GROUND-BASED FACILITIES REVIEW CONSULTATIVE DOCUMENT

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1. Introduction

The UK has a strong tradition in ground-based astronomy. During their lifetimes the AAT, WHT and UKIRT have been front-rank international optical-IR facilities. The UK also has a strong heritage in radio-astronomy and in the near future e-MERLIN will be a world-class facility. UK leadership in submillimetre astronomy will continue with SCUBA2 on JCMT, then ALMA. This strength of the UK ground-based programme made us slow to see the benefits of joining ESO. Initially the UK decided to enter the 8-metre era by joining the Gemini Observatory. When, with generous help from the Government, the UK was able to join ESO in 2002, we found ourselves with a somewhat overheated ground-based programme. To date the STFC response to the joining of ESO has been withdrawal from the AAO and significant reduction in the running costs at ING and JAC. Current commitments for several facilities extend only a few years ahead (eg WHT, UKIRT and JCMT 2012, e-MERLIN 2014). A case can be made for extending the life of these facilities beyond these dates. Joining ESO gave us access to the VLT, VLTI, Apex and the La Silla telescopes, but crucially also gave us a significant role in ALMA. Recently, we have also benefited from a number of niche facilities such as the Liverpool Telescope (LT) and SuperWasp, whilst university consortia have invested in LOFAR, SALT and PanSTARRS.

The present review covers the period 2012-2020 and the community needs to be thinking what ground-based facilities and instruments it hopes to have access to in 2020. Astronomical breakthroughs are driven by technological advances in facilities and instrumentation, so the UK needs to be thinking about how it can remain a strong international player in ground-based astronomy. Some key long-term decisions are looming towards the end of 2009 or early 2010 and this is why STFC has asked for this review and requested the rather short time-scale for a final report of Oct 30th 2009. In the order they will come up these decisions are (1) should the UK continue its partnership in Gemini after 2012 ? (2) should the UK seek a stake in E-ELT and at what level ? (3) should the UK seek a stake in SKA and at what level ? These decisions will affect what options there are for extending the life of smaller facilities, and the level of support for other ground-based facilities. The Panel has been instructed not to include astro-particle, CMB or STP facilities in its review.

The ASTRONET process has provided a vision for European astronomy for the next decade. The ASTRONET Roadmap emphasizes that astronomy has become a multi-wavelength science, requiring front-rank facilities in all wavebands, and needing both space and ground-based facilities to achieve new science goals. It also stresses the key role that ground-based optical-to-radio facilities play for delivery of most of the key science goals. ASTRONET's strong recommendation is for a European commitment to both E-ELT and SKA and it believes both could be achieved, along with their other recommendations in space-based astronomy and the astro-particle area, provided there is a 20% increase in European funding for astronomy. Their estimate of the capital costs for a European ELT is 960 Meu, over ten years, and for a 45% European stake in SKA 580 meu, over eight years. At current GDP levels the UK share in these costs might be expected to be around 20%. Taking into account contributions ESO expects from other sources, the required UK component of E-ELT, is likely to be around 12Meu per year over 10 years. For SKA a 20% stake in the European share would cost about 14Meu per year over 8 years. These would only be possible with a very substantial contribution from the Government's Large Facility Capital Fund. A 20% share of the running costs of E-ELT is projected, at current prices, to be about £11m p.a., and for a 20% share of the European stake in SKA would be about £7m p.a. Although high, these running costs are in fact perfectly feasible within a ground-based programme at the current level of support, assuming the UK community wants to commit to these exciting new facilities. Of course it would be legitimate to be sceptical about the estimated costs of these giant facilities, the proposed time-scales, and indeed the feasibility of the outline designs. The ASTRONET proposal that SKA would start construction just three years after E-ELT construction starts may be unrealistic. Whichever of these facilities goes first, it will require major lobbying and the support of many governments for success. The costs of these projects mean that there is likely to be a separate sign-up process for both, even though E-ELT is an ESO project. The UK could opt for a smaller or larger stake in one of these projects than the ~20% that would be indicated by its GDP. The UK SKA community aspire for a 32% share in the European stake in SKA, amounting to a ~15% stake in the total SKA project.

It would be unrealistic to imagine that in 2020 the UK would have a large stake in large facilities like E-ELT and SKA, and would also retain all its current ground-based facilities. It is always hard to forego a workhorse facility that has supported an active and successful science programme, in order to start construction of some future facility many years hence. But our bid for the capital costs for E-ELT and/or SKA would not be credible if we do not show that we are willing to do this. An important component of any bid for large new facilities, and indeed maintenance of the existing level of support for ground-based astronomy, is demonstration of knowledge transfer benefits to the UK economy. We have a question on this in our questionnaire and we urge you to think about any applications to other areas that might follow from astronomical instrumentation or software developments. We have to find ways to demonstrate that astronomy contributes to the Government's science challenges: energy resources, climate change, security, aging population.

We also need to demonstrate that our ground-based programme meets the needs of the UK space science programme. If funding pressure led to withdrawal from Gemini-N, WHT, UKIRT and LT, there would be no dedicated UK optical-infrared capability to follow up northern hemisphere surveys from space (Spitzer, Herschel, Planck, Chandra, XMM) or in the radio band (e-MERLIN, LOFAR), apart from possible limited access to the Spanish Gran-Tecan 10-m and the Japanese Subaru 8-m via FMOS.

The Panel is also charged with identifying any gaps in facility or instrumentation capability and recommending appropriate strategies. We have therefore included in our document facilities that are still in the early stages of discussion and in which UK interest and involvement is so far modest. The ASTRONET Roadmap placed a strong emphasis on the need for new wide-field spectroscopic instrumentation and has set up a review to explore this issue, from which we hope to have input for our final report. The issue has become critical for the UK following the decision of the Gemini Board not to continue with WFMOS.

In section 2 of this document we outline the key science goals of the UK ground-based programme. This is based on the ASTRONET vision document, previous PPARC and STFC road maps or programmatic reviews, and on consultation with the recently appointed Near and Far Universe Advisory Panels. We have also drawn heavily on the report of the Ad-hoc Advisory Panel chaired by Prof Martin Ward in 2008. Section 3 lists the UK's current and planned ground-based facilities, indicating the strengths of their current or planned instrumentation. Any costs mentioned there (generally 09-10 levels or total cost) are indicative and approximate. We have tried to include all facilities and projects in which the UK has an interest, including those that have been initiated via university funding if there is the possibility of a demand on STFC resources in the future. There is a surprisingly long list of facilities initiated by universities. It is obviously excellent for the ground-based programme that universities can contribute in this way but it can also contribute additional pressure on the STFC budget.

There is an associated electronic questionnaire that we urge you all, and especially young astronomers whose careers will be most affected by the recommendations of this review, to complete. In this questionnaire we ask you to rank the science questions in order of importance and also to specify which facilities you regard as most important to achieve these science goals. There are also some specific questions on some of the key strategic decisions that are pending. There are opportunities for detailed comments, but please keep these short. The questionnaire is modelled on one carried out by Nial Tanvir in 2008. We also invite facility directors and other interested groups to submit papers to the review, but require these to be no longer than 2000 words in length. The **closing date** for the electronic questionnaire and other submitted papers is **July 31st 2009**.

Our web page (http://www.stfc.ac.uk/gbfr) has a selection of useful documents, our Terms of Reference, minutes of our meetings, and the electronic questionnaire. Queries or written submissions may be sent to **gbfr@stfc.ac.u***k*.

Goals of UK Ground-based Programme

In this section we outline the main science goals of the UK ground-based programme, subdivided into ten broad themes. We have closely followed the draft documents of the newly formed Near Universe and Far Universe Advisory Panels, and have also been guided by the ASTRONET Science Vision document and by previous PPARC and STFC road-maps and programmatic reviews.

1. Solar physics

The Sun provides a unique laboratory for the study of plasma phenomena at it surface and for probing the physics of the deep interior of a star using helioseismology. Some of the key questions are:

• how the solar dynamo generates the solar magnetic field,
• how the solar atmosphere is controlled by its magnetic field
• how that magnetic field (in the form of the solar wind and transients) couples from the solar surface to planetary environments within the solar system, particularly the Earth and to apply this knowledge to understanding the implications for stellar structure and evolution.
• The coupling of the solar wind to our own planet is crucial from two perspectives: Firstly for understanding long term climate variations on the Earth, and, secondly, in an increasingly technology reliant society for mitigating against the potentially devastating impacts of variations in the solar wind driven by transient solar events such as coronal mass ejections (CMEs) and energetic particle events (SEPs), to name but two.
• Understanding where the Sun fits within the vast parameter space of other stellar systems will greatly advance our knowledge of the formation of other planetary systems and the conditions necessary to support life.

2. Planetary interiors, surfaces and atmospheres

The planets and minor bodies of the Solar System offer the opportunity for unique insights into solar system formation processes, planetary evolution and how Life developed on Earth. The Solar System contains a bewildering array of different planetary environments – and one of the great challenges ahead of us is understanding what the conditions for Life are, where these conditions may be found in our Solar System (and beyond) and if there is evidence for Life existing on bodies other than Earth.

There are two principle goals to research in this area –

2.1 Solar System & Planetary Formation
• How did the planets evolve – what were the processes and time-scales involved from disk collapse to the present day Sun, planets and minor bodies?
• Is our Solar System typical? What can our Solar System tell us about other planetary systems?
• Can we develop a universal theory of planetary atmospheric structure, circulation and climate? What factors determine the form and character of a planetary atmosphere and its global circulation and climate?

2.2 Extent of Life in the Solar System

• What makes Earth special? Understanding of similarities and differences between Earth, Mars and Venus, Mercury and the Moon

• Are there places in our Solar System that have conditions that could support life today or may have in the past?

• Can we characterise such places in order to identify similar locations in other planetary systems

3. Space Physics

Space Physics investigates the space environments of magnetised (the Earth and the large gas giant planets) and non-magnetised bodies (e.g. Mars, Venus, planetary moons, comets) throughout the solar system. The field of solar terrestrial physics (both ground- and space-based aspects) is covered within this description, as are non-terrestrial magnetospheres, ionospheres, and atmospheres. Investigations of basic plasma processes which are relevant to a wide range of astrophysical phenomena are at the root of many ongoing in situ investigations in the solar system. Telescope observations of solar system objects can provide valuable remote observations of, for example, outer planet atmospheres and aurora, which can be studied and modelled independently or in combination with in situ spacecraft measurements.

4. Exo-planets?

The immediate goal of exoplanet research is an understanding of the formation and evolution of exo-planetary systems, including full characterization of the host stars. This includes the search for biomarkers in the atmospheres of exo-planets. 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:

- The detection and confirmation of bright, habitable zone (HZ) transiting planets, including, in particular, terrestrial planets and Super-Earths. While difficult, the atmospheres of these planets could be studied via transmission spectroscopy.
- Obtaining the planet population 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.
- Direct imaging of nearby, young and bright, and then old and faint giant exo-planets and their spectroscopic examination. Eventually, imaging and spectroscopy of terrestrial planets.

5. Diffuse matter and star and planet formation

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 O stars in regions < 0.1 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. Planet formation often accompanies star formation. We are only now starting to appreciate the diversity of planetary systems and of the physical and chemical processes regulating their origin. The key questions are:

4.1 Triggering of and Feedback in Star Formation

Triggering of and feedback in star formation control global, as well as local, properties of galaxies. Feed-back must have been negative during the births of spiral galaxies for sufficient dissipation to have occurred for discs to develop. However, the stellar age dependence on location in some clusters demonstrates that feedback is sometimes positive. We do not even know why feedback can have such contrasting effects in different regions. Hence, no prescription for the star formation rate used in models of the formation and evolution of galaxies, including the Milky Way, is reliable. Therefore, we do not understand why galaxies have the properties that they do.

- The use of computational hydrodynamic and magnetohydrodynamic simulations, including a wide range of physics, from radiative transfer to cosmic ray advection and diffusion, are required to identify how the properties of a multiphase interstellar medium (ISM) affect triggering and feedback.
- Some multiwavelength surveys will be completed, while others will be initiated, to probe the diverse natures of and provide unbiased samples of Milky Way star forming environments.
- Detailed high spatial and spectral resolution radio, millimetre, submillimetre, and infrared studies to follow up the surveys and probe the structures and kinematics of star forming regions are necessary to understand the physics of triggering and feedback.

4.2 The Path to Life

Star formation can lead to the existence of planets that lie in circumstellar habitable zones and possess chemical initial conditions that lead to life. This is the consequence of:

- The elemental composition of protostellar and protoplanetary gas and dust.
- The masses that stars have. - Though we observe young stars with discs, we have only a rudimentary understanding of the collapse of dense cores (sizes ~ 0.1 pc, particle densities > 10^5 cm^{-3}) within molecular clouds to form them. We also are not certain whether discs play roles in the births of stars considerably more massive than the Sun similar to those that they have in the formation of lower mass stars. Thus, we do not fully understand why stars have the mass distribution that they do.
- The dynamics of protoplanetary discs and the migration of planets that form within them. Arguments continue about the nature and evolution of the protoplanetary discs formed by collapse, and the subsequent formation of planets within them. Key outstanding issues include the initial masses and sizes of discs, the role of self-gravity in driving early evolution, the driving mechanism and nature of disc turbulence, the modes by which planetary systems form, and the influence of migration processes that determine the final planetary system architecture.
- The gas phase and surface chemistry of interstellar clouds and protoplanetary discs.

6. Stellar astrophysics

As newly formed stars age, stellar winds and stellar explosions inject the products of nuclear reactions into the ISM and provide the seeds for dust formation. Subsequent generations of stars form at higher metallicity, and the increasing dust content drives the formation of planetary systems. Massive stars die as core-collapse supernovae, do these supernovae explosions trigger further star formation, or do they blow out the clouds and halt star formation? Partially degenerate low-mass stars share many properties in their structure and atmospheric properties with Jovian-type exo-planets.

Stellar physics is also at the heart of many astronomical questions beyond our Galaxy. The success in modeling galaxy evolution stands and falls with a holistic understanding of stellar physics. A key science objective should hence be to connect experts of stellar populations in our Galaxy with galaxy modelers, since it would be absurd to assume that distant galaxies are less complex than our own. Therefore it is essential to understand the diversity and physics of stellar populations in the Galaxy first.

Supernovae Ia are one of the fundamental cosmological distance rulers, identifying their progenitors requires a deep understanding of the evolution of binary stars. Outflows from AGN are a key ingredient in galaxy evolution, but the physics of jets can be studied in detail in galactic X-ray binaries and young stars. Gamma-ray bursts, the most powerful explosions sending us information from the early days of the Universe, are inherently linked to the evolution of the most massive stars.

Some of the key areas in stellar physics for the UK community are:

* Low-mass stars and sub-stellar objects
* High-mass stars
* Globular clusters
* The white dwarf – SNIa connection.
* Accretion inflows and outflows

7. Cosmology

*** What is the physics of the Big Bang**
*** What is the origin of large scale structure?**
*** What is the nature of the dark matter and dark energy?**
*** Is standard cosmology based on correct physical principles**

In the past decade, a standard model of cosmology has emerged consisting of a nearly flat universe described by general relativity, with 4% of the energy 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. Galaxies and large-scale structure are assumed to have grown gravitationally from primordial seed perturbations, possibly generated during a period of cosmic inflation in the early universe.

However, there remain many unanswered questions with this model. For example, the origin of the primordial perturbations depends critically on the uncertain physics of the early Universe. Within the context of inflation, the scale dependence of the primordial density perturbations, the extent to which they obey Gaussian statistics, and the amplitude of any primordial background of gravitational waves will be key observational tests for discriminating between models. Moreover, recent progress in attempts to realise inflation in fundamental (e.g. string) theory suggest a richer phenomenology than the simplest models, including large non-Gaussianity, cosmic superstrings, and isocurvature modes. The most direct constraints on the primordial perturbations come from the cosmic microwave background (CMB), but observations of galaxy clustering, weak gravitational lensing, the clumping of the inter-galactic medium, as traced by HI, and the abundance of galaxy clusters will play an important role in constraining the scale dependence and Gaussianity of the primordial perturbations on smaller scales than the CMB.

Cosmologists also need to tackle the conundrum of the "dark universe", which now includes two mysterious ingredients: dark matter and dark energy. The basic properties of the dark matter can be probed by cosmological observations, including its temperature and cross- section, and the neutrino mass. Dark energy can be quantified using both the expansion rate of the universe, via geometrical tests from galaxy clustering and supernovae, and its impact on the growth of large-scale structures in the universe, probed using weak gravitational lensing, and galaxy and cluster surveys. The future of dark energy research is the combination of all these probes allowing cosmologists to test the underlying fundamental assumptions (e.g. general relativity) of the standard cosmological model, and isolating them from systematic uncertainties in the observations. It is likely that large surveys of the Universe will continue to drive cosmology in the coming decades.

8. First Light

*** How, when, and where did the first stars and black holes form?**
*** What are the optimal ways to observe the first objects to form in the Universe?**
*** When and how did re-ionization occur?**
*** How and when did early chemical enrichment occur?**

The cosmic "dark ages", before the first objects lit up, is the least studied and understood phase of cosmic evolution. A key issue is the formation of the first stars which were likely massive objects, with short lifetimes, that rapidly enriched the surrounding gas to then form into newer stars. Observationally, this must have happened by z~7 as we already observe massive galaxies at this redshift with stellar masses a billion times the mass of our Sun.

To look beyond z~7, astronomers will need new techniques and instruments since these first objects will have faint fluxes. There are solid theoretical reasons to believe that the first stars may end as supernovae, and/or gamma-ray bursts, suggesting variability searches would be fruitful in finding them. It is also possible that other wavelengths, such as X-rays from early accreting black holes, may lead to the detection of the first objects.

Beyond the study of the first objects, we know that at z>5 the neutral hydrogen made at recombination (z~1100) was ionized again. This must have occurred as a result of the formation of the first objects, and therefore the study of this 'Epoch of Re-ionization' will be a major effort over the next decade. How and when this transition in the Universe occurred is still open for debate, but based on observations of the Gunn-Peterson effect and results from the Wilkinson Microwave Anisotropy Probe (WMAP), our best estimate is z~10 which redshifts the 21cm hydrogen line into the megahertz (radio) regime of the electromagnetic spectrum. New experiments are already underway to probe this new frontier, with more on the horizon.

Today, we witness that the Universe is thoroughly enriched by heavy elements, most of which were probably produced through stellar evolution processes. The details of how the Universe became enriched is an important question for astrophysicists, and based on elemental abundances in high redshift quasars (and damped Lyman-alpha systems), it is clear that this enrichment occurred rapidly at an early epoch, probably via a feedback mechanism related to the evolution of first stars and black holes (e.g., stellar winds, supernovae).

9. Galaxies

*** How and when do galaxies form and evolve?**
*** What is the role of large-scale environment and AGN feedback?**
*** What are the contents and structure of galaxies?**
*** What lies between galaxies?**

Rapid advances in observational astronomy are starting to reveal an intricate picture for how galaxies formed and have evolved. Moreover, numerical simulations have become increasingly sophisticated in modeling how structures emerge in a cosmology dominated by dark matter and dark energy. However, many fundamental problems remain unsolved due to the large dynamic ranges in scale and mass ($\sim 10^7$) involved in such research, and the complexity of the astrophysical processes involved (e.g. star formation, feedback from supernovae and active galactic nuclei).

In the next two decades, new radio, optical, X-ray and gamma-ray facilities will be used to study how galaxies formed and evolved, by probing the Universe to unprecedented depth in time and mass using many complementary techniques. New insights will also be gained into how stars, dark matter, central massive black holes and increasingly, the neutral and cold gas are assembled in galaxies as a function of time. Astronomers will probe the internal kinematics of stars and gas in galaxies to high redshift using the next generation of radio telescopes, extremely large optical telescopes and integral-field spectrographs. Nearer home, our own Galaxy will also be studied in unprecedented detail with both ground-based facilities and space satellite of the future.

In parallel, wide-field surveys of the Universe will map the distributions of galaxy properties as a function of environment, which will provide an insight into the role of energy feedback and chemical enrichment to explain the inter-galactic medium. It will also help determine the importance of mergers and interactions in shaping the global properties of galaxies. Such research will be performed in tandem with improved numerical simulations (with greater spatial and mass resolution), which incorporate more realistic astrophysics of star formation, magnetic fields and accretion.

10. Extreme Astrophysics

*** What are the laws of physics under extreme conditions?**
*** What is the physics of accretion and feedback?**
*** What are the sources of gravitational waves and neutrinos?**
*** How and where does relativistic particle acceleration occur?**

One of the most fundamental questions we can ask is whether our laws of physics work under the most extreme physical conditions. The Universe is the most natural laboratory available to scientists for such tests as it provides extreme ranges of gravity, density, temperature, magnetic field and radiation. By observing these regimes across the entire electromagnetic spectrum, and via gravitational waves, cosmic rays, and neutrinos, we can, by comparison with detailed theoretical models, provide the strongest possible test of our understanding of astrophysics.

The behavior of light and matter close to a neutron star or black hole probes the strong-field regime of general relativity where the effects of light bending and 'frame drag' are maximal. The coupled processes of accretion and outflow, whether radiatively or magnetically driven, link accreting objects to their surroundings via a feedback mechanism. This is the route by which massive black holes grow across cosmic time, changing the black hole mass and spin, while large amounts of energy are deposited into the host galaxy and beyond helping to drive star formation, regulate galaxy evolution and heat the ambient medium. The observation of gravitational waves or neutrinos provides unique insights into the formation and evolution of systems such as binary mergers and core-collapse supernovae. Extreme environments are also prime sites for relativistic particle acceleration, often resulting in intense non-thermal radiation from phenomena such as pulsars, gamma- ray bursts and giant radio galaxies.

Existing and planned Ground-based facilities

In this section we give some notes on existing and UK ground-based facilities with strong UK involvement, listed in wavelength order from optical to radio.

ESO optical/IR facilities

The European Southern Observatory (ESO), operates optical-IR telescopes at the Paranal and La Silla observatories in Chile, on behalf of its 14 member countries. The UK joined the partnership in 2002 to enable UK participation in ALMA and E-ELT, and to provide access to competitive 8m-class telescopes. The current annual cost of membership for the UK is £18.9 M/yr, with an additional £10 M/yr residual contribution to entry costs being paid until 2012.

The current flagship ESO facility is the Very Large Telescope (VLT) at the Paranal Observatory in northern Chile, comprising four 8.2-m Unit Telescopes (UTs), equipped with 11 facility-class instruments that deliver imaging and spectroscopy at optical, near- and mid-IR wavelengths. Recent developments include the successful commissioning of the X-Shooter spectrometer and the first on-sky demonstration of wide-field adaptive optics (MAD). The UK is currently building the K-band Multi-Object Spectrometer (KMOS), a second-generation VLT instrument.

The VLT Interferometer (VLTI) brings the light from either the UTs or four 1.8-m auxiliary telescopes (ATs) to a coherent focus, enabling near- and mid-IR interferometry. Current instruments include the near-IR AMBER which combines 3 beams at once with a sensitivity at H of 7 with the UTs or 5 with the ATs at medium spectral resolution (low and high also available). Spectrally resolved visibilities are measured on baselines up to 100 to 200 m giving information on 2 milli-arcsecond scales. MIDI operates in the mid-IR and combines 2 UT beams with a sensitivity of about 1 Jy at 12 microns. Future instruments planned are a 4 beam thermal-IR instrument, MATISSE and astrometric instruments PRIMA and GRAVITY, whilst plans for a new 4-way near-IR beam combiner VSI are on hold.

Two new survey telescopes have also been constructed at Paranal: the VLT Survey Telescope (VST), a 2.6-m telescope for optical surveys due to start operations in 2010, and the Visible and Infrared Survey Telescope for Astronomy (VISTA), a new 4m-class wide-field telescope, constructed by a UK consortium and funded via the UK Joint Infrastructure Fund (JIF). The VISTA camera has a detector-filled field of view three times that of WFCAM on UKIRT. Final VISTA commissioning is now nearing completion and full survey operations will commence in the third quarter of 2009. VST and VISTA will be used for large scale public surveys in the optical and IR with a duration of five years. Following competitive peer review by ESO, nine public surveys have been selected with six survey PIs from the UK. The science goals of these surveys include the provision of targets for follow-up with the VLT and cover a wide range of science ranging from the nature of dark energy, high-redshift quasars, galaxy evolution including obscured star formation, the stellar initial mass function, the structure of the Milky Way and the lowest mass stars.

The La Silla Observatory comprises the ESO 3.6-m, the New Technology Telescope (NTT; also 3.6m) and shared-time on the 2.2-m telescope with the Max Planck Gesellschaft. La Silla operations have been restructured in recent years to reduce costs, but continues to deliver good science. The prime example of this is the dedicated use of the 3.6-m with the High Accuracy Radial velocity Planet Searcher (HARPS) for studies of extrasolar planets.

While E-ELT is ESO's overwhelming priority for the foreseeable future (after ALMA), the community has also been pushing for a wide-field spectroscopic capability. As a result, a Call for New Instrumentation is imminent.

E-ELT

ESO are now in the advanced design stages of a 40m-class European Extremely Large Telscope (E-ELT), which will be the largest optical-IR telescope (0.36-24 m) in the world. IR observations near the diffraction limit will provide images more than five times sharper than those from the JWST. When coupled with the 16-fold increase in collecting area compared to current telescopes, this will provide a dramatic increase in discovery power, enabling European scientists to address some of the most fundamental questions in astronomy and physics. The nine 'Prominent Science Cases' identified by the E-ELT Science Working Group are exo-planets; stellar disks; initial mass function in stellar clusters; resolved stellar populations; black holes/AGN; the physics of galaxies; metallicity of the low-density IGM; the highest redshift galaxies; and dynamical measurement of the universal expansion.

The E-ELT Basic Reference Design was endorsed by ESO Council in December 2006, leading to the start of the telescope Phase B in Jan 2007. The UK has been a key partner in this activity, leading instrument studies and development of the science case, partly funded by FP6 and FP7 programmes, technology R&D in partnership with industry, and industrial design studies funded directly by ESO. STFC has invested £3.2M since May 2005 into targeted technology development, including participation in the initial instrumentation studies. In this phase, technology development has been focused on critical areas where UK research groups and industry can add significant value: large adaptive mirrors, adaptive optics simulation and on-sky validation and IR detectors.

If the UK aspires to take a major role in building and exploiting E-ELT, it must lead the development of the instruments needed to do the science. UK groups currently lead the evaluation and further development of its science capabilities through a Design Reference Mission, and are developing and proving critical adaptive optics and instrument technologies. The aim is to maintain and expand UK leadership in instrumentation and adaptive optics, as well as develop opportunities for UK industrial participation as the project moves towards the construction phase from 2011 onwards. Total cost of 20% share of E-ELT capital costs and instrumentation to the UK would be about 12Meu per year for ten years.

Indeed, E-ELT provides a range of important opportunities for knowledge transfer, ranging from large deformable mirrors to novel IR detectors. The current R&D into large deformable mirrors has industrial partners (BAe Systems, Teer Coatings and ECM) and support from the Ministry of Defence through the Joint Grants Scheme. The study on applicability of novel IR detectors in astronomy has QinetiQ as a partner, and interest from Selex Systems Ltd. A Basic Technology research project on Ultra-precision Surfaces has resulted in development of a new facility for process development and manufacture of large optics in North Wales, driven by demanding E-ELT primary mirror segment requirements, but resulting in capability attractive to a range of industrial and space applications. In the wider context, several UK industries are involved in central E-ELT contracts on issues associated with technology proving (e.g. in prototyping polishing of the primary mirror segments).

The recent ASTRONET Infrastructure Roadmap identified the E-ELT as one of two top-priority facilities for the coming decade, the other being SKA, and a construction proposal will be presented to the community in 2010, with the start of operations planned for 2018. The UK is one of the major partners in the project, involved in Phase-A studies for four E-ELT instruments, industrial studies for elements of the telescope design and continued leadership and development of the science case.

There are several competing development programmes working towards an ELT. In the US, two projects (TMT, GMT) are underway. In Canada, ACURA has been formed and is currently working with TMT to implement an ELT with major Canadian Fund for Innovation support. Japan is also a possible TMT partner.

Gemini

The Gemini Observatory consists of two 8.1-m telescopes, the Gemini South telescope on Cerro Pachon in Chile, and the Gemini North telescope on Mauna Kea, Hawaii. The telescopes were designed to provide the best image quality possible from the ground together with the lowest possible emissivity, for optimal infrared observing.

Both Gemini telescopes are equipped with GMOS - workhorse optical imagers and multi-object spectrographs, which also have optical IFUs. Gemini North also employs Altair - a natural/laser guide star adaptive optics system which feeds a near-IR imager (NIRI) and a 3"x3" IFU (NIFS). Uniquely, NIFS is also equipped with a coronograph, designed for spectroscopy of extra-solar planets. Depending on instrument switching, Michelle - a mid-IR imager and spectrometer is also available, although demand is low. By 2010A it is expected that a repaired GNIRS (a cross-dispersed near-IR spectrograph) will be operating at Gemini North. Before instrument problems in 2007B, GNIRS was one of the most requested instruments on Gemini.

At Gemini South, together with GMOS there is a high-resolution near-IR echelle spectrometer (Phoenix), a mid-IR imager and spectrograph - TeRECS, and NICI - an near-IR coronagraphic imager designed to detect Jovian planets around nearby stars. GMOS remains the most requested instrument on Gemini-South. By 2009B/2010A it is expected there will be a new MCAO-fed near-IR imager and multi-object spectrometer (2'x6' FoV), FLAMINGOS-2 on Gemini South. Further along the line is the Gemini Planet Imager (GPI) - an extreme-AO coronagraph. Unfortunately the Gemini Board has not been able to take up their options to progress beyond the study phase a number of high-profile instruments - PRVS, HRNIRS, GLAO and WFMOS – several of which had significant UK participation.

Membership of the Gemini Observatory also enables access to the 8m-class Subaru telescope, at a low level (3 nights/semester), through a programme of time exchange - a very popular option for wide-field imaging.

The current cost of membership to STFC is approximately £5.4M/yr, though this will not be sufficient to cover the full cost of future instrumentation upgrades. UK support is provided by the Gemini National Office in Oxford, at an additional cost of around 0.4 M/yr. STFC is currently committed to selling up to 50% of its Gemini time to other partners.

STFC must consider whether UK involvement in Gemini, and funding for the National Office, should be renewed, and must do so well ahead of the expiration of the current agreement in 2012. Several options may be available, such as restricting the UK's involvement to that of Gemini North, though this would be dependent on the cooperation of existing and/or new partners

ING (INT+WHT)

The ING is comprised of 2 telescopes: the 4.2m WHT, and the 2.5m INT. The WHT is an alt-az mounted telescope and is equipped with Nasmyth platforms able to support substantial instruments. The WHT was constructed in the mid 1980's and has developed a comprehensive instrument suite able to deliver observations at both optical and near-IR wavelengths. The WHT also has a natural and laser-guide star AO imaging and spectroscopy instrument suite. These instruments serve a broad user community (solar system to cosmology). It is expected that the high precision stabilized spectrograph, HARPS-NEF, will begin commissioning in 2010. This will be used for follow-up of candidates from NASA's Kepler satellite in the search for Earth-like exo-planets. The ING are also proposing a new wide-field, high-efficiency, multi-object spectrograph for the WHT to exploit the large number of deep photometric surveys operating in the northern hemisphere (eg UKIDSS, PanSTARRS). The WHT has also attracted many privately owned, specialist instruments. This includes SAURON, PNS, UltraCAM amongst others. The WHT AO infrastructure is to be used as an e-ELT AO testbed. Since its inauguration, the WHT has remained one of the UK's most over-subscribed and productive telescopes. It currently has no fund for further instrument developments.

The INT is a fork mounted equatorial telescope. It is equipped with a Wide field camera and cassegrain spectrograph. It focuses on wide-field imaging surveys and large-scale spectroscopic programmes.

As the facility has been restructured in recent years, the UK share of telescope time on ING telescopes has been reducing in recent years from 60 to 33%. This is in line with the reduction in the UK contribution to operations (2009/10 £1.0M/yr). As the support model for the telescopes has evolved the ING have combined their Student Education Scheme with visitor introductions on the INT to good effect. The UK share will further decline as Harvard University (the lead partner in the HARPS-NEF project) buys up to 50-60 nights per year (with a UK contribution of about 20 nights).

Liverpool Telescope (LT)

The Liverpool Telescope (LT) is a fully robotic instrument owned by the Astrophysics Research Institute of Liverpool John Mores University. It was constructed on La Palma using funds made available from the European Union, JMU and STFC. STFC currently provides operational costs (£0.5M/yr) for the telescope in return for 40% of the available time (allocated through a PATT committee). The telescope became fully robotic in 2003.

Using the faculty optical and IR imaging instruments the telescope executes proposals over all areas of science ranging from solar system objects to active galactic nuclei. The LT's robotic control makes it ideal for exploitation of the time domain and proposals are executed that require observations on all timescales from seconds to years.

In addition to the workhorse imaging camera, JMU have provided some novel instrumentation, such as RINGO which was built to detect polarisation signatures in GRB's. The RISE (high speed imaging camera) is heavily used by the UK Exoplanet community. The faculty integral field spectrograph (FrodoSpec) is currently being commissioned. JMU also have plans for a second generation, wide field, optical/IR imaging instrument.

The LT’s active outreach and schools program makes use of 5% of the available telescope time provided by JMU.

SuperWASP

The SuperWASP experiment originated amongst a group of UK universities with the purpose of detecting large extrasolar planets via the transit technique. As the problem required novel equipment the WASP consortium raised funds locally for the construction of 2 nearly identical facilities on La Palma (commissioned in 2004) and at SAAO (2006). The £1.5M funding for this came mostly from local SRIF awards. STFC originally supported the project at a low level through the grants line but in 2008 a Project grant was awarded (£0.4M/yr during 2008-10). This supplies software support to finish the infrastructure development and support costs at the facility sites. The STFC award also provides support for the development of a public archive (along with interrogation tools).

Each facility has a field of view of nearly 500 square degrees and is designed to detect variations in stellar brightness of just a few millimags. A recent upgrade has led to a significant reduction in noise sources and hence significantly smaller planets are now detectable. WASP planets are amongst the brightest transiting planets and are therefore used as targets elsewhere eg atmospheric studies with HST/JWST. Thanks to the STFC award, the WASP project is now the largest source of bright transiting exoplanets (>30% of known transiting planets). This will continue even in the CoRoT/Kepler era - their fields of view are much smaller than SuperWASP and hence their candidates are, in general, much fainter.

MROI

The Magdalena Ridge Observatory Interferometer (MROI) is a near-IR (JHK) imaging interferometer being built in New Mexico. It will consist of six 1.4 m telescopes in a reconfigurable Y shape with baselines out to 350 m. The capital funding (~$70M) is mostly coming from New Mexico Tech. A team at the University of Cambridge has led the design of the system and is building the delay lines and, together with St Andrews, is proposing to build the science beam combiner. The total STFC investment since 2002 has been £1.2M. A further £3.2M is being requested, which includes £2.1M for the beam combiner, to take the project to completion, in return for which 30 nights p.a. for 10 years would be available to UK astronomers.

The design aims to deliver a sensitivity of 13.5 magnitude at H or K and model-independent imaging of targets at sub-milli-arcsecond resolution - over an order of magnitude more sensitive than AMBER at the VLTI. Six-way beam combination allows for the recording of visibilities - and hence high-fidelity imaging - 5 times faster than AMBER. Low (R~35) and medium (R~300) resolution spectral modes will be available, with first light in 2011 and operation of the full array in 2014.

Upgrade paths will be available for high spectral resolution, an extension to optical wavebands, and an increase to ten telescopes. Options are available for the purchase of additional UK access for an extra 50 nights per year at a cost of ~£330k p.a. The main science areas for the UK community are the imaging of planet formation and accretion phenomena in proto-planetary discs, mass-loss in evolved stars and the broad-line region in AGN.

UKIRT

The 3.8-m UK Infrared Telescope (UKIRT) is owned by STFC and operated on its behalf by the Joint Astronomy Centre. 10% of time is allocated to the University of Hawaii as a site tax and, more recently, the Seoul National University has purchased access to a small proportion of nights. UKIRT is also a member of the Opticon trans-national access programme. The continuing search for international partners, along with the withdrawal of the Cassegrain instrument suite in February 2009, reflects recent pressure to reduce UKIRT's operating costs (~£2M/yr). Currently engineering and operational costs are shared with JCMT.

The wide field camera (WFCAM) is currently UKIRT's sole operational instrument and is being used to undertake a range of survey programmes of the northern sky in the near-IR (UKIDSS). Citations and publication rates for the UKIDSS show that UKIRT remains at the peak of its productivity.

The completion of the UKIDSS survey is the highest priority for UKIRT over the next few years (to 2012). The science goals of UKIDSS are: the coolest and nearest brown dwarfs, high-redshift dusty starburst galaxies, elliptical galaxies and galaxy clusters at redshifts 1‹z‹2, and the highest-redshift quasars, at z=7. There would be demand for additional surveys beyond the present planned end-date of 2012. A further opportunity exists to exploit UKIRT's unrivalled performance by equipping it with a fibre-fed high-resolution spectrometer - the UKIRT Planet Finder (UPF). UPF will search for earth-mass planets orbiting in the habitable zones of nearby cool stars by measuring radial velocities via their near-infrared stellar spectrum. It can also slew immediately to z>7 GRBs to probe the ionization history of the universe. With an operating model closely integrated with that of WFCAM and scientific requirements perfectly matched to UKIRT's modest collecting area and high efficiency, UPF would maintain UKIRT as a productive facility beyond 2012. . Funding for UPF is being sought from STFC.

STFC has set the Director of UKIRT the task of finding new partners and sources of funding for UKIRT in order to reduce the operational cost to no more than the costs shared with the JCMT via the JAC.

JCMT and CCAT

The JCMT is the world's largest single-dish submillimetre telescope. It is a partnership between the UK as owners (55%), Canada (25%) and the Netherlands (20%). The University of Hawaii has access to 10% of nights as a site. JCMT is a member of the RadioNet consortium, which offers transnational access to European astronomers. The management and operation of the facility by the Joint Astronomy Centre is widely viewed to be exceptional, with a current cost of 1.4M/yr.

The JCMT Legacy Survey will exploit the unparalleled mapping speed of JCMT's flagship instrument, SCUBA-2, as well as the HARP/ACSIS heterodyne imager. SCUBA-2 is expected to be fully operational by the end of 2009. The Legacy Survey, which is open to all UK astronomers, comprises: SCUBA-2 'All Sky' Survey, SCUBA-2 Cosmology Legacy Survey, Nearby Galaxies Survey, JCMT Galactic Plane Survey, Gould Belt Survey, Spectral Legacy Survey and Debris Disk Survey.

The high-frequency receiver, RxW, provides access to, e.g., high-J lines of CO and is providing a glimpse of what ALMA will be capable of in the middle of the next decade. Membership of JCMT also offers access to eSMA, though the delivery of this option has been delayed and may be of little interest beyond the start of the ALMA era in 2011-12.

The future of the international partnership needs to be reconsidered well before the current agreement expires, in 2012. There is a case for extending to 2015 in order to complete the full originally conceived 5-year Legacy Survey. JCMT must be judged against the 12-m Atacama Pathfinder EXperiment (APEX), which aims to be equipped with Artemis - a 200/350/450-micron camera with 2048 bolometers and in which ESO has a 27% stake - and the proposed 25-m Cornell-Caltech Atacama Telescope (CCAT).

CCAT, to be sited on an excellent high altitude site for sub-mm observations in Chile, is designed to provide the wide-field complement in the era when ALMA becomes fully operational (2014-). The main scientific priorities are to carry out deep, wide-field surveys in the 200-450-micron range to unprecedented depth - this being a region critical to understanding the high-redshift universe and how stars form and evolve. Although the UK is formally a partner in the CCAT project, our contributions at the present time are only through relatively small-scale design studies. A more serious commitment could be justified by the UK's heritage in submillimetre astronomy.

It should also be recognized that CCAT will not be completed until well into the next decade. The JCMT Legacy Programme will map large areas of sky to the confusion limit and much of the accessible sky to a shallower level, thus providing the UK with a competitive edge in the early ALMA era, in the same sense that VISTA complements VLT as a wide-field `finder' telescope.

ALMA

The Atacama Large Millimeter/Submillimetre Array (ALMA) is currently under construction at an altitude of 5km in the Chilean Andes. ALMA is a global endeavour - a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile - an array of 66 reconfigurable antennas with a correlator capable of 10^{16} operations per second and receivers covering every atmospheric window between 0.3 and 9.6mm, providing an impressive combination of sensitivity, angular resolution, spectral resolution and imaging fidelity.

In the nearby Universe, ALMA will study the processes of star and planet formation, revealing the details of young, still-forming stars,and is expected to show young planets still in the process of developing. ALMA will also explore the complex chemistry of the giant clouds of gas and dust that spawn stars and planetary systems. Further afield, ALMA will study the first stars and galaxies that emerged from the cosmic dark ages.

UK astronomers played a key role in the development of the ALMA science case and the technological development that has made it a reality. Professor Richard Hills is the ALMA Project Scientist. Several UK groups are making key contributions to the water vapour radiometer calibration system, the data transmission system, the software that allows astronomers to plan and execute their observations, and the archiving system. The UK also hosts the European Front End Integration Centre.

UK astronomers have access to ALMA via the subscription to ESO. Time allocation procedures have yet to be hammered out, but a call for Early Science programmes will be made in late 2010 when the array is expected to have 16 antennas with receivers for bands 3, 6, 7 and 9 (3, 1, 0.85 and 0.45mm).

The UK's ALMA Regional Centre (ARC) is based in Manchester. The ALMA support group at ESO HQ will provide only archiving services, with no direct support to observers or proposers. For that reason the UK, and its main competitors, have all planned for local support structures (ARClets) to aid in the expected large number of non-specialist users of this facility. In the UK this support will benefit from the interferometry experience at JBO. Without this Centre, UK astronomers would be at a severe disadvantage relative to astronomers in the US, Europe and Japan. The cost is £0.3M/yr.

In the future, the UK aspires to design and build the band 1 (9.6mm) receiver system, and there is keen interest in the science possible in that waveband, e.g. wide-field unbiased surveys of redshifted CO(J=1-0) to complement those possible with E-VLA at lower frequencies and searches for prebiotic molecules in circumstellar disks..

APEX

The Atacama Pathfinder EXperiment (APEX) is a modified VERTEX prototype 12-m antenna on the high-altitude Llano Chajnantor site in Chile. UK astronomers have access through ESO, which has a 27% stake. It is, or will soon be, equipped with heterodyne receivers in the 211--270, 275-370, 375-500 and 1250-1384-GHz windows, and with the 295-pixel LABOCA submm (870-um) camera. Artemis, a wide-field 200-350-450-micron imager, is expected to be commissioned in the next year or so.

e-MERLIN

e-MERLIN is the UK's array of six 25-32m radio telescopes with baselines up to 217 km operating at wavelengths of 1, 6 and 20 cm. It is owned by the University of Manchester and operated by Jodrell Bank Observatory on behalf of the UK community under a grant provided by STFC. Recent upgrades worth £8M, achieved with significant funding contributions from the University of Manchester and the regional development agency, have increased the sensitivity by a factor of 10 compared to the old MERLIN array, mainly through the use of broad bandwidth optical fibre connections provided by the telecommunications company Global Crossing Europe, as well as upgraded receivers and a new correlator. At 6 cm a further factor of two increase in sensitivity is achieved with inclusion of the re-surfaced 76 m Lovell Telescope on payment of a £2.5k per day access charge. This provides imaging at the microJy level on baselines that are similar to those that will form the core of the SKA. The combination of this sensitivity with an angular resolution (40 milli-arcseconds at 6 cm) that is 8 times that of the EVLA at cm wavelengths enables a wide range of science to be addressed, as illustrated by the recent Legacy Programme awards. These will take up half of the available time and address topics such as galactic star and planet formation, star formation history and black hole growth in galaxies at low and high redshifts, AGN physics and dark matter distributions. The previously small user base for MERLIN has been expanded to 325 users from 20 countries for the e-MERLIN Legacy Programme. First light fringes with e-MERLIN have been achieved and full operations will start in 2010 for an initial operating period of up to

2014. Post-2014 e-MERLIN could be seen as complementary to JWST, until the arrival of SKA-Phase 1. MERLIN operations are currently supported by a grant worth around £2.4M per annum but it is expected the STFC contribution to this will reduce over the next 5 years, with increasing support from Manchester.

JIVE/EVN

The Joint Institute for VLBI in Europe (JIVE) is the umbrella organization for the coordination of the European VLBI Network (EVN). UK participation in this organization currently costs STFC £100k/year. The EVN is the most sensitive VLBI network in the world (except for times when the GBT combines with the VLBA), with potentially the highest angular resolution when utilizing intercontinental baselines to China and/or South Africa. The extremely high angular resolution provided has allowed e.g. structural studies of extragalactic supernovae, high redshift radio galaxies and H_2O masers in the early universe. The EVN has also developed the first large-scale open e-VLBI system, in which the data are correlated in real time; the system can routinely correlate at data rates of 1 Gb/sec or higher.

In a global context, the key competition comes from the VLBA, which is a VLBI array in the USA operated by NRAO, and the High Sensitivity Array which can include VLBA, phased VLA, Arecibo, Effelsberg and GBT. The VLBA is less ad-hoc than the EVN, but has not implemented e-VLBI. Several other smaller VLBI arrays are available across the world.

As well as technical coordination, JIVE provides user support (even at the level of assistance with writing proposals and analyzing data) and travel support for visitors (via European trans-national access funding).

LOFAR(-UK)

LOFAR is a Dutch-led low-frequency (30-240 MHz) software telescope currently under construction and about to issue its first call for proposals (with full capability to be offered by 2011). LOFAR is one of several pathfinders for the low-frequency component of the SKA. LOFAR-UK is a consortium of more than 20 UK institutions, mainly university astronomy groups, which have contributed collectively enough money (~£1.2M), in combination with SEPNET (South-East Physics Network, funded by HEFCE) to buy a LOFAR station for the UK. This station will be installed at Chilbolton, an STFC site, and LOFAR-UK are looking to STFC for operations costs (approximately £200k / year), and have aspirations for further stations. The return for this investment would be considerable UK involvement in LOFAR science, as well as training in the use of 'next generation' radio technology and the associated very large data volumes. LOFAR has six key science projects, *The Epoch of Reionisation*, *Surveys, Transients and Pulsars, Cosmic Rays, Solar* and *Cosmic Magnetism*. The UK consortium is involved in all six of these KSPs, with leadership of the *Surveys* and *Transients* KSPs. Starting in 2009, the ratio of KSP to open time will be 90:10, evolving to < 50:50 by 2014.

The VLA and GMRT offer observations within the LOFAR band, but should not be competitive in terms of sensitivity or fields of view. The MIT-led Australian Murchison Wide-field Array (MWA) is comparable to a short-baseline version of the high-frequency end of LOFAR, and at a better site, but will not have open access. The US Long-Wavelength Array (LWA) will operate at comparable frequencies to the low end of LOFAR but is not currently fully funded. In terms of science goals some are being tackled by other facilities (e.g. searching for the direct HI signal of Epoch of Reionisation), but in the context of deep and wide extragalactic surveys, nothing will supersede those performed by LOFAR prior to *Phase-2* of SKA.

SKA

The Square Kilometre Array (SKA) is the primary goal for most of the world's radio astronomy community and is a transformational facility with a diverse science case. The final SKA will consist of three separate types of receptor (a sparse low-frequency aperture array, a dense mid-frequency aperture arrays, and high-frequency dishes) sharing the same infrastructure (fibre links, computing). A choice will be made around 2011-12 between proposed sites in South Africa and Australia, both of which are currently constructing ~$200M GHz-frequency pathfinders (MeerKAT and ASKAP respectively). Following the site decision, work will begin on the *Phase-1* SKA, which is the initial deployment of the array, providing 10-20% of the array collecting area at intermediate frequencies. *Phase-1* aims to deliver scientific data from 2017 and be complete around 2018/19; it will be followed by *Phase-2*, the full deployment of low- and intermediate frequencies. The implementation of the highest frequencies, SKA *Phase-3,* up to 25 GHz or higher, will take place in the 2020s.

Key science areas addressed by SKA Phases-1 and -2 are: (1) Mapping the Epoch of Reionization through, for example, tomography of the neutral inter-galactic medium during the 'dark ages'; (2) Studying galaxy evolution, cosmology and dark matter and dark energy through, for example, a billion-galaxy HI survey which will provide an inventory of the atomic gas content of the Universe over at least half its age, and will constrain dark matter properties (e.g. neutrino mass) and dark energy through baryon acoustic oscillation and velocity-space-distortion measurements; (3) Determining the origin and evolution of cosmic magnetism through observations of Faraday rotation towards millions of background radio sources; (4) Performing fundamental physical measurements through strong-field tests of gravity using pulsars and black holes and, via pulsar timing, detecting and characterizing gravitational waves.

The SKA is being designed as a general purpose facility with the specifications being defined by the requirements of the key science areas. However, with a sensitivity of more than 50 times the EVLA, e-MERLIN or LOFAR and with a survey speed that will be up to 10^6 times greater than the EVLA it will be capable of a range of science far greater than that encapsulated in the key science areas.

The current funding model for the SKA requires, in 2007 Euros, €300M for Phase 1 and an additional €1200M for Phase 2. These costs are being refined through aggressive R&D. The costs for Phase 3 will be determined in the next decade. The mid- to long-term funding proposal for the SKA, maintaining the current R&D activities within the UK, within UK is ~£3M/year for the next three years, followed by a possible ramped uplift to ~£10M/year starting in 2012/13 and then ~£13M/year from 2018/19 corresponding to the actual construction of the *Phase-1* and *Phase-2* SKA.

The UK currently holds a leading role within the European programme of R&D development towards the SKA, with a current major focus on developing mid-frequency-range aperture arrays as well as electromagnetic design, signal processing and communication technologies. The international SKA Program Development Office is based at The University of Manchester and the EC-funded, but global, SKA Preparatory Study (PrepSKA) is led by the STFC.

The technology required for radio astronomy is, amongst all fields of astronomy, most closely aligned with the commercial market; witness that radio astronomy R&D led directly to the development of wifi. The return to the UK for its potentially large investment in the SKA is already tangible, e.g. R&D contracts let to ~17 major companies including BAe, SELEX Galileo, IBM UK, Xilinx, Roke Manor (Siemans) as part of the SKADS programme; and ~£4M to Fujitsu-UK and Global Crossing for the installation and maintenance of the e-MERLIN dark fibre network, which is testing the technology required for the SKA. The continued funding of advanced SKA R&D will lead to further contracts and will place UK companies in an excellent position to bid for and win some of the major contracts that will be let for SKA construction.

Theory, high performance computing and virtual observatory

Although the issue of science exploitation is beyond the scope of this review, it is worth stating that investment in facilities is pointless without strong support from the grants line for exploitation and theory. Many of the facilities discussed here involve huge data volumes and innovative techniques will be necessary to process these data. Both theoretical modeling and data processing are likely to generate demand for high performance computing. The international Virtual Observatory represents a way forward to tackle some of these data processing and data access issues. ASTROGRID is the UK contribution to the world-wide Virtual Observatory activity. Phase 1 of ASTROGRID development is complete, but further development and maintenance may be needed over the next decade (an SoI has been submitted for a successor activity, VOTC).

Other facilities

Other projects and facilities in which the UK has an interest include:

FMOS

STFC has contributed £2.3M towards construction of the Fibre-Multi-Object Spectrograph on Subaru, with shared risk operation from the second half of this year, then a collaborative programme plus open time to be available from Semester 2010A. FMOS has 400 fibres operating at 0.9-1.8 m, with a field of view of 30 arcmin. UK observers are expected to get 30% of the total time on FMOS on Subaru, equivalent to around 100 nights over the next 10 years. There is a UK PI (Gavin Dalton). The prime science is expected to be - galactic archaeology, brown dwarfs, dark energy and high redshift galaxies.

DES (Dark Energy Survey): a 5000 square degree wide area galaxy photometric survey using a new 3 square degree CCD imaging camera with a new corrector on the CTIO 4.0m to estimate dark energy properties. The DES Consortium, in exchange for the instrument and a community pipeline will receive 525 nights over 5 years to carry out the Dark Energy Survey. STFC supported UK participation (UCL, Cambridge, Edinburgh, Portsmouth, Sussex) by contributing to funding of the DES camera (1.8M). DES is scheduled to start in mid to late 2011.

PanSTARRS4: an array of four 1.8m telescopes surveying the whole sky at fortnightly intervals, allowing even larger galaxy surveys than DES and with additional science goals like near-earth asteroid (main funding justification) and supernova searches. Individual universities (Edinburgh, Durham and QUB) have funded entry fees to PanStarrs1, which uses a single telescope, and have aspirations to be involved either in PanStarrs4 or LSST. Cost would be of order $1m per faculty member, spread over 10 years.

LSST (Large Synoptic Survey Telescope): 8.4 m telescope under construction making nightly surveys of sky and with an even larger survey capability than PanSTARRS4.

SALT (South African Large Telescope): several UK universities (Central Lancs, Southampton, Nottingham, Keele, OU and Armagh Observatory) have formed a consortium to participate in this 10-m telescope, the largest in the southern hemisphere.

GTC (Spanish Gran Tecan 10-m telescope on La Palma): The GTC is a Spanish built and run 10m telescope now entering routine operations on La Palma. It is similar in design to the Keck but is updated and will include, a full suite of optical and infrared instruments. Limited access to the GTC is available through ESO until 2012. It is possible that a more formal allocation of GTC time could be available for a reasonable fee.

EST

The European Solar Telescope is a pan-European project involving 29 partners, plus 7 collaborating institutions, from 14 different countries aimed at the development of a 4m class solar telescope optimized for studies of magnetic coupling between the deep photosphere and upper chromosphere that will answer fundamental questions related to the origin and evolution of magnetic fields on the Sun and their role in producing solar activity. The focal plane instrumentation will provide diagnostics of the thermal, dynamic and magnetic properties of the plasma over many scale heights, by using multiple wavelength imaging, spectroscopy and spectropolarimetry. EST will be the premier ground-based solar facility in Europe (first-light ~2019) and is the top ranked medium scale ground-based observational facility in the ASTRONET Roadmap. UK participants (QUB, UCL-MSSL, and Andor Technology) are currently funded by an EC design study and is participating in the science definition, detector and data flow work packages, and aspire to continue these roles into construction.

The attached Table shows publications and citations data for UK facilities, with selected international comparisons, taken from the study by Trimble and Ceja (2008). The publications are from the years 2001-2003, and the citations refer to the three years after publication. These give a snapshot from over five years ago, but may be of interest, at least for facilities that were well-established at the period being analyzed.

Publications and citation rates of UK facilities, with selected international comparisons:

Facility	no. of papers 2001-2003	citations/paper
8-m		
Gemini	36.4	17.25
VLT	345.5	16.49
Keck	*365.5*	*23.33*
Magellan	*27.6*	*17.39*
Suburu	*109.1*	*13.07*
4-m		
AAT	170.2	26.98
WHT	158.6	12.69
NTT	128.0	12.69
UKIRT	130.3	11.50
ESO 3.6m	117.0	10.90
KPNO 4m	*79.2*	*15.71*
CFHT	*123.8*	*15.07*
Palomar 5m	*57.8*	*12.53*
CTIO 4m	*96.0*	*12.48*
2-m		
INT	87.8	11.10
ESO 2.2m	60.9	11.02
Las Campanas 2.5m	*56.7*	*12.93*
U Hawaii 2.2m	*53.3*	*12.51*
Calar Alto 2.2m	*49.1*	*11.34*
Radio		
Merlin	56.2	8.9
EVN	27.0	7.6
VLA	*582.2*	*14.6*
AT/ATCA	*139.4*	*12.2*
VLBA	*105.2*	*11.0*
Westerbork	*61.3*	*10.5*
GMRT	*36.1*	*5.7*
Submm		
JCMT	178.1	18.1
CSO	*31.5*	*14.6*
IRAM 30m	*113.2*	*14.0*

[Data from V.Trimble and J.A.Ceja, 2008, Astron.Nachr. 329, 632]

Appendix: Declarations of interest

M.Rowan-Robinson:
Deputy PI, Spitzer-SWIRE Survey
Co-I Herschel-SPIRE, Planck-HFI

R.Fender
PI LOFAR-UK, PI LOFAR Transients Key Science Project
UK representative LOFAR International Working Group
Co-I VOTC
Member SKADS Oversight Committee

D. Pollacco
P-I SuperWASP-N
Chair LT Oversight Committee
Chair ING Science Advisory Committee
PI PLATO
Past Chair LT TAC, ING TAC

R.McMahon
Ex-chair Gemini TAC
PI VISTA Survey
CoI DES
CoI ASTROGRID, VOTC
Grant holder LSST science case development
CoI VISTA data flow system

M.Hoare
Member SKA International Science WG
PI eMerlin Legacy Survey
Contributor MROI case
Chair JCMT Survey Oversight Committee

R.Ivison
ESO: STC member; instrument scientist for KMOS study phase
ALMA: Chair, UK ALMA Oversight Committee; European Science Advisory Committee; ALMA Science Advisory Committee
Gemini: instrument scientist, GMOS-S; project scientist, HRNIRS study phase
CCAT: UK Project Associate
JCMT: past Chair, UK and International TACs; past Chair, JCMT Survey Steering Group; SCUBA-2 GT team member; past member, JCMT Board
eMERLIN: Chair, Legacy Steering Group
LOFAR-UK: management council
FIRI: Cosmic Vision proposal, co-PI
Herschel/SPIRE: Associate Scientist
UK ATC staff