candidate EChO or potentially a larger mission such as SPICA). E-ELT imaging with a second generation instrument.
- A HZ terrestrial planets discovery mission. Currently the only concept with this aim is the ESA M3 candidate PLATO.

### 3.2 The formation of stars and planets in the Milky Way and other galaxies

- What processes govern star formation in our own as well as in other galaxies?
- How does the formation of stars affect the structure of the interstellar medium and feedback?
- What processes control the formation of planetary systems and their habitability?

Stars form in a very wide range of environments: from hot metal-poor, UV and X-ray irradiated gas in galaxies at high redshifts to cold, dark, metal-rich cores in nearby molecular clouds. The stars produced span factors of more than  $10^3$  in mass and more than  $10^7$  in luminosity, in systems ranging from isolated sub-stellar mass brown dwarfs to superstar clusters with  $10^4$  massive stars in regions  $< 1$  pc in size. The goal of much of diffuse matter and star formation research is to obtain an understanding of the relationship between the diverse range of star forming environments, the physical processes involved, and the stars that are produced.

In order to achieve such goals we prioritize the following milestones.

- a) Characterization of the early stages of star formation: a central problem in star and planet formation concerns the precise properties of dense cores and the evolution of them to produce protostars and protoplanetary discs. The UK millimeter and sub-mm observational star-formation community is one of

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<sup>4</sup> A. Heward & R. Massey, "Finding the Real Media Stars: Analysis of Media Coverage of the UK's National Astronomy Meeting", in "Communicating Astronomy to the Public", Issue 4, pp. 5–11, August 2008

the strongest in the world. Its scientists interpret dust continuum emission and molecular line data (JCMT, Herschel and now ALMA data) to diagnose dense cores ranging from those that are starless to those containing young high mass stars. Key in the understanding and interpretation of observational data are i) astrochemical, ii) radiative transfer and iii) hydrodynamical models. Several UK groups have contributed greatly to the development of chemical and radiative transfer models (including measurements and computation of fundamental collisional and chemical data) which are routinely used worldwide to exploit diagnostic spectral line observations. In fact, the 2000 International Perceptions of UK Research in Physics and Astronomy report identified astrochemistry as an area ‘... where UK leadership is recognised.’ The UK has a strong record in numerical innovation in both smoothed particle hydrodynamics and adaptive mesh refinement techniques and dominates the world in theoretical and computational studies of the dynamics of protoplanetary discs.

- b) Star formation triggering and feedback: Triggering of high mass stars and their feedback control global, as well as local, properties of galaxies. Whether feedback is always negative during the births of spiral galaxies or can sometimes be positive, or why feedback can have such contrasting effects in different regions, and, finally, why star formation sometimes occurs quiescently are all questions that are central to UK science. Only once these questions are answered, can a physical prescription for the star formation rate in dynamical models be reliably constructed. The use of computational chemical, hydrodynamic and magnetohydrodynamic simulations, including a wide range of physics, from radiative transfer to cosmic-ray advection and diffusion, are required to identify how a multiphase interstellar medium is regulated and how its properties affect triggering and feedback.
- c) Star formation history of the Universe: the UK high production rate and leadership in star formation research has naturally led several UK groups to gear their efforts towards star formation in extragalactic environments. Detailed high spatial- and spectral-resolution radio, millimeter, sub-mm, and infrared studies from low to high redshift galaxies are necessary to probe the structures and kinematics of star forming regions and are essential if one wants to understand star formation as a function of redshift. Taking into account the UK and STFC investments in ALMA, star formation in extragalactic environments should be one of the top priorities in UK Astronomy.
- d) Formation and characterization of planets: the boom of discoveries in extrasolar planet detections in the last twenty years naturally make the study of planet formation and characterization one of the most important topic in Astronomy. Star formation can produce planets that lie in circumstellar habitable zones and possess chemical initial conditions that lead to life. Environmental conditions and the star formation process affects planet formation and key outstanding issues include the initial masses and sizes of discs, the role of self-gravity in driving early evolution, disc turbulence, the role of dead zones, the growth of solid bodies from meter to kilometer and larger sizes, and the influence of migration processes, planet-planet and star-planet interactions that determine the final planetary system architecture.

Key facilities and observational requirements:

- The major observational breakthroughs in this area are mainly via sub-mm and infrared spectral and spatial surveys as well as targeted observations using Herschel, JCMT and ALMA.
- Future facilities that are necessary to continue to produce new breakthroughs are ALMA, e-MERLIN, JWST, SPICA.
- HPC investment is required to maintain UK leadership in star and planet formation research.

### 3.3 Stellar evolution and stellar populations

- How do single and multiple star systems evolve?
- What is the stellar content and structure of the Milky Way and external galaxies?

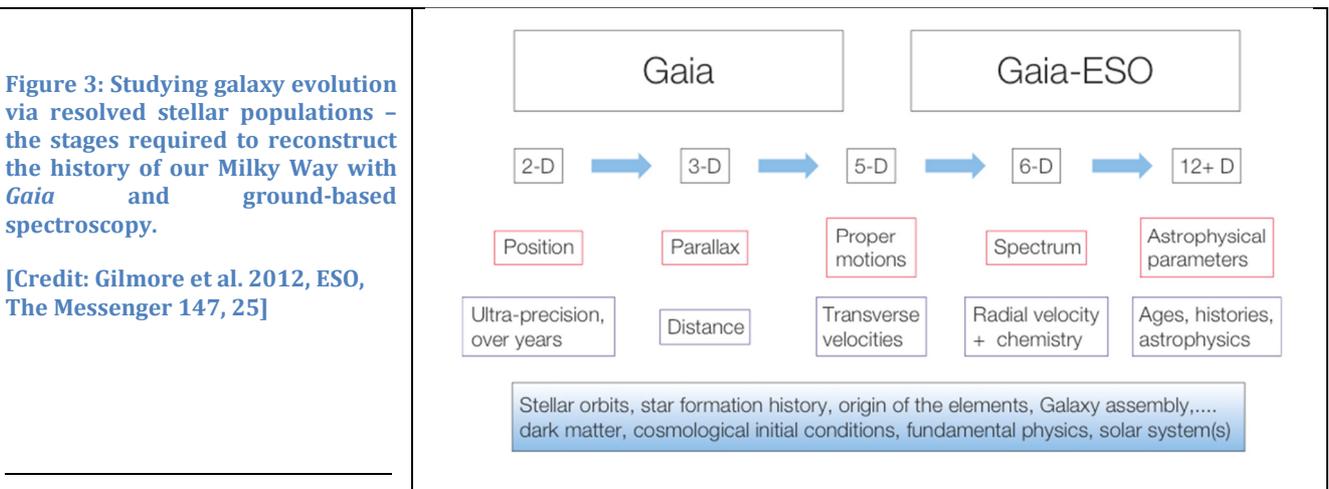
Our understanding of distant galaxies is only as good as our knowledge of the properties of their constituent stars. To characterise these unresolved populations we need a good handle on the physics and evolution of stars across their full mass range, from the cool, long-lived objects at the boundary of the sub-stellar regime,

up to the most massive stars and their dramatic, explosive deaths.

The UK is a world leader in stellar astrophysics<sup>7</sup>, with the interplay of observations and theory vital to refine our understanding of the processes at work in different types of stars. Armed with this understanding, we can then use them as diagnostic tracers to study the evolution of their host galaxies (both in the Milky Way and beyond) and to develop robust models of populations of stars to study the properties of even more distant galaxies (Section 3.4). Detailed knowledge of stellar atmospheres and stellar evolution also feeds into a wide range of other areas, e.g., interpretation of exoplanets (Section 3.1), where we need a good grasp of the characteristics of the host star. We also note the UK leadership in the observation and modelling of star clusters, from young massive clusters (location of the most massive stars) to ancient globulars.

One of the key future objectives is to arrive at secure predictions for the latter evolutionary stages of stars such as Supernovae (SNe)/Gamma-ray Bursts (GRBs) and AGB stars, which have a significant impact on their host galaxies via, e.g., mass loss, kinematic feedback, and dust production/destruction. Only then can we address the question of how feedback affects the evolution of galaxies. Moreover, a considerable challenge to our view of stellar evolution comes from the fact that a large fraction of stars are born in binary (or multiple) star systems. Mergers, interactions and mass transfer can lead to transient phenomena and directly influence the type of SNe explosion and end-state of the system, such as binary pulsars, cataclysmic variables, and white dwarf binaries. Indeed, with the latter thought to be the progenitors of type Ia SNe (and in light of the recent Nobel Prize for the discovery of accelerated expansion) it is worth noting that the nature of Ia SNe is still uncertain (e.g., whether the progenitors are single- or double-degenerate systems, and whether environment is a factor on their properties).

Once we have a handle on the behaviour of individual stars, resolved stellar populations will be a powerful tool with which to study galaxy evolution. The Milky Way provides a fantastic laboratory to study the formation and history of a large spiral galaxy directly. In the coming decade, 3D velocities and chemical abundances (from the Gaia mission and ground-based spectroscopy, as shown in Figure 3) will transform our understanding of the different populations of the Milky Way. This will provide essential information on Galactic structure, such as the accretion of dwarf galaxies and if there were major mergers in the past. In parallel, to address the question of how typical the Milky Way's history has been in the context of galaxy evolution, we have already begun exploring the broad range of galaxies beyond the Milky Way, both in the Local Group (M31, M33, metal-poor dwarfs) and beyond (Sculptor Group, Cen A, etc.). These efforts are already at the sensitivity limits of our capabilities, but the new facilities on the horizon will provide us with unrivalled insights into the histories of a diverse range of galaxies.



<sup>7</sup> As examples of UK excellence, we highlight leadership of both ESO Public Spectroscopic Surveys: the Gaia-ESO survey (300 nights at the VLT) and the Public ESO Spectroscopic Survey of Transient Objects (PESTO; 450 nights at ESO's La Silla Observatory). We also note the leading UK roles in large surveys of the Galactic Plane and Magellanic Clouds with VISTA/VST.

Key facilities and observational requirements:

- The ‘workhorses’ are optical and near-IR imaging and spectroscopic surveys (WHT, VLT, VISTA/VST, Gaia, HST, MOS spectroscopy, JWST, E-ELT).
- Multi-wavelength support (XMM-Newton, e-MERLIN, ALMA, Herschel, SPICA) is also required.
- Identification and follow-up of transients will likely grow in importance in the coming decade ( $\gamma$ -ray satellites, LSST).

### 3.4 The formation and evolution of galaxies

- How do galaxies form and evolve?
- What determines the typical properties of galaxies?
- Why are there so few stars in the Universe; where are the missing baryons?

Rapid advances in extragalactic astronomy are revealing an intricate picture of how galaxies form and evolve. At the same time, sophisticated numerical simulations are now able to place these observations in a cosmological context and to relate observations of galaxies to the growth of their dark matter haloes. We have gained an increasingly well-defined picture of how galaxies emerge from the near uniform state of the Universe at the end of re-ionization and the principle of feedback from stars and black hole in shaping the galaxy population has become well established. However, many fundamental problems remain unsolved due to the complex interplay between gravity, gas cooling and feedback from stars and black holes. While an outline theory is emerging, no theory currently explains all the observational data.

In the next decade, new observational facilities will revolutionise our view of galaxies, allowing us to probe the properties of galaxies to unprecedented depth, combining complementary techniques and wavelengths. An immediate goal is to expand our knowledge of the demographics of the galaxy population, in particular mapping out how the galaxy population (including the star formation and black hole accretion rates) evolves with redshift.

With our improving knowledge of the demographics of the galaxy and black hole populations, the questions shift from “how” the star formation rate and stellar mass density of the Universe evolves to the question of “why”. Increases in the size of optical telescopes, coupled to the development of multi-object integral field spectrographs and space-based imaging from JWST, Euclid and balloon-based missions such as HALO, will allow us to understand how the evolution of the global galaxy population is driven by changes in the internal structure, dynamics and star forming regions of young galaxies. These studies need to be complemented by far infrared observations of the molecular make up of external galaxies.

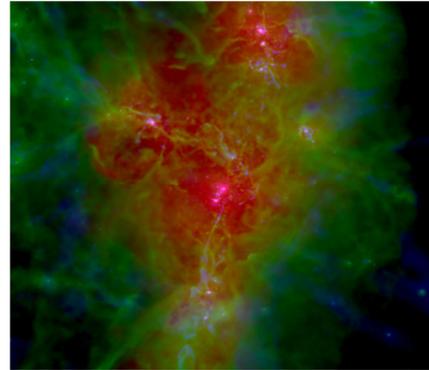
At the same time, advances in radio and sub-mm telescopes will make it practical to study the gas content of galaxies in detail across large galaxy samples, potentially obtaining data surpassing optical surveys of the present day. As a result, we are seeing a shift to studying galaxies as a complete system, treating the gas fuel reservoir on an equal footing to the stellar population. Our ability to measure the total bolometric output of galaxies with Herschel is proving of crucial importance. Construction of complementary high-redshift samples of galaxies will be led by SCUBA-2 and e-MERLIN initially. This lays the essential ground-work for subsequent follow-up with ALMA and JWST while, in the longer term, the SKA will provide HI based measurements of large samples of galaxies out into the distant Universe, simultaneously mapping both the global statistics of the galaxy population and the internal gas structure of galaxies. At the same time, Gaia observations of the stellar populations of the Milky-Way will allow us to uncover the formation history of our own galaxy and its satellites.

It is important to remember that 90% of the baryonic content of the Universe is not associated with galaxies, but resides in a tenuous distribution that traces the large-scale filamentary structure of the Universe. Despite its dominant contribution to the baryon mass budget, this gas is almost invisible. Yet it will become increasing the focus of observation and theoretical understanding. It has only recently become possible to

efficiently probe this gas through studies of absorption along QSO and stacked faint galaxy sight-lines, and through X-ray studies of galaxy groups and clusters (where the diffuse gas is sufficiently heated to be visible). In the longer term, a new high-throughput X-ray spectroscopic mission will make it possible to study the gas that is left behind by galaxy formation, providing orthogonal insight into the galaxy formation process. Combined with better treatment of radiative effects and metal diffusion in computer models, these studies will revolutionise our understanding of this key component, unlocking its thermal history.

**Figure 4: The formation of a small galaxy group in a cosmological simulation. Red, Green and Blue show the density of Hot ( $T > 10^{5.5}$  K), Warm ( $10^{4.5} < T < 10^{5.5}$  K) and Cold ( $T < 10^{4.5}$  K) gas. Stars are shown in pink. Less than 10% of the baryonic mass forms into stars in this simulation, which has been matched to the observable Universe.**

[Credit: VIRGO consortium/University of Durham]



Such observations will provide a snapshot of the galaxy population at different eras in the Universe. Improvements in theoretical models of galaxy formation will remain key to sewing the observations together. Numerical simulations are making rapid advances in the accuracy and fidelity of galaxy formation models thanks to developments in techniques and the growth in available computing power. However, the next generation of observations challenge the resolution that can be achieved in global cosmological simulations, and require the development of better treatments of the interstellar medium and global galaxy instabilities. This is on the threshold of what can be achieved with current simulation techniques. In a rapidly evolving field, we can foresee simulations routinely utilising 100,000 core machines to address these problems. In order to remain competitive in this key thread the UK must invest strongly in the next generation of HPC. The UK community has a very strong track record in galaxy formation studies, having produced some of the most influential papers of the last decade.

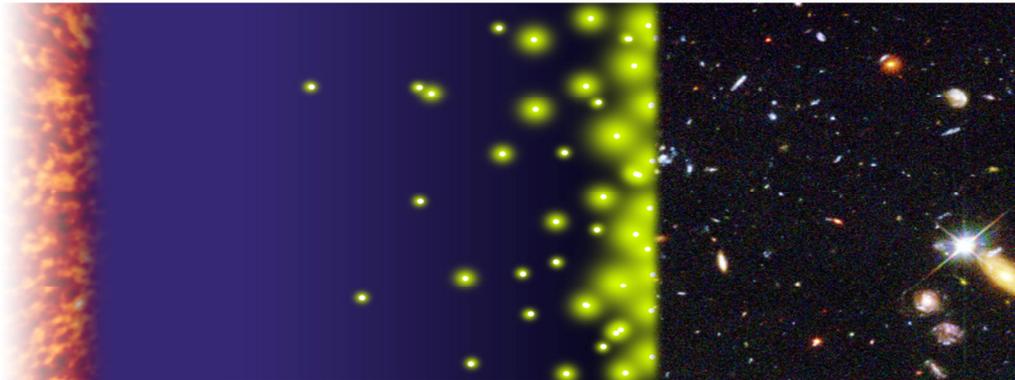
Key facilities and observational requirements:

- MOS to survey the galaxy population of the Universe and to optimise the galactic archaeology that can be undertaken with Gaia. Integral field spectrographs, such as VLT/KMOS, together with space-based imaging will be key to studying the internal properties of young galaxies.
- SCUBA-2 and e-MERLIN play a crucial role in the construction of high-redshift samples of dusty galaxies, laying the essential ground-work for subsequent follow-up with ALMA and JWST. In the longer term, the SKA will provide HI-based measurements of samples galaxies out into the distant Universe, simultaneously mapping both the global statistics of the galaxy population and the internal gas structure of galaxies.
- In the longer term, E-ELT will enable studies of galaxy evolution over all redshifts, for example it will allow higher signal sight-line measurements to fainter galaxies and quasars, greatly increasing the number of sampling points. A new high-throughput X-ray/E-UV spectroscopy mission is essential for revealing the bulk of this material. Finally, following on the Herschel legacy, a far-infrared instrument, such as SPICA, will be essential for spectroscopic studies of high-z galaxies.
- Numerical simulations are making rapid advances in the accuracy and fidelity of the models thanks to developments in techniques and the growth in available HPC power. In order to remain competitive in this key thread the UK must invest strongly in the next generation of high performance computing and in access to Europe's tier-zero network of the world's most powerful super-computers, PRACE.

### 3.5 The dark ages and first light

- How and when did the first stars, black holes and galaxies form?
- How and when did the Universe become re-ionized?

Observing and understanding the evolution of the Universe during the “dark ages” and the “epoch of reionization” is one of the great remaining frontiers of knowledge in astronomy. The dark ages encompass the period between recombination, approximately 400,000 years after the big bang, and re-ionization, thought to be complete by around 800 million years after the big bang (Figure 5). This is the least studied and least understood phase of cosmic evolution and offers perhaps the greatest potential for new discoveries in the future.



**Figure 5: The epoch of reionization describes the transition from a state where the baryonic content of the Universe is dominated by neutral atomic Hydrogen at early times (the “dark ages”, left-hand side) to the current state where the Hydrogen is fully ionized (right-hand side). This transformation is thought to be due to ionizing radiation from the first generation of stars and galaxies, here depicted as forming bubbles of ionized Hydrogen, which eventually merge, signaling the end of the reionization era. [Credit: S. Djorgovski et al. (Caltech) & Caltech Digital Media Centre]**

A key issue is the formation of the first stars, which were likely massive short-lived objects that rapidly enriched the surrounding gas, which subsequently formed into newer stars. Observationally, this must have happened by  $z \sim 7$  as we can observe massive galaxies at this redshift with stellar masses at least a billion times the mass of our Sun. Looking beyond  $z \sim 7$  will require new techniques and instruments since the objects in question have very faint fluxes. The first stars are expected to end their lives spectacularly as SNe and/or GRBs suggesting that variability searches may be fruitful in finding them.

It is almost certainly true that we have yet to observe truly primeval galaxies, i.e. the very first galaxies to have formed in the early Universe. Techniques pioneered by UK astronomers and which have proved very effective in locating extreme-redshift objects at  $z > 5$  to date include selecting Lyman Break Galaxies based on the signature of neutral hydrogen absorption in their continuum emission and the selection of Ly $\alpha$  emitters via their highly-redshifted Ly $\alpha$  emission lines. Using these techniques and their variants, detailed studies of galaxies at redshifts  $z \sim 7$  over several tens of square degrees will be facilitated in the future by the near infrared Euclid deep surveys, complemented by wide-field optical surveys from the ground. In the shorter term, a further promising probe that is only now reaching its potential is to select high- $z$  galaxies via sub-mm/millimetre observations of their redshifted thermal dust emission. The potential discovery of large numbers of high- $z$  dust-enshrouded galaxies via this technique is now becoming possible by way of new sub-mm facilities such as SCUBA-2 on the JCMT and ALMA. Other approaches for finding extreme-redshift objects that will remain important for the future include quasar searches and the identification and follow-up of GRBs.

The advent of JWST by the end of the decade should extend the search for the highest redshift galaxies to  $z > 10$ . An open question at the current time is whether the currently detected  $z \sim 7$  galaxy population is responsible for the reionization of the Universe or if there is a further population of galaxies capable of

achieving this by an earlier time as suggested by recent measurements of the polarization of the CMB.

In addition to studying the sources of ionizing radiation, there is currently great excitement surrounding attempts to detect the reionization epoch through its imprint on observations of the 21cm emission line of neutral hydrogen. For a source around the epoch of reionization at  $z \sim 10$ , the 21-cm hydrogen line is redshifted into the megahertz (radio) regime of the electromagnetic spectrum and experiments such as LOFAR, MWA and PAPER are currently searching for the 21-cm signal from this epoch. The UK is in the vanguard of preparations for the SKA, which is the future key facility that will revolutionise this emerging field. It will facilitate the mapping of the neutral hydrogen fraction in great detail across the period straddling the reionization epoch. The SKA will also allow us to directly probe, for the first time, the evolution of the matter distribution during the dark ages themselves.

One can also probe the ionized fraction of hydrogen using features in high- $z$  quasar spectra (e.g. the Ly $\alpha$  forest), through 21 cm absorption studies and also by measuring the signatures of reionization on the CMB radiation. The latter include the generation of CMB polarization on large angular scales allowing a measure of the optical depth to last scattering, and the kinetic Sunyaev-Zel'dovich (SZ) effect due to the scattering of CMB photons off of objects with bulk peculiar velocities. All of these probes are sensitive to different aspects of the reionization signature and therefore complement each other – Lyman-alpha forest observations probe the latter stages of reionization, optical depth measurements from CMB polarization provide an integral constraint, while the kinetic SZ effect can potentially provide information on local variations in the ionized fraction (patchy reionization).

The combination of all of these techniques can also be used to discriminate between different reionization scenarios, e.g. reionization that occurred as a single sharp transition, or a more gradual event. The answer to this question will have key implications for our understanding of the formation and early evolution of the very first bound structures to form in the Universe.

Key facilities and observational requirements:

- Current (HST, VLT) and future (JWST, E-ELT, Euclid) optical & near-IR facilities for finding the most extreme-redshift objects.
- SCUBA-2 on JCMT and ALMA to identify and characterize high-redshift dust-enshrouded galaxies.
- Current (LOFAR) and future (SKA) low frequency radio facilities to detect and characterize the epoch of reionization and the clustering of HI at the end of the dark ages.
- CMB experiments for optical depth measurements and to constrain spatial variations in the ionization fraction via the kinetic SZ effect.

### 3.6 Precision cosmology

- What physical processes occurred in the very early Universe?
- What is the nature of dark matter?
- What is the origin of the current accelerated expansion?

Over the past two decades, a standard model of cosmology has emerged. This consists of a nearly flat universe described by general relativity, with 4% of the energy density in the form of ordinary baryonic matter, 21% in “dark matter”, and the remaining 75% in some form of “dark energy” thought to be responsible for the present accelerated expansion of the Universe. Galaxies and large-scale structures are assumed to have grown gravitationally from primordial seed perturbations, possibly generated during a period of cosmic inflation in the early Universe. The UK has played a key role in defining this standard model through leadership of large surveys, such as the 2dF Galaxy Redshift Survey, and by pioneering calculations of its observational consequences.

The standard cosmological model provides a remarkably efficient description of a host of astrophysical measurements. The simplest six-parameter model is an excellent fit to data and its parameters are now

determined with almost percent-level precision. However, the key ingredients of the model – inflation, dark matter and dark energy – are not understood at the fundamental level and thus provide critical challenges for the next decade(s).

The basic predictions of inflationary cosmology – a flat universe in which structure was seeded by Gaussian, adiabatic curvature fluctuations with an almost scale-invariant power spectrum – are spectacularly consistent with observations of the cosmic microwave background (CMB) and the clustering of galaxies. These predictions will be tested severely over the next two years with the CMB data from Planck. Further critical tests of inflationary cosmology for the coming decade will focus on precisely characterising the primordial perturbations. These tests include searching for the signature of gravitational waves from inflation in the B-mode polarization of the CMB, measuring the shape of the power spectrum of primordial curvature perturbations via clustering in the distribution of galaxies, dark matter (via weak gravitational lensing) and the intergalactic medium (IGM), and testing the wide model-space of primordial non-Gaussianity with the CMB, large-scale clustering and cluster abundances. Critical facilities include wide-field optical imaging and spectroscopic surveys (galaxy clustering, weak gravitational lensing, clustering in the IGM and galaxy cluster abundances), CMB polarization experiments, and wide-field Sunyaev-Zel'dovich and X-ray surveys (galaxy cluster abundances).

The existence of non-baryonic dark matter is required by a range of astronomical observations, but currently only its gravitational influence has been detected. Uncovering the nature of dark matter will have profound consequences for particle physics. The breakthrough in this area will likely come from direct-detection experiments and, potentially, indirectly through detection of the decay products ( $\gamma$ -rays, cosmic rays or neutrinos) from pair annihilation. These topics are considered in detail by the PAAP. Astronomy also plays an important role by probing the distribution of dark matter from cosmological scales down to that of dwarf galaxies via gravitational lensing and studies of stellar dynamics. Such observations can constrain basic properties of dark matter such as its temperature and interaction cross-section. A further issue in fundamental particle physics where astronomical observations are proving very constraining is the determination of the absolute mass scale of neutrinos. While flavor oscillations are sensitive only to differences in the squared masses, massive neutrinos suppress the small-scale clustering of matter in a way that depends on the total mass. The suppression must be at least at the percent level and should be detectable with the same range of observations that can be used to probe the shape of the primordial power spectrum.

The current acceleration in the expansion of the Universe is a profound puzzle for fundamental physics. Acceleration might be due to a new form of (dark) energy density that now dominates the energy budget of the Universe, or it might signal a breakdown of general relativity on cosmological scales. Further quantification will come from precision measurements of the expansion history, via geometric tests from the baryon acoustic oscillation feature in the clustering of matter and supernova luminosities, and from the evolution of large-scale structures and the associated perturbations to the spacetime metric. The latter can be probed with weak gravitational lensing, the statistics of line-of-sight velocities measured from galaxy redshift surveys (via “redshift-space distortions”), and the abundance of galaxy clusters as a function of redshift. The future of dark energy research is the combination of all these probes, allowing cosmologists to test the underlying fundamental assumptions of the standard cosmological model (e.g. general relativity), and isolate them from systematic uncertainties in the observations.

Large surveys of the Universe will continue to drive cosmology in the coming decades. The UK has a rich history in this field and should continue to play a leading role in forthcoming international CMB experiments and radio, optical and infra-red imaging and spectroscopic surveys. Moreover, the UK has underpinned this work with world-leading theoretical expertise ranging from early-universe physics to computational astrophysics. It is essential to maintain this theoretical expertise, along with access to world-class HPC, if we are to capitalize on the scientific potential of our observational programmes.

Key facilities and observational requirements:

- Wide-field multi-colour optical imaging. Surveys (e.g. DES) of more than  $10^8$  galaxies with photometric redshifts, covering a large fraction of the observable Universe are critical for weak

gravitational lensing, galaxy clustering and cluster abundance studies and to serve as target-finders for spectroscopic surveys. Looking further ahead, Euclid, for which the UK enjoys significant scientific leadership, and LSST will provide further step changes in survey volume, imaging more than  $10^9$  galaxies over much of the extragalactic sky to  $z=3$ . Transient surveys (e.g. LSST) will further discover large numbers of SNe.

- Wide-field spectroscopic surveys providing precise redshifts of over  $10^7$  galaxies (e.g. the proposed DESpec, WEAVE, 4MOST and BigBOSS) to  $z=2$  are critical for measurements of baryon acoustic oscillations and exploiting redshift-space distortions in the clustering of galaxies. Such surveys will provide large numbers of quasar spectra for Ly $\alpha$  studies of IGM clustering. From 2020 onwards, order of magnitude advances in the number of galaxy spectra will come from Euclid and the SKA (phase 2), the latter also, potentially, mapping the clustering of HI in the pre-galactic medium at the end of the dark ages ( $z < 20$ ). On route to the SKA, very large survey volumes for clustering studies may be achievable at relatively low cost by intensity mapping in the 21-cm line of HI or molecular lines.
- CMB polarization measurements on large scales to probe for the signal of primordial gravitational waves, and on small scales for weak gravitational lensing, non-Gaussianity and (in temperature) galaxy cluster studies. UK involvement in this area is through AMI (galaxy clusters), scientific leadership of several flagship Planck projects, and minor roles in ground-based and balloon-borne experiments. The UK still enjoys European leadership in several areas of critical technology (reflected in the UK coordinating the instrumental aspects of the two previous Cosmic Visions proposals for a post-Planck CMB mission) but this is at risk since there is currently no UK-led polarization experiment.

### 3.7 Extreme astrophysics

- Do the known laws of physics on earth apply under extreme conditions in the Universe?
- What is the astrophysics behind the accretion of matter and energetic feedback around compact objects?
- What are the sources of gravitational waves?
- How and where does relativistic particle acceleration occur?

The Universe is the best laboratory available for testing the laws of physics under extreme conditions. It provide for free ranges in density, gravitational field and temperature unattainable in an Earth laboratory while also subjecting matter to intense radiation and neutrino fluxes. To understand whether the laws of physics we have constructed apply under such extreme conditions we need to observe cosmic objects simultaneously across the entire electromagnetic spectrum and via gravitational waves, cosmic rays, and neutrinos. Observations then have to be compared to theoretical models and numerical simulations run on the most powerful high performance computers. In modern astrophysics we are rapidly approaching an era where we can truly explore extreme conditions using a “multi-messenger approach”. Observational facilities applicable to this theme to which the UK has contributed funding include UKIRT, JCMT, VLT, WHT, LT, MROI, AMI, e-MERLIN, Swift, XMM-Newton, HESS, CTA and aLIGO. Some of these will be reviewed by PAAP.

There are multiple extreme astrophysics research topics for which the UK is world leading and which play to our strengths in observation, theory and instrumentation. Examples include:

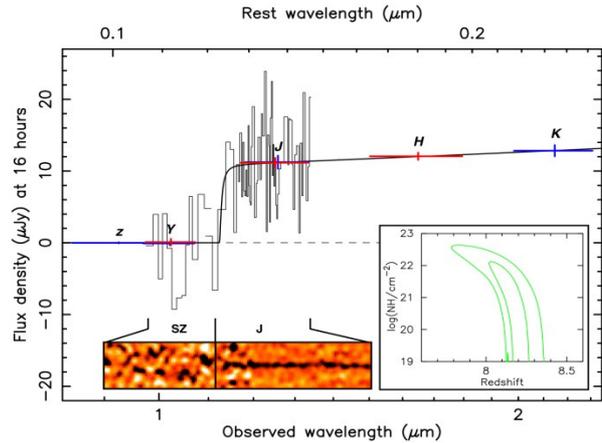
- a) The physics of black holes and neutron stars – how do such objects form and interact with their surroundings? Close to neutron stars or black holes the strong-field regime of general relativity becomes important. Light is subject to gravitational bending and “frame dragging”, which can be revealed by multi-wavelength observations often requiring monitoring of sources over a variety of timescales (e.g. monitoring of X-ray iron lines). The coupled processes of accretion and outflow, whether radiatively or magnetically driven, link accreting objects to their surroundings via a feedback mechanism. This requires observations of the accretion process through the study and modeling of discs and outflows whether semi-isotropic or jetted. X-ray observations probe the regions closest to the compact object, UV-IR observations probe the outer disc and sub-mm and radio observations probe the dust torus and jet-disc connection. We need to compare and contrast the behavior of stellar-mass and super-massive objects,

some of which are dust-enshrouded and hence hidden from direct IR/optical view but visible in X-rays and radio.

- b) Observations of gravitational waves (and/or neutrinos) provide unique insights into the formation and evolution of systems such as binary mergers and core-collapse supernovae. The gravitational wave observatories should soon provide the long-sought observational detections but to fully understand transient sources requires access to complementary all-sky electromagnetic data and theoretical models.
- c) Extreme environments are common sites for the acceleration of particles to highly relativistic speeds often accompanied by intense non-thermal radiation. The sensitivity of very high energy observatories has been rapidly improving enabling studies of diverse phenomena such as pulsars, GRBs and giant radio galaxies.

**Figure 6: The VLT/ISSAC spectrum and complementary photometric data for GRB 090423, which has the highest spectroscopically confirmed redshift,  $z=8.2$ . The sharp break in the spectrum is due to Ly $\alpha$  absorption. This GRB was discovered by the Swift satellite. Its extreme redshift puts this GRB close to the epoch of reionization and illustrates how the discovery of transients can probe the first light epoch (Sections 3.4 and 3.5) and probe stellar evolution (Section 3.3).**

**[Credit: Nial Tanvir/Klaas Wiersema (University of Leicester)]**



Thanks to past investment, the UK currently has access to the entire electromagnetic spectrum in both hemispheres through its own facilities ranging from e-MERLIN and LOFAR to XMM-Newton and Swift. The UK has an excellent track record in extreme astrophysics encompassing surveys to find large source populations, transient survey detectors which can discover the birth of compact objects and HPC simulations to make sense of the data. Our diverse facilities have enabled the UK community to lead discoveries ranging from investigating how galaxies and black holes grow to discovering the most distant GRBs. This research leadership can continue through investment in suitable diverse future facilities.

Key facilities and observational requirements:

- Multi-wavelength access. To find sources it is particularly important to have all-sky access to high energies (X-ray and  $\gamma$ -ray) and to the radio (although LSST will become a competitive optical survey facility in the next decade). Targeted follow-up optical/IR/sub-mm imaging and spectroscopy on 8m+ telescopes then provides source classification (Figure 6). Future investment in X-ray spectroscopic missions (successor to XMM-Newton), wide-field survey telescopes (Swift and successor), multi-purpose large telescopes (VLT, E-ELT) and radio arrays (LOFAR, SKA) is required.
- Time domain access. To enable monitoring for source classification, for disentangling emission components (e.g. dust, synchrotron, inverse Compton) and for determination of the total energy budget requires all-sky access across the electromagnetic spectrum.
- Access to multi-messenger data. If the UK is to continue its leadership role in multi-messenger science, STFC should ensure an appropriate balance of expenditure between photonic and non-photonic observing facilities and HPC.

## **4. Technology, high-performance computing, exploitation grants, fellowships and studentships, and UKSA**

### **4.1 Technology**

Many of the most significant breakthroughs in our understanding of the Universe have been enabled by technological advances which have opened-up new parameter space (e.g. wavelength, sensitivity, field-of-view on the sky, time domain). The UK has long been at the forefront of astronomical instrumentation, such as the development of the AAT-2dF multi-object spectrograph, which revolutionised our view of large-scale structure and cosmology and XMM-Newton/EPIC, the most powerful X-ray imager yet built. The present-day legacy of this rich heritage is illustrated by the UK's world-leading positions in, for example, sub-mm astronomy (Herschel-SPIRE, SCUBA-2), near-infrared imaging surveys (UKIRT-WFCAM, VISTA) and X-ray surveys (XMM-Newton). Indeed, the proliferation of UK Principal Investigators (PIs) in the VISTA surveys is an excellent example of how the UK benefits from leadership roles in development of a new capability; the same will undoubtedly be true of the new VLT/KMOS instrument.

Through collaborations of university groups, STFC's laboratories, and industry, the UK is leading important aspects of technology R&D (e.g. near-IR/sub-mm detectors, CCDs, work on Gaia and Euclid) which feed-in to ground-based astronomy and space missions. The R&D investment toward both E-ELT and SKA is already paying its dividends with UK leadership of one of the two first-light E-ELT instruments, a leading role for the UK in the SKA preparation phase, and healthy engagement with UK industry. Equally, the UK is well-placed to lead the technology development toward a future ground-based MOS. However, such innovation is not purely the domain of big facilities, with smaller projects, such as ULTRACAM and SuperWASP on the ground and bi-lateral mission like Swift in space, showing the success of focussed projects providing access to new parameter space.

We note that STFC's Project Research and Development (PRD) scheme provides a useful channel for funding of innovative new techniques/technologies. In a landscape of increased funding across STFC, we would welcome an increase to the PRD line to underpin future UK technological leadership in the science areas prioritised in this report.

Lastly, we comment that an increasingly important aspect of getting the most out of facilities is the manipulation, curation and analysis of 'big data'. The UK's record in survey astronomy has put it in good standing and, with continued investment we will be a strong position to extract the best results from data-rich future facilities such as Gaia, large MOS surveys, LSST, E-ELT and SKA.

### **4.2 High-performance computing**

Progress in our understanding of the dominant processes that shape our Universe is reliant on simulations and modeling that in turn rely on access to world-leading HPC. As observational projects scrutinize the Universe in depth and detail, ever more sophisticated computational models are required to allow effective interpretation of new data. The UK has traditionally been, and continues to be, a recognized world leader in theoretical astrophysics, and this has allowed the UK to realise world leadership that greatly exceeds our capital investment. In order to sustain this position, however, it is fundamental to our future success that theoretical models are not treated as an optional add-on to a core technological/observational project. Cutting-edge models need now to be based on many-body equations for gravity and fluid dynamics (or even magneto-hydrodynamics) and large sets of ordinary differential equations to treat time-dependent chemistry for which HPC is the essential tool. This is an increasingly competitive area, and a clear funding strategy is needed to ensure that the UK can continue to compete at the top level.

Support for HPC needs to be integrated into the STFC's financial planning (or, better, funded direct by BIS along with hardware upgrades). If STFC have to fund running costs, the financial plan needs to include a yearly allocation. The recent investment in DiRAC has been a windfall for STFC, and we must fully capitalise

on this. However, the power of HPC, and thus the computing power needed to retain a competitive advantage, is continually advancing and this is allowing ever more accurate interpretation of observational data. To remain at the forefront of world science, the UK needs a strategy for investment in future HPC. Moreover, the industrial relevance of the computational techniques that we develop, the computational boundaries that we push and the highly sought-after skills of the students and staff we train greatly strengthens the case for this investment.

### **4.3 Exploitation grants**

The AAP regrets the recent reduction in the funding allocated to the exploitation grant line. We appreciate that STFC has attempted to protect this funding in relative terms, based on the recommendations from the last programmatic review. However, the strongest message from the community is that the current level is low. The exploitation funding line supports basic science and technology research and is vital to the health of the UK astronomy programme. Recent reductions, coupled with the abolition of postdoctoral fellowships, provide a particularly bleak outlook for young scientists. The AAP does not support any further reductions in this source of funding, even if the total funding envelope is reduced further. If funding is increased, exploitation grants should be increased pro-rata. The community would also like a review of the consolidated grant scheme.

### **4.4 Fellowships and studentships**

We, and much of our community, believe that it is essential to protect and enhance the support for young researchers in our universities and laboratories. The abolition of STFC's postdoctoral fellowship scheme has demonstrably had a negative impact on the ability of the UK to retain its best new postdoctoral researchers. Reinstating the postdoctoral scheme should be a high priority should funding become available. Some of our community expressed the view that the Ernest Rutherford Fellowship scheme is now too generously funded both in terms of the number of fellowships offered (12 per annum across the entire PPAN area) and the ring-fenced grant funding (600k per annum awarded in competition amongst the new fellows and, in future years, requests for continuation funding) for additional research support. The AAP believe that, while it is important for the Rutherford Fellowships to be attractive compared to other overseas prize fellowships, the ring-fenced funding is rather generous in comparison to the consolidated grant funding available for other academics and runs the risk of supporting mediocrity. We recommend that the ring-fenced funding be used to support a renewed postdoctoral fellowship scheme or transferred to the regular grants line, and that Rutherford Fellows be encouraged to apply for additional research support through consolidated grants in competition with the rest of the community.

STFC studentship numbers have fallen more slowly than PDRAs since 2008 and this has led some of our community to question whether we are now training too many students. We disagree with this statement. First, PDRAs and students are very much at the coal-face of research and we believe cutting student numbers would significantly reduce the productivity of UK astronomy. Second, a significant part of the economic and societal impact of government funding for astronomy is that we provide excellent training for our students, some of whom later transfer these skills outside of academia. However, as a community we must be realistic with our graduate students over the chances of postdoctoral (and longer-term) academic employment in the UK. We note that it is typically the small- and medium-scale, innovative projects that make the best training ground for students which is a key reason to maintain a diverse programme.

### **4.5 The UK Space Agency**

The formation of the UK Space Agency (UKSA) was taken by the community as a very welcome opportunity for space science to have a stronger single voice within the UK. In the last few years UKSA has become a well-known entity, but the astronomy community wonders if the voice of astronomy is heard particularly loudly within the agency relative to that of industry and other activities (most notably the "growth strategy"<sup>8</sup>).

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<sup>8</sup> Chris Castelli, presentation at RAS meeting "Future UK Space Science Missions, 12<sup>th</sup> October 2012

We acknowledge the interaction between UKSA and the STFC Science Board which provides the formal route for commenting on the relative merits of proposed space science missions. However, we do not think UKSA is currently open enough about how decisions are reached and does not request sufficient input from the astronomy community on the future direction of funding priorities.

The AAP does not have access to detailed funding figures for UKSA-supported astronomy missions, but a useful overview was provided recently<sup>9</sup> by the Secretary of State for Business, Innovation and Skills in a written answer to the relevant House of Commons committee. This answer listed supported activities with outlined spending plans for the next few years. It is clear that UKSA is under considerable financial pressure, with even the highest-profile ESA missions receiving modest funding allocations. This situation does not bode well for any desire within the UK to act as PIs of major instruments and could lead to a reduction in technology innovation in addition to damaging science leadership. Currently we feel the UK is spending a relatively low amount on participation in astronomy science missions relative to the ESA subscription cost. There is also insufficient funding available for “bi-lateral activities”, by which we mean opportunities for the UK community to take a significant role in non-ESA missions. We welcome the signing of various memoranda of understandings with non-ESA agencies, but, unless these are backed up by suitable levels of funding, opportunities to participate in cost-effective science missions outside of the ESA Cosmic Vision programme may be missed, reducing science, technology and training activities in the UK.

## 5. Recommendations for different funding scenarios

Space science, including astronomy, is the most successful area of physics in terms of UK world ranking. We have a world-class research programme providing excellent value for money. Astronomy is the most popular area of physics with the public/children – hence vital to STEM recruitment – and provides technology opportunities for UK industry as well as training scientists/engineers. This success is due to sustained investment over many decades. In this section we outline the current situation for astronomy funding and recommend a set of priorities to maintain our leadership role.

Recent years have seen major reductions in the funding of both astronomy research staff and facilities. These cuts continue to work through the system, and have led to a sense of a community which has chosen to reduce its capability. In addition to cuts in the numbers of postdoctoral scientists and students, the UK has withdrawn from the AAO and Gemini and plans to withdraw from the JCMT and UKIRT on Hawaii. Final decisions on other facilities, such as the WHT on La Palma beyond 2015 and e-MERLIN in the UK beyond 2014, have yet to be made, but clearly the current situation is serious and getting worse. This issue is illustrated in Figure 7 where we show the timeline for those current STFC-funded ground-based photonic observational facilities that we believe are of high priority (at least) for the UK astronomy programme (see Section 5.1). Some of these facilities (such as WHT) could possibly be kept under current plans, but most could not and there are multiple future opportunities (e.g. LSST) which would likely be unaffordable. Similar challenges face UKSA.

**To achieve the UK astronomy science objectives discussed in Section 3, and provide headroom for innovative new projects, we believe the budget for astronomy requires a modest uplift relative to current plans roughly equivalent to a return to the 2011–12 budget level.**

Here we outline three scenarios for prioritisation assuming: (a) a modest uplift (Section 5.1); (b) the current STFC plan (Section 5.2), which actually involves further phased reductions; and (c) further reductions in funding beyond those already planned (Section 5.3).

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<sup>9</sup> Hansard, Commons Debates, 2012 September 14, Column 407W

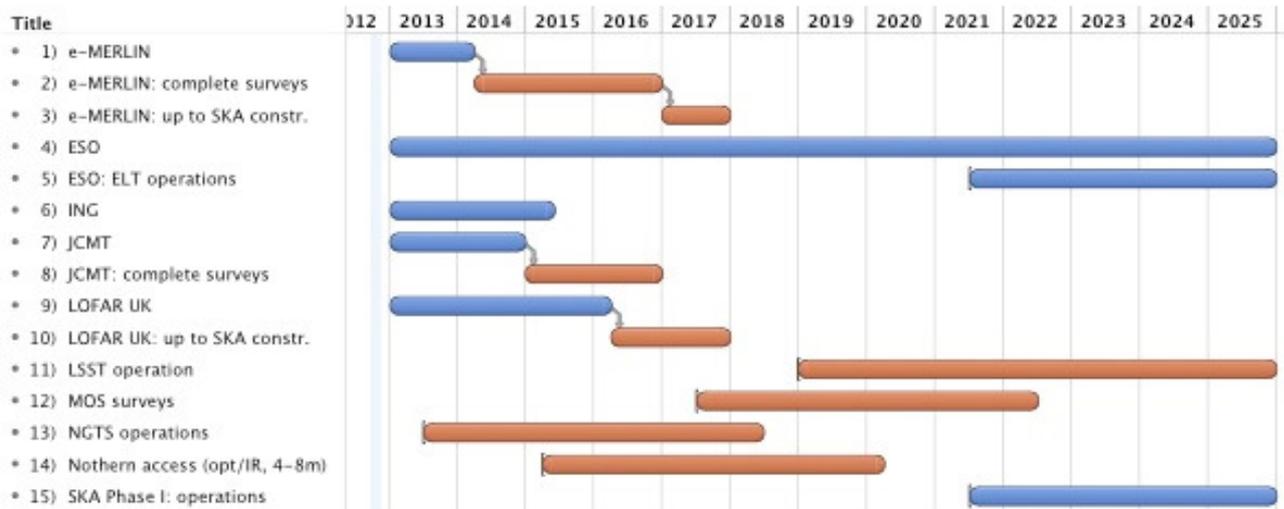


Figure 7: Timeline of the highest-priority and high-priority ground-based (photonic) observing facilities listed in Section 5.1. The blue and orange bars indicate facilities which are affordable under the sustainable astronomy programme described in Section 5.1. Only a small number of the facilities options shown in orange could be pursued under the current spending plan described in Section 5.2. Several of the facility options shown in blue would also become unaffordable under the scenario of further reductions in funding described in Section 5.3.

### 5.1 A sustainable astronomy programme

If we are to achieve our science objectives and exploit our involvement in existing and future facilities we need to have a coherent policy on observing capability. We need to train the next generation of scientists to maintain success at winning time where we do not have guaranteed time – e.g. our VLT and NTT success rate is higher than our fractional subscription rate. We need to maintain scientific/technical expertise so as to win construction/instrument contracts. Examples of these issues are: (a) in the sub-mm, if we fully withdraw from JCMT before the SCUBA-2 survey is complete and have no further sub-mm instrument development; (b) in the radio if we leave e-MERLIN/LOFAR before SKA phase 1 (we might then host the project office/Organisation Headquarters but have no active radio telescopes); and (c) in space missions if we participate in ESA but do not adequately fund instrument development or take advantage of bi-lateral opportunities.

Other countries have reached the same conclusions as us and are striving to keep diversity in non-ESO facilities, including access to the Northern hemisphere, while they await the advent of 40- m class telescopes and the SKA (e.g., Italy: TNG, LBT; France: CFHT, IRAM; Germany: LBT, Calar Alto, IRAM, SOFIA; Spain: GTC, Calar Alto, IRAM; Netherlands: LOFAR, WSRT). The USA also plans to maintain diversity<sup>10</sup>.

We stress that we are not requesting that no current facility closes but rather that such a process be phased to maintain a balance and prevent loss of access before new facilities come on-line. Astronomy is an active science based on continuous discoveries of dynamic sources (e.g. from surveys such as SCUBA-2 or VISTA) – we cannot just depend on archival data or far-future facilities. We believe the UK can maintain its world-leading reputation with a modest adjustment in funding.

Here we give our priority list for the future astronomy programme required to achieve our science objectives.

<sup>10</sup> NSF AST Portfolio Review, August 2012

*Highest priority:*

1. Exploitation grants. The grant line supports all of the astronomy science and technology activities in the UK (including science exploitation of space missions). This funding line is under intense pressure and requires an increase pro-rata to any uplift in the total astronomy programme.
2. ESO. STFC should continue to provide access to ESO facilities (VLT, ALMA, VISTA, VST and La Silla) and provide access to the E-ELT. These facilities are vital to the entire science programme.
3. SKA and ELT R&D. STFC should continue to support SKA development at current levels and should support a major UK role in E-ELT instrumentation.
4. High Performance Computing. STFC should support future bids to BIS for upgrades to HPC hardware and negotiate an affordable scheme to fund HPC running costs.

*High priority:*

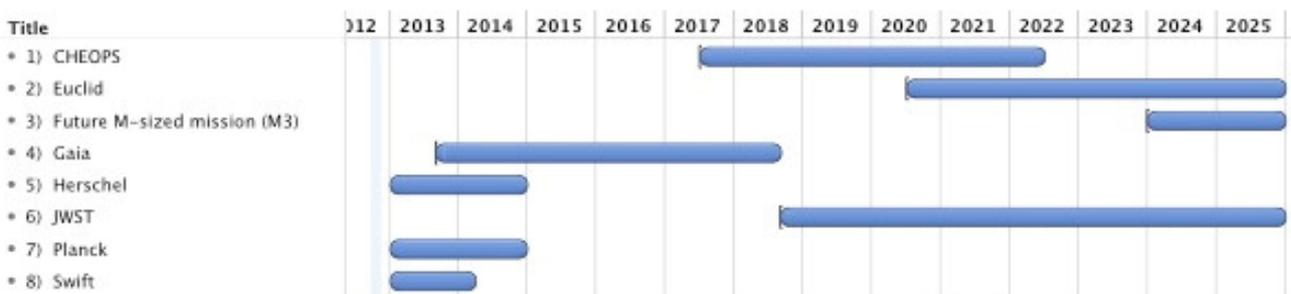
1. Complete the JCMT/SCUBA-2 survey. STFC should support continuation of the survey to 2016 but only if a low-cost operational model can be developed and implemented as soon as possible.
2. Complete the e-MERLIN legacy surveys and then review its role as an SKA pathfinder.
3. Participate in and preferably lead a Multi-Object Spectrograph project. STFC should follow the recommendations of the forthcoming review of MOS options when selecting which MOS(s) to support.
4. Fund a UK role in the operations of the NGTS exoplanet finder.
5. STFC should help facilitate negotiations for UK community access to LSST, to enable an MOU to be signed but delay STFC funding until the middle of the decade.
6. Northern hemisphere access. STFC should investigate how to provide Northern hemisphere 4–8 m telescope access beyond 2014–15 (e.g. via a low-cost operations model for La Palma/ING).
7. Maintain participation in LOFAR-UK as an SKA pathfinder.

*Medium priority:*

1. Fund the operation of AMI as a common-user facility for 3 years in the first instance.
2. Continue current level of support for UK involvement in the MROI until the array is commissioned and then review UK involvement.
3. Continue STFC support for the LT with regular reviews of productivity.

The timeline of the ground-based photonic facilities in our highest- and high-priority categories is summarised in Figure 7.

In addition to the above list, we believe STFC should be responsive to new innovative ideas. Furthermore, UKSA should support involvement in approved ESA astrophysics missions and bi-laterals and STFC should support exploitation of these missions. Possible future ESA missions of particular interest relevant to the science discussed in Section 3 of this report include EChO, PLATO and Athena. The timeline of current and approved astrophysics space missions with UKSA funding is summarised in Figure 8.



**Figure 8: Timeline of approved space astrophysics missions with UKSA funding as well as the future ESA S1 (CHEOPS) and M3 missions. The ESA L2 launch date would likely be 2028+. Post-launch phases are shown in blue for each mission. For missions currently in flight (Swift, Herschel and Planck) funding extensions are possible.**

## 5.2 No change to current spending plans

The community made difficult decisions in the last programmatic review (e.g. closure of UKIRT, withdrawal from Gemini, ramping-down of JCMT), with the intent of generating headroom for new projects which included, but was not limited to, leading roles for the UK in E-ELT instruments and the SKA project. Looking at the near-future, if the reductions contained in the current spending plan for UK astronomy occur we face a situation in which we will continue to lose observational capability (Figure 7), without new facilities coming on-stream; without doubt we will become less successful on the world stage – an astronomical version of 'dumbing down'.

If the current planning reductions occur up to 2015-16 we will be unable to carry out all of the high priority items listed above, perhaps limited to completion of the e-MERLIN legacy surveys and the JCMT survey (but only with a low-cost operations model) and participation at a reduced level in a MOS project. We would likely also need to reconsider the level of support and spend profiles for E-ELT instrumentation and SKA. This funding scenario would result in a loss of UK leadership in E-ELT and SKA, which would harm our science return. Reduced participation in a MOS would reduce UK leadership in survey science, fail to fully exploit our investment in Gaia and weaken UK leadership in the Euclid mission. Failing to complete the SCUBA-2 surveys would significantly reduce our exploitation of ALMA. Failure to invest in NGTS would result in a loss of opportunity to lead a world-ranked science area and to find targets for future ESA space missions.

## 5.3 Further reductions in funding beyond those already planned

Any further funding cuts would cause a further dramatic reduction in diversity as the core activities would have to be protected. These core activities include postdoctoral and studentship funding, HPC, access to both ESO and ESA, and technology capability to retain some hope of building future instrumentation. In this scenario several of the following measures would be needed to balance the budget:

- Complete withdrawal from the Northern hemisphere (e.g. e-MERLIN, WHT, LT and LOFAR-UK).
- Tension photonic and non-photonic astronomy based on the science return to the UK. This could result in reduced participation in aLIGO and no funding for the Einstein Telescope.
- No new-starts for future astronomy projects.
- Withdraw from or delay/reduce involvement in a currently-funded future very large project, most probably SKA in order to preserve access to ESO.

Any of these measures would be a disaster for both UK astronomy and STFC, with significant harm to the entire UK astronomy science programme. We would cede UK leadership and influence to our international partners, irreversibly damaging our reputation in the process and diminishing both our science output and technological innovation.