ASTRONOMY ADVISORY PANEL STRATEGY 2003

- AIM

1.1 The aim of the strategy document is to provide a summary of the science priorities and requirements in the area of astronomy and astrophysics, as viewed by the Astronomy Advisory Panel, over the coming ten years. The document will allow:

- PPARC Science Committee to make informed decisions over allocation of resources
- The UK science community to be aware of PPARC's science priorities in the area
- The Grants and Fellowship Panels to know and to respond to the science priorities

2. BACKGROUND

2.1 The last long-term review of Astronomy policy (the Long Term Science Review - LTSR) was undertaken in 2000. It identified the perceived strengths of UK astronomy, indicated the science key themes for the coming decade and outlined the resources and facilities required to deliver the future programme as identified at that time. Since that time, UK astronomy has undergone several major changes, with facilities planned at that time now entering operation, new missions and facilities on the horizon, and most recently, membership of the European Southern Observatory (ESO) organisation. As part of the process of joining ESO, the UK ground-based community was required to make operational savings in several areas. The outcome of this process has resulted in refocusing of the science priorities and operational procedures of UK telescopes.

3. PHILOSOPHY

3.1 The strategy presupposes that funding will only be given by PPARC for excellent research.

3.2 Beyond the assumption of excellence, the strategy will:

- Promote research in areas of strategic importance
- Promote research which will have significant international impact
- Promote research which will clearly lead to development of new areas of strategic importance
- Not exclude research in areas not directly within the key science priority areas where its real significance can be demonstrated and in particular, where breakthroughs would have a wide implication for astrophysics in general

3.3 The strategy must:

- Enable production of world-leading, high impact science
- Ensure access to a range of relevant, world-competitive facilities
- Recognise areas of UK strength
- Meet the broader requirements of the PPARC strategy, interacting with other areas of the programme where appropriate
- Maximise the UK's return on ongoing investment in existing facilities and projects
- Prioritise appropriately between new and diminishing science areas and associated facilities
- Provide a balanced programme including ground- and space-based instrumentation, technology development and theoretical work
- Provide a route to developing and encouraging long-term, 'blue-sky' projects

4. KEY SCIENCE PRIORITIES

4.1 Based on the advice of the advisory panels, the Science Committee, in its recent strategy paper, has laid out a recommended science programme with the goal of investigating a series of fundamental questions crossing the PPARC remit:

- What are the basic properties of the fundamental particles and forces?
- Is there a 'Theory of Everything', and if so what form does it take?
- What is the origin of the Universe?
- How did it evolve?
- Can we understand the origin of the observed structure?
- What constitutes the dark mass and dark energy of the Universe?
- How does the Universe work?
- What is the present and future influence of the Sun on our solar system?
- How do stars and planetary systems form and evolve?
- Has life existed elsewhere in the Universe, and does it exist elsewhere now?

4.2 Clearly, some of these fundamental questions lie within the remit of the astrophysics and cosmology communities. A single approach, technique, or even broad sector cannot however, tackle these questions in isolation. A coordinated approach encompassing several topics contributing knowledge to the larger, overarching questions is needed. Four key science themes for astronomy were originally identified in the LTSR, where the UK would be able to make a significant impact in the following 10-15 years. These, slightly updated, remain as our priorities:

- Cosmology
- The formation and development of galaxies
- Star formation and the formation and evolution of planetary systems
- Extreme environment astrophysics

4.3 Concentrating on research in these areas will enable the UK to make major advances in answering the fundamental questions of universe origin and evolution, missing mass, structure and planetary formation encompassed within the four headings. More detailed discussion on the topics is included below. Projects outside these broad areas are not excluded, but would be expected to justify their importance and eventual relevance to astrophysics and cosmology in general.

4.4 Underpinning the experimental activities laid out below, the UK currently has a vibrant theoretical astrophysics and cosmology community, including three major consortia. Research by members of these groups crosses all four priority science areas, and is world-leading in many areas. Although maintaining this work largely depends on attracting funding for individuals through the grants line, there is an ongoing requirement for computing and data processing equipment. The Consortia and individual researchers need access to powerful supercomputing resources, while there is a corresponding need for adequate personal computing support. With theoretical astrophysics and cosmology relying increasingly on supercomputing, a failure to support and develop these resources will result in the UK losing its world-competitive status.

4.5 e-Science – Over the coming years, the sheer amount of observational data, and the rate of acquisition of those data from our facilities will provide a major challenge to the astronomy programme. Developments in e-Science will be required to manage the data rates and archiving from the WFCAM and VISTA surveys. In addition, a common theme of the four science areas discussed in detail above is the need for more comparative study of different datasets. New tools and techniques relating to advanced archiving, data-mining, visualisation and analysis will be needed in order to maximise the exploitation of the major new datasets. Currently, the AstroGrid project coordinates these activities, but this will likely evolve over time, and as new opportunities and the Virtual Observatory develops.

5. CORE SCIENCE THEMES

1. Cosmology

- What is the origin of the Universe?
- Can we understand the origin of the observed structure?
- What constitutes the dark mass and dark energy of the Universe?

In the post-WMAP & 2dF era, cosmology is likely to see less emphasis on cosmological parameters and more emphasis on detailed studies of galaxy formation, the intergalactic medium and the distribution of various forms of matter: stellar, gas, non-baryonic....... An essential target of cosmology will be to test the current belief that around 99% of the matter in the Universe is dark, and to tie down its properties and nature. Work in this area crosses the boundary between cosmology and particle physics. In the near future, Planck is the key experiment for "pure" cosmology, not just as a consistency check on cosmological parameter determinations, but also probing the ionization history. Large-scale structure surveys will continue to be relevant over this timescale. In the medium-term, ALMA and JWST will be key to improving cosmological understanding of the intergalactic medium, as well as star formation in the early universe. In the longer term, SKA furnishes the most direct probe of the ionisation history of the universe, as well as allowing direct mapping of the cold gas distribution on cosmological scales using HI surveys. XEUS will open up a spectroscopic capability for studies of distant X-ray sources, particularly early-forming groups and clusters. LISA may detect cosmological gravitational waves, an area of overlap with the particle astrophysics panel.

2. The formation and development of galaxies

- How did galaxies form?
- How did they evolve?
- Can we understand the origin of the observed structure in the Universe?

In recent years, the study of galaxy formation and evolution has moved to position where they now incorporate enough of the relevant physics that they should allow the first meaningful tests of computer simulations against observational data, although is still limited by the huge dynamic ranges involved, and by our limited understanding of the processes of cooling, and of feedback from AGN and star formation

On the observational side, it is now possible to investigate galaxies at redshifts beyond 1 using our current 8-m class telescopes, VLT/Gemini, and by gravitational lensing or in cases of extreme luminosity, out to redshifts beyond 5. To study the formation and early evolution of galaxies which are more typical of most of the population of present-day galaxies will require a new generation of optical, infrared (OWL/ELT, JWST), submillimetre (ALMA) and radio telescopes (e-MERLIN, SKA – mapping HI from reionisation to the present). Underlying the push to observe normal galaxies throughout their lives will be studies of comparator nearby galaxies and extensive theoretical modelling of galactic evolution. Wide-field surveys will generate the huge samples needed for studies of structure development. Herschel (FIRST) will map out cold gas and dust in forming galaxies at a range of epochs. GAIA will perform crucial independent 'archeology' of the formation of our own and nearby galaxies. XEUS will map out the hot intergalactic medium from the earliest forming groups of clusters to the current epoch.

3. Star formation and the formation and evolution of planetary systems

- How do stars and planetary systems form?

- How do planetary systems evolve?
- Has life existed elsewhere in the Universe and does it exist elsewhere now?

Understanding the birth of stars is fundamental to astrophysics. Any realistic explanation of the formation and evolution of galaxies requires us to know what determines the rate of star formation, what determines any variation in the mass distribution of stars formed, and what determines the characteristics of multiple star systems. The star formation process also produces planetary systems. The study of star formation – and associated protoplanetary discs - requires both imaging and spectroscopy into the highly-obscured collapse phase (e.g. with ALMA, Herschel, JWST), while details of the accretion and outflow phase will need high resolution observations from optical to radio (using VLT/Gemini, ALMA and e-Merlin). To probe planets in the process of forming requires still higher resolution, with IR interferometry (VLTI/and possibly other Ground Based facilities, Darwin). The detection and investigation of exoplanetary systems is clearly an area of growing interest, particularly among the wider community and public. Observational capability will move beyond the current capability of detecting Jupiter-sized planets. The near-term objectives are to exploit new search methods to place characteristics of the systems on a sound statistical basis (e.g. Eddington, later GAIA), in the mid-term detection of terrestrial planets and spectroscopic studies of giant planetary atmospheres, and in the long term spectroscopic studies (Darwin, ELT) of nearby terrestrial planets to search for signatures of life. The whole field of star and planetary formation and evolution will need to be backed by theoretical studies (a UK strength), involving powerful computing resources.

4. Extreme environment astrophysics

- What are the fundamental laws of physics
- How does the Universe work?
- What is the nature of energy production in the Universe?

The exceptionally strong gravitational, magnetic and radiation fields, and high densities and temperatures observed in many astrophysical objects simply cannot be reproduced in the laboratory. These extreme environments provide a unique opportunity to test and develop the fundamental laws of physics. A wide range of astrophysical processes and a veritable zoo of exotic objects are involved. Research requires facilities operating throughout the electromagnetic spectrum from radio to – ray, and therefore depends on both space-born and ground-based observations. The current suite of observatories XMM-NEWTON and CHANDRA in X-rays and Integral in – rays will dominate the next decade. The ambitious next-generation XEUS ESA mission is under development, with strong potential roles for UK groups in shaping this mission and its instrumentation. The – ray burst mission Swift has UV/Optical/X-ray instruments involving UK groups. The most energetic phenomena will be detected in the the astroparticle domain with VERITAS. Complementary optical/IR observations (particularly time-resolved spectroscopy) require VLT/GEMINI (eventually ELT) access, with a valuable survey/monitoring role for smaller telescopes. Infra-red/sub-mm observations (including spatial resolution by interferometry) are an essential component in understanding the supermassive black holes in the highly-obscured active galactic nuclei. The new field of gravitational wave astronomy offers the prospect of studying supernovae, black holes and neutron star systems in a completely new domain, requiring both ground-based (LIGO) and space-based (LISA) facilities to achieve the required wavelength coverage.

6. FACILITIES

6.1 It is clear that in order to achieve the science goals in the areas outlined above, a range of techniques and facilities are required. The table at the end indicates the current immediate, medium- and long-term infrastructure requirements for the programme, alongside a brief discussion of their relevance and impact on each of the four science areas.

7. IMPLEMENTATION

7.1 The strategy should be implemented by:

- Linking the science requirements to the provision of the necessary facilities;
- Ensuring that the overall resources into particular areas are appropriate, in particular ensuring that the necessary research personnel are available to achieve the science goals;

Maximising world impact by either the direct visibility of the UK role, for example by PI-status, lead authorship, or by playing a smaller, but critical role (by virtue of specialist expertise) in large projects where the scientific return will be outstanding

- The UK should be supportive and centrally involved in high UK priority science, ESA missions. Only where a high priority scientific area cannot be addressed by an ESA mission should the UK seek other partnerships.
- The UK should exploit its membership of ESO. We should be seen as a key influence in the development of ESO's strategic vision and seek to become a significant partner in new developments, where these match UK science goals and utilise UK technological and/or instrumentation expertise.
- Appropriate support for the grants line must be viewed as critical for the programme overall.
- The UK must engage in maximum exploitation of its current world-class facilities, including the JCMT, UKIRT, ING and AAT on the ground, and observatories such as XMM-Newton in space. Capability should be upgraded where appropriate, but decreasing involvement should be sought where a facility is no longer globally competitive.

Major infrastructure requirements currently funded or required in the near future	
FACILITY	**SCIENCE IMPACT**
8m telescope time (ESO VLT/Gemini/VLTI)	**Cosmology** Access to 8m telescopes, and instruments such as multi-object spectrographs (eg VIMOS on the VLT and GMOS on Gemini) will be essential to perform detailed statistical studies of the distribution and characteristics of galaxies in the Universe. Such studies will be key to understanding the large-scale structure of the Universe. **The formation and development of galaxies** The 8m class ground based telescopes are currently heavily involved in understanding the formation and development of galaxies. With their narrow field infrared capabilities, the Gemini telescopes allow study of how high redshift galaxies are assembled, while the VLTs are optimised for large spectroscopic surveys using instruments such as VIMOS. The capability of VLTI will be required to resolve the broad line region in AGN. **Star formation and the formation and development of planetary systems** High-resolution infrared imaging and spectroscopy on 8m telescopes will allow detailed study of star forming regions, young stellar objects and debris disks. They will also enable Doppler searches for giant planets, direct detection of hot Jupiters and in the longer term, spectroscopic follow-up of transit candidates. Interferometry will allow astrometric detection of cool giant exoplanets, high resolution observations of young stars and disks revealing magnetospheric accretion, jet formation and planet formation processes. **Extreme environment astrophysics** Time on these large telescopes will allow unprecedented investigation of high redshift AGN; ultra-luminous X-ray sources in distant galaxies; supernovae; GRBs; galaxy cluster environments; isolated neutron stars; supersoft sources; accretion processes; shocked winds and jets.

<u>Planck</u>	**<u>Cosmology</u>** Planck will have a critical role to play in cosmology, through determination and confirmation of the basic cosmological parameters and the ionization history of the Universe. Polarization studies possible with the mission may reveal information about primordial gravitational waves. Planck will also open up an important avenue for cosmological studies of galaxy clusters via the Sunyaev-Zel'dovich (S-Z) effect. **<u>The formation and development of Galaxies</u>** Planck will perform all-sky survey of dusty galaxies and AGN down to fluxes of tens of mJy and investigate the demographics and evolution of dusty star-forming galaxies. The mission will allow a detailed census of many thousands of galaxy clusters using the S-Z effect. Combining these signals with X-ray observations will constrain the properties of the intergalactic gas in clusters out to z~1.
<u>Wide field surveys</u>	**<u>Cosmology</u>** Wide-field surveys are vital to cosmographic studies as well as cosmological applications of gravitational lensing. The latter, in particular, will prove important at unravelling the complex relationship between the distributions of dark matter and luminous galaxies. **<u>The formation and development of galaxies</u>** Large datasets are needed for statistical studies of galaxy formation and evolution. Survey data from UKIRT, VISTA and the VST will provide the all-sky coverage necessary for the task. **<u>Star formation and the formation and development of planetary systems</u>** Studies of star formation will also rely on the large sample datasets yielded by UKIRT and VISTA. To detect planetary systems, the SuperWASP programme will undertake surveys for hot Jupiters transiting nearby stars while the VST will contribute to a microlens survey for cool planets. **<u>Extreme environment astrophysics</u>** Wide-field surveys will contribute to source population studies and time domain studies of accreting sources (both AGN and galactic binaries).

e-Merlin	**Cosmology** e-MERLIN will allow the study of gravitational lenses that will advance the determination of the cosmological parameters $_{m}$ and $_{L}$. The facility will also enable the study the distribution of mass through detection of microlensing in high-redshift dark matter halos. **The formation and development of galaxies** Ultraluminous mergers (e.g. Arp 220) will be detectable to z~5 with e-MERLIN, and dust-shrouded starbursts (sub-mm galaxies) studied in detail. Star formation activity and rates will be mapped and estimated on fine scales out to z~3. It will also allow detailed study of SNR populations in z<0.1 starburst galaxies. **Star formation and the formation and development of planetary systems** e-Merlin will provide high-resolution images of the ionized jets and winds from young stars, multi-transition maser studies of magnetic fields, and kinematics in star forming regions. **Extreme environment astrophysics** The enhanced facility will allow study of the obscured nuclei of active galaxies, AGN at high redshift; jets from compact galactic and extra-galactic objects, GRB studies, pulsars and neutron stars.

Herschel (FIRST)	**Cosmology** Herschel will carry out multi-wavelength far infrared and submillimetre deep surveys to reveal and study the statistics and physics of the population of high-redshift galaxies responsible for more than half the energy produced in the universe since the big bang. **Formation and development of galaxies** With its sensitivity to a wide redshift range and capabilities for photometry and spectroscopy of cold dust and gas, Herschel observations will allow the chemical and physical evolution of the interstellar medium in galaxies to be explored in detail. **Star formation and the development of planetary systems** Herschel will carry out detailed photometric and spectroscopic studies of star-forming regions in the galaxy, clarifying the connection between stellar mass and clustering and the initial conditions that lead to star formation. The circumstellar envelopes of evolved stars and the diffuse phases of the interstellar medium will also be observed by Herschel, allowing the physics and chemistry of the stellar-interstellar cycle to be understood in detail.

Medium Term Infrastructure requirements (to ~2010)

JWST	**Cosmology** JWST will have a significant impact on cosmology through studies of the intergalactic medium and imaging and spectroscopy of dusty high-redshift galaxies. The mission will also allow study of lensing, high-z supernovae and detection of obscured AGN. It will complement Herschel (and also SIRTF). **The formation and development of galaxies** A central goal of the JWST mission is seeing 'First Light', i.e. the earliest galaxies to form, and hence to map out their entire evolution. **Star formation and the formation and development of planetary systems** JWST will enable infrared imaging of protostellar disks, and will undertake high sensitivity infrared spectroscopy and imaging of star forming regions. **Extreme environment astrophysics** JWST will image obscured nuclei of active galaxies, AGN at high redshift, ultra-luminous X-ray sources in external galaxies, supernovae (especially at high redshift), GRB and galaxy cluster environments.

ALMA	**Cosmology** ALMA has direct cosmological applications by the detection of dust-obscured galaxies beyond z = 5, CMB foregrounds and S-Z fluctuations that can track the intergalactic medium in galactic clusters. **The formation and development of galaxies** ALMA will enable: Detection of continuum emission from warm dust in the first dusty galaxies (ultraluminous infrared galaxies out to z~20), detection of CO emission (and determination of z) in ULIRGs to z>6 and normal galaxies to z~1 and detailed imaging of individual molecular clouds in galaxies to ~100 Mpc. **Star formation and the formation and development of planetary systems** The facility will allow high resolution molecular line and dust continuum studies of the star formation process, detailed imaging of planet-induced structures in protostellar disks and astrometric detection and measurement of giant exoplanets. **Extreme environment astrophysics** ALMA will image the obscured nuclei of active galaxies, AGN at high redshift; jets from compact galactic and extra-galactic objects.
GAIA	**Cosmology** In providing an experimental test of General Relativity with improved precision and range of measurements, GAIA will impact on our knowledge of fundamental physics and cosmology. **The formation and development of galaxies** An essential complement to high redshift studies of galaxy formation is archeology performed on our own present day Galaxy. GAIA will map out the formation process using indicators such as tidally stripped streams of stars in the halo, and also provide superb kinematic and distance data throughout the major part of our own Galaxy. **Star formation and the formation and development of planetary systems** Using astrometric techniques, GAIA will detect and measure the orbital parameters of cool giant exoplanets. **Extreme environment astrophysics** GAIA will perform an all-sky census of accreting Galactic objects for population studies. Its large sample of QSOs will result in advances elsewhere, such as galaxy evolution.

Long-Term infrastructure requirements (>~2010)	
SKA	**Cosmology** SKA will open up the possibility of HI redshift surveys to very large volumes. This will provide a means of measuring directly the clustering properties of cold gas, providing a direct test of galaxy formation theory. It will also allow detailed studies of the ionization history of the Universe, likely to be a key science goal long beyond the Planck mission. **The formation and development of galaxies** Evolution of the HI content of galaxies will be studied to z~3, and galaxy surveys selected on HI content can be carried out to the same depth, with immediate determination of z. Denser parts of Lyman α forest clouds will be detected in emission and their relationship to galaxies studied. The evolution of molecular gas in galaxies will be studied via detection of redshifted CO emission at z>4. Cluster mass distributions will be mapped to large radius using weak lensing. SKA will have high sensitivity to SNR and diffuse radio emission associated with star formation, allowing study of starburst activity to cosmological distances, and SNR evolution throughout the local Universe. **Star formation and the formation and development of planetary systems** SKA will provide high resolution kinematic studies of ionized jets and winds from young stars, and high resolution imaging of cool dust emission from the inner optically obscured regions of protoplanetary disks. **Extreme environment astrophysics** SKA will probe obscured high redshift AGN, jets from compact galactic and extra-galactic objects, GRB and pulsars, with improved resolution and sensitivity,

LISA	**Cosmology** LISA is clearly the leading project for cosmological gravitational wave astronomy. It offers the possibility of opening an entirely new view on the early Universe. It may be possible to detect primordial gravitational waves produced during an inflationary epoch, along with gravitational radiation produced by astrophysical sources. **The formation and development of galaxies** LISA should enable the detection of gravitational wave signals from massive black holes forming in galactic centers via collapse of star clusters or multiple mergers of ~1000M_o seed black holes. It will also probe signals from the final months before the merger of central black holes following galaxy mergers to z>3. **Extreme environment astrophysics** Along with the ground-based facility, LIGO, LISA will open an entirely new window on prompt gravitational wave emission from supernovae, coalescing black hole/neutron star/white dwarf binaries, and constant emission from ultra-compact binary systems. It will also probe the properties of massive black holes (e.g. spin) via signals from compact objects falling into them.
DARWIN	**Cosmology** Although not a major priority of its mission, the unprecedented spatial resolution of DARWIN will provide a useful tool for observing high redshift infrared-bright or dusty galaxies. **Star formation and the formation and development of planetary systems** DARWIN will image the 300 nearest planetary systems, search for and undertake spectroscopy of 30 systems with habitable planets, in a search for extra-solar life. It will obtain high-resolution mid-infrared images of the planet-forming disks around young stars. **Extreme environment astrophysics** DARWIN will image the cores of objects such as AGNs and QSOs with exceptionally high resolution.

OWL/ELT	**Cosmology** A future ELT will allow studies of the furthest and faintest galaxies in the Universe. Key goals will include looking out to the first generation of stars, and the era of reionisation, investigation of the emergence of large-scale structure, and the evolution of basic cosmological parameters. **The formation and development of galaxies** The potential gains in collecting power and spatial resolution offered by an OWL/ELT will be essential for imaging and spectroscopy of 'normal' (rather than exceptionally bright) galaxies in formation. The spectroscopic capability will be required for astrophysical study of the very faint objects discovered by facilities at other wavelengths. **Star formation and the formation and development of planetary systems** Imaging and spectroscopy of fine structure in protoplanetary disks, giant exoplanet atmospheres, possibly extending to terrestrial exoplanets. **Extreme environment astrophysics** Obscured nuclei of active galaxies; AGN at high redshift; ultra-luminous X-ray sources in external galaxies; supernovae, especially at high redshift; γ-ray bursters; galaxy cluster environments, isolated neutron stars; supersoft sources.
XEUS	**Cosmology** XEUS will follow large-scale structure evolution through studies of high-redshift galaxy groups and how they turn into clusters, and probe the intergalactic medium using absorption lines. **The formation and development of galaxies** XEUS will allow spectroscopic detection of the earliest forming groups and galactic clusters to $z\sim3$, the evolution of heavy element abundances in clusters, and detailed spectroscopic study of effects of hierarchical merging on hot baryons to $z\sim2$. Other areas would include the study of the hot IGM outside clusters via resonance absorption line studies using background AGN, detection of massive accreting black holes to $z>10$, and statistical study of mass growth via variability timescales, determination of abundances in hot galaxy winds, and study of the relationship between starburst and AGN activity to $z>2$. **Extreme environment astrophysics** XEUS will examine AGN at high redshift, ultra-luminous X-ray source populations in external galaxies, supernovae, GRBs, cluster IGM physics, galaxy cluster environments, and isolated neutron stars.