Road Map to DARWIN and Beyond:

A Ten Year Strategy for Exoplanet Research in the UK 2006 - 2015

Prepared by the PPARC Exoplanet Forum Working Group for the Astronomy Advisory Panel

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Executive Summary

The existence, or otherwise, of potential life-bearing planets outside the Solar System remains as one of the outstanding questions in modern science. The characterisation of other planetary systems, and the search for life on planets outside the solar system, is going to happen within the coming decade. Given the immense scientific and cultural impact this will have, it is essential that the UK plays a leading role. This requires a coherent strategy for the long-term support and development of UK Exoplanet science.

The Exoplanet Forum Working Group was requested by PPARC to develop a 10 year strategy for enhancing UK involvement in Exoplanet science. The goal was to ensure that UK researchers will be positioned to hold leadership positions in future space-based (specifically ESA's DARWIN mission) and ground-based (the development of ELTs) Exoplanet search programmes. The strategy developed here seeks to maintain and increase the short-term support of areas of existing UK strength and expertise, to enhance the international credibility of UK Exoplanet research, whist setting the scientific and technical developments that will serve as a stepping stone to DARWIN and beyond. Our starting assumption is that a primary goal of Exoplanet research is to detect and study light directly from an Earth-like planet orbiting in the habitable zone of a Sun-like star.

The cost to PPARC by Financial Year of the strategy is as follows a) *New money*:

Project (costs in £k)	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	**Total**
Planet Searches											
SuperWasp	150	150	150	150	150						750
AAPS	90	90	90	90	90						450
GENIE		100	100	100	100	100	100				600
Robotic Telescopes	1000	2000	1000	100	100	100	100	100	100	100	4700
Science Exploitation											0
Project Manager	20	30	50	100	100	100	100	100	100	100	800
Science focus meetings	15	15	20	20	25	25	25	25	30	30	230
Visiting Fellowships	50	53	55	58	61	65	68	70	73	75	628
Technology											0
Systems modelling	100	100	100	100	100	100					600
ELT EU FP7 matching finds			80	140	140	140	140	140	140	80	1000
Laboratory test-bed		50	100	450	100	100	100	100			1000
Technology focus meetings	15	15	20	20	25	25	25	25	30	30	230
Total	**440**	**603**	**765**	**1228**	**891**	**655**	**558**	**460**	**373**	**315**	**6288**
Total with Robotic Array	**1440**	**2603**	**1765**	**1328**	**991**	**755**	**658**	**560**	**473**	**415**	**10988**

b) *by providing support for money funded by other programmes*:

Project (costs in £k)	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	**Total**
Planet Searches											
PRVS				1100	100	100	100	100	100		**1600**
Science Exploitation											
Visiting Fellowships	30	30	30	30	30	30	30	30	30	30	**300**
Ph.D. students	100	100	100	100	100	100	100	100	100	100	**1000**
PDRAs	500	500	500	500	500	500	500	500	500	500	**5000**
HPC facilities	350	100	100	350	100	100	350	100	100	350	**2000**
Technology development											
EU FP7	?	?	?	?	?	?	?	?	?	?	?
Total	**980**	**730**	**730**	**2080**	**830**	**830**	**1080**	**830**	**830**	**980**	**9900**

Our main recommendations are listed here. They are justified in more detail in section 6:

Planet Searches

- Provide increased operational support for SuperWASP
- Maintain funding for the AAT Planet Search programme
- Support development of the Precision Radial Velocity System on Gemini (North)
- Negotiate entry to Las Cumbres Observatory global telescope network, or to fund an 8 x 1 m telescope network to expand the UK microlens detection capability
- Support participation in the ESA-ESO GENIE science programme as a precursor to DARWIN

Science Exploitation

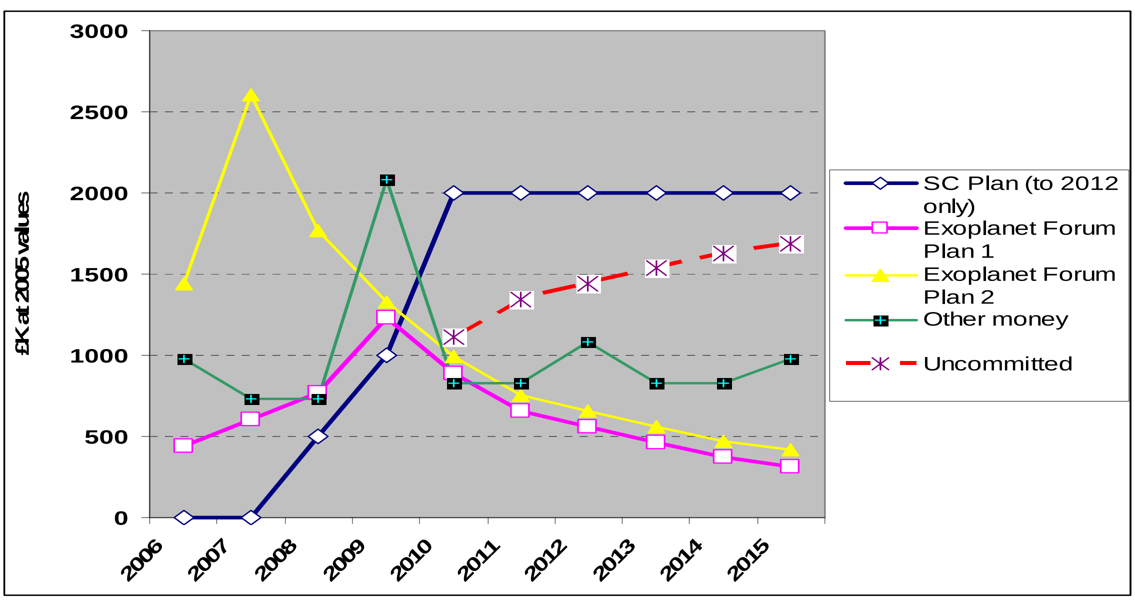
- Provide support for a Project Coordinator ramping up to full time position by 2009
- Establish an (initially) virtual DARWIN Integrated Science Centre (DISC) with a targeted Visiting Fellowship programme and a series of Science Focus Meetings
- Provide *targeted* Ph.D. support in Exoplanet research, at >5 studentships yr^{-1} for 10 years
- Provide additional support for PDRAs in Exoplanet research at >5 per yr^{-1} for 10 years
- Provide stable and continuous investment in HPC facilities over the next 10 years to support Theory and Modelling
- Support the establishment of a UK GAIA Data Centre

Technology Development

- Develop end-to-end systems modelling to allow optimisation of the science capability of the DARWIN and ELT systems
- Fund or support a major UK laboratory facility as a test-bed for ultra-high quality imaging, coronography, and image quality evaluation techniques
- Support a series of Technology Focus Meetings

Beyond DARWIN

- Plan for full engagement in ESA's Cosmic Visions 2015 - 2025 Far-IR observatory mission (FIRM), and the 2015 – 2018 Japanese SPICA mission
- Plan for full engagement in a 100 m class ELT
- Provide flexibility of an uncommitted funding line to respond to new opportunities



The Exoplanet Forum Plan 1 is the yellow row in the first Table on Page 3, Plan 2 is the same programme but with additional costs included to purchase 8 x 1m telescope if the Las Cumbres discussions fail to produce an acceptable solution to the Microlensing Community requirements. The SC plan is the current operational plan. The uncommitted line provides projected flexibility to respond to new opportunities, but is based on Science Committee agreeing to provide £2M/year in the forward look for 2012/13 and beyond.

Introduction

The existence, or otherwise, of life-bearing planets outside the Solar System is one of the major unresolved questions in science. The discovery of planets orbiting stars other than the Sun has given this question renewed urgency, leading to the emergence of a new discipline within astronomy: Exoplanet science. Exoplanet research puts our own solar system in context through the characterisation of other planetary systems; aims to understand the origins of planets; and to answer whether habitable planets exist outside the Solar System. Understanding the origins of planets, and the emergence of life, is a multifaceted problem, encompassing other areas such as astronomy, physics, biology, chemistry, geology, etc.

Advances both in technology, and our astrophysical understanding, guarantee that the detailed characterisation of extrasolar planetary systems will occur within the coming decade. It is anticipated that results (either positive or, just as significantly, negative) from studies on whether biological life could be present on Exoplanets will be available within the next 20 years. Technological advances in both ground-based and space-based instruments are expected to result in significant progress towards detection of Earth-like Exoplanets. New ground-based telescopes are under investigation, including the ESO Overwhelmingly Large Telescope (OWL) and the USA/Canadian Thirty Meter Telescope (TMT). Both ESA and NASA also have major missions planned for searching for Exoplanets from space. The ESA mission is called DARWIN, in which a series of telescopes form an interferometer in space are planned with a projected launch date is 2015. Through the UK's subscription to ESA, PPARC is anticipating a strong UK contribution to the mission. The purpose of this report is to outline a strategy for Exoplanet research in the UK that paves the way for our participation in the DARWIN mission, and future ground-based planet search programmes (such as those using ELTs). We start from the assumption that a primary goal of Exoplanet research is to detect and study light directly from an Earth-like planet in the habitable zone of a Sun-like star.

ESO and ESA recently commissioned an Exoplanet Roadmap, which was published earlier this year[1]. This and an equivalent NASA report[2] provide extensive background surveys summarising the present status within the field. In previous strategic exercises, PPARC has also expressed strong commitment to developing a long-term programme to search for life on worlds in other planetary systems[3]. The present report does not attempt to reproduce or update the findings of the ESO-ESA and NASA reports. Rather, it focuses on our national interests and activity, to identify a UK strategy that will lead to our full involvement in major international programmes of Exoplanet research which is supported by one of PPARC's four core themes of the astronomy programme, that of understanding star formation and the formation and evolution of planetary systems, as well as providing a roadmap to DARWIN.

Our strategy is based on a 10 year science-driven programme that supports the UK's current internationally competitive position in Exoplanet research, and focuses on the delivery of resources and expertise needed to maintain this position. Our aim is to ready the community to bid for scientific and technical leadership in future space missions (especially ESA's DARWIN). It will also enable us to develop skills and expertise that allows UK scientists and engineers participate in developments in ground-based instrumentation (e.g., the design of the next generation of telescopes such as the ELT). The strategy attempts to stimulate commercial competitiveness in our industrial base, and to maximise the return of our ESA subscriptions through juste retour, and to optimise our ESO membership through success in the overall instrumentation bidding process.

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[1] Perryman et al. ESA/ESO Working Group Report 1, March 2005, (http://www.eso.org/gen-fac/pubs/esaesowg/espwg_report1.pdf)

[2] Asrar, Spergel & Burrows (2004) (http://planetquest.jpl.nasa.gov/documents/SearchforEarth-LikeCDB59.pdf)

[3] PPARC Science Roadmap (http://www.pparc.ac.uk/Rs/Pp/Sp/Roadmap.asp)

1 Science

A better understanding of the occurrence and significance of Exoplanets is achieved through a two-fold strategy: (i) discovery and observation of Exoplanets, thus gaining a more complete and statistically significant overview of their number, distribution and characteristics and (ii) studying how planetary systems form and evolve. Each strategy is a necessary part of the road map to the DARWIN mission, and has technological challenges that need to be overcome in order to achieve the goal of the observation and characterisation of an Earth-like planet orbiting within the habitable zone of a Sun-type star.

1.1 Discovery and Observation of Exoplanets

The first Exoplanet orbiting a star was discovered in 1995; as of September 2005, 169 Exoplanets had been recorded[4]. Of these, about 25% are designated 'hot Jupiters': Jupiter-sized planets orbiting (periods < 1 week) close in to the central star. Discovering more long-period and low-mass Exoplanets is essential if we are to build up sufficient statistics to inform planetary formation and evolution theories. Interesting correlations are already apparent between host star metallicity and period distributions, however, there are still major selection effects contributing to the interpretations. Establishing the abundance pattern (vs. star mass, planet mass, orbit size) of Exoplanets will test planet formation theories. For example, some recent core accretion models predict large numbers of low-mass rock/ice planets for every gas giant. Planetary searches have been labour- and telescope-time intensive, and much of the current emphasis is now on automated searches. There are several different techniques that have been used by which Exoplanets can be observed.

1.1.1 Search techniques

Radial velocity searches have provided the great majority of Exoplanet detections to date. The method is based on differences in the radial velocity of a star's motion brought about by the presence of a planet or planetary system. The mass of an orbiting planet moves the centre of gravity of the star-planet system away from the centre of the star, thus inducing a variable Doppler shift in the detected radiation as the planet orbits the star. For UK scientists, the Anglo-Australian Planet Search (AAPS) has been in operation since 1998, and has already discovered 20 planets, 16 spectroscopic binaries, a brown dwarf, and made several confirmations and two non-confirmations of others earlier results. The discoveries include HD70642, often quoted as the best solar system analogue so far detected. Nonetheless it remains unclear whether radial velocity accuracies much better than ~ 1 m s^{-1} will be achievable over long timescales (the Earth in a nearby Habitable zone would give rise to an ~ 0.1 km s^{-1} signature).

This limitation can be partly overcome by searching for habitable zone planets around low mass stars (M and L dwarfs) where the low mass of the star results in a higher reflex velocity, further increased because the habitable zone is closer to the star. Such sources are best observed at near-IR wavelengths. The next generation of instruments proposed for Gemini includes one to tackle this problem: PRVS (Precision Radial Velocity Spectrometer). A UK-led consortium (University of Hertfordshire Science Lead, UK ATC managed, University of St Andrews partners) as well USA partners (IfA Hawaii, Penn State University) is bidding to build PRVS for Gemini, to search for these planets. Since low-mass stars make up the majority of stars in the local neighbourhood, the planets discovered by PRVS are likely to be the closest ones to the Solar System.

Microlensing is the unique ground-based method capable of discovering cool planets (1-10 AU orbits) with masses as small as the Earth. The Optical Gravitational Lensing Experiment

[4] An up-to date list is maintained at http://vo.obspm.fr/exoplanetes/encyclo/catalog-main.php

(OGLE) run by Warsaw University currently record ~ 600 Galactic Bulge microlensing events each year. Cool planets near the lens stars are discovered by intensive photometric monitoring to find brief flashes or dimmings caused by the planet's gravity; to date 5 Exoplanets have been detected by this method. Participation in the RoboNet microlens planet search has recently been enabled with PPARC funding. In 2005 the PLANET/RoboNet Microlens Planet Search (PRoMPS) discovered two cool planets, one with a mass of 3 Jupiters and one with a mass of 5 Earths.

Microlensing experiments currently can detect cool planets in 1 – 10 AU orbits down to the mass of the Earth. Simulations suggest annual discovery rates of 60 f_J for cool Jupiters and 10-30 f_e for cool Earths, where f_J and f_e are the numbers of cool Jupiters and cool Earths per lens star. Current estimates suggest that $f_J \sim 0.05$ – implying 3 cool Jupiter detections per year, which is close to the current detection rate. For cool Earths the numbers are more difficult to estimate as we do not have strong constraints on f_e. Theoretically f_e is expected to be much higher than f_J, and observationally the fact that the third of fourth microlens planet has a mass close to 5 earth masses is consistent with this. The 5-year PRoMPS experiment will give a significant constraint on f_e - we expect to detect ~ 100 f_e cool earths in 5 years and thereby determine whether f_e is high or low.

The transit method detects the dimming of stellar light by occultation by an orbiting planet. Transit experiments offer a number of very important contributions: (i) searches can be conducted over wide fields over long periods (5 years or more), and are therefore potentially efficient at detecting previously unknown systems; (ii) they can detect planets around stars at large distances (several kpc) and are therefore ideal for determining statistical properties of planetary systems; (iii) from the ground they are able to detect massive transiting planets, especially the ‘hot Jupiters’, while from space, planets down to Earth-mass or below can be detected; (iv) spectroscopy during the planet transit can yield physical diagnostics of the transiting planets. The UK based SuperWASP transit search project is a world-leading planet detection programme, being a consortium of eight academic institutions which include Cambridge University, Keele University, Leicester University, the Open University, Queen's University Belfast and St. Andrew's University. WASP hardware and deployment costs have been met by the participating UK universities, including £1.2 M SRIF allocations. A few dozen candidates from the first (2004) WASP observing season are currently undergoing spectroscopic confirmation.

Direct Imaging would be the ideal method by which to find and characterise extra-solar planets. While the contrast between star and planet (10^{-10} for Earth/Sun at visible wavelengths) as well as the close angular separations makes this very difficult for solar-type stars, extrasolar planets can be imaged in lower contrast environments. A planetary mass object has recently been imaged around a brown dwarf using an adaptive optics coronagraph together with simultaneously differential imaging on the VLT. The UK is engaged in a major effort using Gemini to constrain the abundance of planetary mass objects around white dwarfs. Direct imaging is an area where very substantial advances in hardware and software, e.g., the delivery of NICI, Gemini ExAO, VLT planet finder, GENIE should result in very substantial improvements in the capabilities for direct imaging of much fainter and cooler extra-solar planets.

1.1.2 UK Strengths and Contributions

The UK is involved in the Anglo-Australian Planet search, the SuperWASP transit-search project, the PLANET/RoboNET microlensing project, ground breaking instruments such as PLANETPOL as well as pioneering techniques for detection of reflected light from Exoplanets. The UK is internationally perceived as being among the world-leaders in these areas, despite stiff competition. Essentially these are all using current facilities and small, novel developments in instrumentation and software.

The precision and long baseline of the AAPS programme means that it is arguably the leading planet search in terms of the most scientifically interesting Jupiter analogues. Continuation of the AAPS programme is essential for the UK if it is to continue to play a leading role in the developments in this area. For transit studies, SuperWASP will become a clear world leader in detection of transiting planets. From 2005, its discovery rate in terms of sky coverage and depth will exceed that of its nearest competitors by nearly an order of magnitude. With adequate continued support, SuperWASP discoveries will dominate the first comprehensive studies of the Exoplanet mass-radius relation. SuperWASP has the additional advantage of discovering bright planets suitable for detailed follow-up studies to measure the planets' physical and atmospheric properties.

Other methods of detecting directly the light from an Exoplanet include from its polarised light and by recognising planetary spectral features in the integrated light of star+planet. The University of Hertfordshire's PLANETPOL is leading the way in the former technique. Further development of techniques devised at St Andrews for the latter method are close to setting useful limits on planetary albedos and will be a key element of Exoplanet studies on 30m-sized telescopes.

1.1.3 Forward look for the discovery and observation of Exoplanets

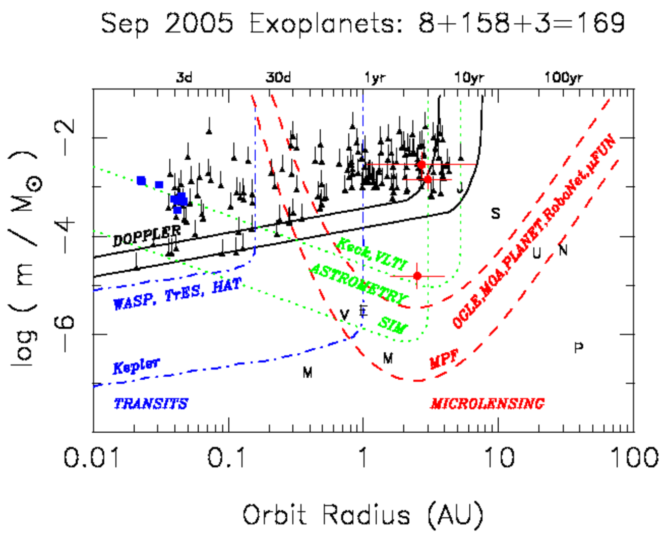
The ESA-ESO report estimates that the various techniques will provide detections as shown below, for various telescopes currently operational or in a planning phase:

M_{Planet} (M_J)	2004	2008-10	2008-10	2008	2015	2016	2016
	Radial Velocity (ground)		Transits (ground - WASP)	COROT	SIM	GAIA	
						astrom	photom
1-10	90	200-250	65	5-15	200	15 000	3 000
0.1-1	30	150-200	65	50-150	50	5 000	0
0.01-0.1	0	10-20	6	10-30	20	0	0
0.003-0.01	0	0	1	0-3	0-5	0	0

Given continued support, the UK's WASP cameras on La Palma and at SAAO will enable UK discovery of several hundred transiting 'hot Jupiters' over the next 5 years. These potential UK discoveries will establish the mass-radius-period-age distribution of hot Jupiters -- testing key predictions of models for the internal structure and orbital migration of planets. By targeting bright stars, the WASP planets will be suitable for UK-led reflected light and transit spectroscopy studies to measure the albedo, temperature and composition of the planetary atmospheres.

A recent development in the search for Exoplanets is establishment of the Las Cumbres Observatory (LCO). This will be a global network of 2m-class robotic telescopes, of which the two Faulkes telescopes will be an important component. This exciting project may represent an important opportunity to develop the long-standing UK ambition to establish RoboNet for a variety of time-domain astrophysics experiments – however we cannot be sure at this stage of whether negotiations with PPARC may lead to a solution that satisfies the community’s aspirations.

The area of discovery space that is expected to become accessible can be broadly summarised in the Figure on the right which shows the current and expected situations for Exoplanet detection as a function of planet mass for transits (blue), microlensing (red), astrometric (green) and radial velocity (Doppler) measurements (black). In each set of curves, the upper curve shows the areas of parameter space accessible from ground-based instrumentation, and the lower curve that accessible from space observations.



The measurement of 'cool Earth' abundances (determined by the microlensing technique), combined with the COROT/KEPLER measurement of 'hot Earths', will establish the probable distances to the nearest habitable planets that are the prime targets for bio-signature searches by DARWIN and ELTs. By 2015 (projected DARWIN launch), we should have the technical capability to observe Earth-like Exoplanets in their habitable zones, measuring their spectra and physical characteristics directly from spectroscopic observations.

1.2 Formation and Evolution of Planetary Systems

Complementary to the discovery, observation and characterisation of Exoplanets is a study of the processes that lead to their formation and evolution. This strand of Exoplanet research is carried out on three fronts: (i) theoretical modelling of planetary system formation; (ii) observation and modelling of debris disks and (iii) laboratory-based analyses of planetary materials. Each of these research areas has its own strong and vibrant community; one of the challenges of preparation for DARWIN is to ensure that the several communities interact and collaborate on a regular and productive basis.

1.2.1 Theory and Modelling

Theory is essential to Exoplanet studies as it provides the framework within which observations are interpreted, and provides predictions that can guide present and future planet finding missions. The relative youth of the subject, combined with the varied and complex physics involved on a range of spatial and temporal scales, means that Exoplanet science is being driven currently by observational discoveries rather than theoretical predictions. Further investment will help change the balance, allowing theory and modelling to gain increased predictive power, playing a more central role in the design of future planet searches.

The eventual goal of planet formation theory is to develop models that predict distributions of planet mass, semi-major axis, eccentricity and multiplicity for comparison with observations. Reliable predictions require complex disc models that include MHD processes, chemistry, dust physics, radiation transport, radiation from the central star, and input concerning the environment in which the protoplanetary disc is embedded (e.g. in a stellar cluster or isolated cloud core, in a single star or binary system). These models will include dust coagulation, planetesimal formation, the assembly of larger planetary bodies, and the interaction of these bodies with the surrounding disc. Such comprehensive models are some way off in the future, but the UK community is well placed to take such developments forward. Within this broader picture, there are a number of key problems that are being addressed now, which include: the origin of Exoplanet eccentricities; terrestrial planet formation and stability in Exoplanet systems, including post-migration formation in systems containing ‘hot Jupiters’; preventing rapid migration of low mass planets; the structure and effect of turbulent zones in protoplanetary discs; disc dispersal and halting migration; tidal interaction between short-period planets and host stars; forming the cores of gas giant planets; gravitational stability of protoplanetary discs. Research in many of these areas is being actively pursued within the UK theory community. Theoretical work is also required to understand the internal structure of planets and to make predictions concerning their observational appearance. Some of the issues are: the thermal structure/dynamics of irradiated 'hot Jupiter' atmospheres; the structure, dynamics and chemistry of giant Exoplanets around stars of different type with different orbital elements; the thermal and chemical state of extrasolar terrestrial planet atmospheres as a function of host star type and orbital elements. Research in a number of these areas is being pursued within the UK, and some would appear to be ideal topics for cross-research council collaboration between PPARC and NERC scientists.

1.2.2 Debris Disks

The discovery of a debris disk around Vega in 1984 by the IRAS satellite was, arguably, one of the first stages in the rapid and escalating development of Exoplanet research. Only now, as the disks are studied across a range of wavelengths from optical to sub-mm, by both ground- and space-based telescopes, are we really beginning to get our first glimpses of what they are telling us about planet formation and evolution. In the context of this report, debris disks are the very high dust-to-gas ratio disks around main sequence stars that are seen via their long wavelength IR and sub-mm excess radiation over that expected from the stellar photosphere. They were initially important because they first indicated the existence, then the prevalence, of dusty and rocky material around main sequence stars. Further work, based on theoretical modelling, showed that they could be used to test for the presence of planets, and give valuable information on the size distribution of the material of which they are comprised. Now it is known that they can be seen in various ways from scattered optical and near-IR light, thermal emission at mid- and far-IR wavelengths signifying the presence of fairly small grains and sub-mm wavelengths measuring emission from ‘grains’ up to several cm in size.

Numbers indicate that >15%, possibly up to 25% of main sequence stars (and even up to 50% of young A stars) still have debris disks. Does this mean that the same or an even higher percentage of stars have planets? In the few cases (still in single figures) where their morphology is amenable to study, often the structure is best interpreted as indicating the presence of one or more planets. At present, debate continues about the interpretation (or even presence) of warps in the disks. The evolution of the disks from gas rich to gas poor is also very poorly understood.

1.2.3 Laboratory-based analyses

There are several different aspects of laboratory-based research that contribute to exoplanetary research; for the purposes of this report, remote-sensing projects are also considered within this category. UK Expertise is spread across several institutions, and a variety of departments (astronomy, biology, chemistry, Earth sciences, mineralogy, physics), showing the very broad nature of planetary science contributions to Exoplanet research. Astrochemistry is the study of the chemistry that occurs in the interstellar medium and in molecular clouds. Current projects are seeking to understand molecule formation in the interstellar medium (in the gas and on dust grains) and the role that these molecules play in controlling the physical and biological evolution of the Universe. The formation of organic prebiotic molecules and probing non-biogenic formation of potential remote markers of life are studied. Laboratory studies are complemented by observations of molecules and dust from the IR to UV in stellar, circumstellar, nebular and cometary media. There is also a significant effort in understanding of the origin of chirality. Astromineralogy is the determination of the composition, generally by infrared spectroscopy, of dust in a variety of astrophysical environments (interstellar, circumstellar, cometary, etc). Laboratory-based projects directly analyse analogues of astrophysical dust, including crystalline and amorphous silicates, radiation-damaged silicates, organic molecules, coated grains and ices, in order to match and model astrophysical dust in terms of composition, mineralogy, size, shape, surface morphology, opacity, etc. Comparative planetology encompasses studies of the solid fraction of planets, their magnetic fields, planetary surfaces and atmospheres. Studies of the solid planet look at fundamental parameters (such as mass, composition, etc.) that control how a planet evolves and therefore whether a given Exoplanet is geologically suitable for supporting life. Planetary magnetospheres are important because of the role that they have in radiation shielding. Investigations of planetary surfaces and atmospheres, mainly by remote sensing, look at the geochemical and biological signatures of life and life-supporting environments, as well as climatology. Meteoritics: meteorites are the only physical examples that we have of material from the protoplanetary disk that was the precursor of our Solar System. Meteorites are not a homogeneous group of specimens: they exhibit a variety of compositions that indicate the heterogeneity of the nebula from which they aggregated. Components within meteorites formed over a restricted, but measurable timescale, giving a chronology for early planetary formation processes, including dust aggregation, melting and differentiation.

1.2.4 UK Strengths and Contributions

The UK has a long standing research effort in the areas of planetary formation and protoplanetary disk theory. UK researchers are at the forefront of much of the theoretical work in this area. Significant areas of success have been in modelling protoplanetary discs, disc-planet interactions, astrochemical modelling, stability studies of extrasolar earth-analogues in known extrasolar planetary systems, studies of tidal interaction of close orbiting planets with their parent star, and the study of debris disks disturbed by unseen planets. Continued investment in these and other areas will help ensure that UK research maintain its high profile and status. The theory community has a disproportionately large international impact at present, particularly in numerical simulations, and much world leading work has been done in this area. Using instruments such as SCUBA on JCMT, UK observational astronomers have been at the forefront of discoveries of debris disks around stars, and their interpretation. Their discoveries have been complemented by results from the strong astromineralogy and astrochemistry communities that have sought to understand dust grain-gas-ice interactions through laboratory analyses. The end point (or starting point) of Exoplanet research is undertaken by meteoriticists. The UK has one of the world's most comprehensive meteorite collections that acts (literally) as a solid basis for investigation of the dust from which planets form. The community of UK scientists that studies planet formation and evolution is widely-distributed across many institutions, but totals at least 100 individuals.

1.2.5 Forward look for formation and evolution of planetary systems

The resource that was identified most consistently as necessary to facilitate the community's preparation for DARWIN was a steady and increased flow of PDRAs and Ph.D. students. Development of theoretical models is labour intensive, calling for trained researchers to assist in developing novel algorithms and codes. Increased postdoctoral support is required to prevent the U.K. theory effort falling behind the growing international competition, and to develop areas which are currently not U.K. major strengths (e.g. terrestrial planet formation; internal structure of giant planets), but nonetheless of central importance to Exoplanet studies and future planet search programmes. DARWIN is some way into the future, so a continuous flow of young researchers is required to ensure that the UK maintains input to the mission, and will have immediate access to returned data. Given an expanding UK community, it is essential that we develop a national strategy for HPC to support future development. If there is no investment in new HPC facilities we will also lose our place at the forefront of the theoretical field, and this will happen very rapidly

Modelling is an important area where UK theorists are amongst the world leaders, and for many years theory has led the observational capability. However, the situation is now that the theorists need crucial observational material to take this work forward. Thus instruments now and in the future that will between them continue the extremely exciting developments in this area include SCUBA2 on JCMT, Michelle and TReCS on Gemini, Spitzer, Herschel, ALMA, and JWST/MIRI.

2 Technology Development

We start from the assumption that a primary goal of Exoplanet research is to detect and study light directly from an Earth-like planet orbiting in the habitable zone of a Sun-like star. We suggest that the elements of a UK strategy for Exoplanet technologies should:

- Identify the technologies needed to meet the highest priorities in the Exoplanet programme
- Identify existing UK strengths in these technologies and build on them.
- Identify any technologies that have potential large growth areas and support new initiatives in these areas.
- Identify existing or imminent programmes where (additional) UK funding can exert good leverage

2.1 Space-based Instrumentation

Space missions have a distinct advantage over ground-based instrumentation in their ability to have extremely stable and reproducible instrumental point spread functions - allowing efficient removal of the central star, and permitting constructive and nulling interferometry of Earth-like Exoplanets at even higher resolutions than an ELT. This is the premise behind ESA's DARWIN mission. There are many technical challenges to the mission, among which are requirements for optical test-beds for interferometry, beam-combiners, achromatic nulling techniques, large lightweight optics, cryogenic opto-mechanics, low vibration cryo-coolers, precision formation flying and precision deployable structures. Some of these technologies are advanced in the planning, if not the development. They have been highlighted at numerous conferences over a number of years and major resources have already been committed to solving many of the technology problems. (This should not be taken to mean that they have already produced all the solutions!). Bids for work are already being done by industry and much information will be commercial in-confidence. The opportunities for mid-term technology development here are already well known to major space industry companies that have outlets in or are based in the UK, such as EADS Astrium. However, there are still opportunities to work with these companies. Longer term, the need is to continue to improve PPARC/Establishment/Academic/Industry communications so that credible, well planned partnerships can be put together in time to win study contracts and R&D funding. One of the experiments in preparation for DARWIN is GENIE, an ESO-ESA instrument that will be positioned on the VLTI. Planning for this instrument is in progress, and offers an opportunity for the UK to become involved with DARWIN technology at an early stage in its definition, by providing staffing to support the operations and development of the instrument at the VLTI.

2.2 Ground-based instrumentation

Long term the ground-based route to study Earth-like planets is through ELTs. To achieve this requires significant technology development, as outlined below. Continued UK scientific and technical participation in such development is essential if UK industry is to be competitive at the build phases of ELTs. A key development route will be through the UK's involvement in ESO but funding will also be sought through the EU. In the EU FP6 programme 10M Euro over 5 years was secured for Joint Research Activities (JRAs), about 5M Euro of which has strong links to technologies important for ELTs (e.g. for Adaptive Optics). EU funds require matching funds for some aspects of the programme. The UK's contribution to ELT-relevant areas of FP6 was ~ 0.5 MEuro. The rules and budget for the next EU programme, FP7, are being defined now. The earliest date that funds will flow from this is late 2007; mid-2008 is more likely - probably as a 7-year programme. Broadly, it is hoped that twice as much money will come into astronomy from FP7 than FP6, assuming it gains the same fraction of the total budget. On this basis alone we therefore identify a line of a minimum of £1m total to enable the UK to access EU FP7 funds relevant to ELTs, assuming that ELT work becomes a slightly larger fraction of the total bid. Note this line does NOT include continuation of money to enhance UK's strength in ELT development in the same way as the current PPARC contribution of £2m for instrumentation development in the ESO-led ELT Studies.

The general science case for ELTs is made elsewhere (http://www-astro.physics.ox.ac.uk/~imh/ELT/). We summarise briefly some opportunities for Exoplanet research that will arise from development of ELTs. One of the most exciting prospects for ELTs of 100 m-class is the possibility of not only directly detecting Earth-like planets orbiting other stars, but studying large numbers of them in detail. Only by doing this can we determine to what extent our own planetary system is unique, and assess the probability for other planetary systems to support life. Specific gains that come from an ELT would include the ability to: (i) perform a survey of stars sensitive to low mass planets out to distances of ~ 30 pc; (ii) measure planet properties by spectroscopy, with detailed studies of gas giants possible in addition to the low-mass planet study goals; (iii) study entire exoplanetary systems; (iv) measure planetary orbits and (v) study planets around low mass stars.

Although the problems associated with ground-based Exoplanet studies have been discussed and some systems modelling started, investment in technology development so far is much smaller and less well advanced than the complementary space-based technologies. Yet the technology development required is both broad in scope and challenging in nature. The following section attempts to define some of the requirements where technology development and facilities are needed.

Contrast: between the very faint Exoplanet signal and intense emission from the host star. As an indication of the extent of the problem, the Earth/Sun contrast is ~ $1.5\ 10^{-10}$ at visible wavelengths and ~ 10^{-6} at thermal (mid-IR) wavelengths. Current technologies do not allow separation of the faint reflected Exoplanet from the central stellar emission at these levels.

High background: (from scattered light and from thermal emission at mid- infrared wavelengths).

Scattered light: a G2V star at 10 pc, observed with spectral resolution R = 30 at 1 μm, gives a total signal of ~ 5.10^{10} photons s^{-1}, assuming 100% throughput. In contrast, about 7 photons s^{-1} would be received from an Earth observed at an optimum phase angle under the same conditions. The technology challenges therefore include 'dumping' as many of the stellar photons early as possible in the optical path (coronography, nulling interferometry), providing ultra-smooth surfaces to minimise scattering of the remaining photons and building detectors that have the capacity to cope with very high photon rates. None of the current technologies do this adequately, but the UK has industrial companies capable of making major contributions in each of these areas.

Thermal background: this can not only be reduced by choice of site (cool, dry) and/or going into space (with passive or active telescope cooling) but also by use of an ELT in diffraction limited regime, where the background per pixel becomes smaller (e.g. see Angel 2003, in Towards Other Earths, Proceedings of DARWIN/TPF Conference, Heidelberg; ESA SP-539 p221).

Size: collecting area and angular resolution: ELT's have an advantage over space missions because of their large collecting area and they can provide competitive angular resolutions if operated close to their diffraction limit. Therefore stars can be studied at greater distances, with a requirement probably to ~ 30 pc (goal 50 pc) to obtain a statistically significant survey of planetary systems. 1AU at 50 pc subtends an angle of 20 milliarcsec, or 10λ/D for a 100 m aperture. The contrast performance mentioned above must be achieved on this angular scale. There are no current technologies to build ELTs that have such high angular resolution. In addition to the technologies already described, an ELT must work with extreme adaptive optics to achieve the required performance levels. Complex AO systems will undoubtedly include large Deformable Mirrors (DMs) as part of the telescope optics, close-packed actuator high-order DMs and major advances in computing power and 'clever' processing algorithms: without the last of these computing developments on timescales much faster than Moore's Law would be needed. The UK has on-going HEI and commercial research that will enable them to be competitive in each of these areas. There is then an urgent need to end-to-end system modelling that is able to generate realistic error budgets for each of these technology developments, to allow trade-offs and to show the final system is indeed capable of detecting Earth-like planets.

We therefore identify a line of a minimum of £1.6m of new money to enable the UK to develop end to end simulations of DARWIN to bring up a laboratory facility aimed at high quality optics/photonic engineering to address the key issues of high background suppression simultaneously with high contrast specifically related to DARWIN, but also benefiting an ELT programme.

2.3 Industrial Contribution

The change in procurement practices by ESA from national grant funded instrumentation to instrumentation acquired through its prime contractors has reconfigured the ESA instrument supply chain. In this new arrangement, industry naturally feels exposed since they do not possess the necessary domain knowledge to propose solutions that are scientifically the most competitive, nor to manage procurements that are fundamentally driven by potential technical capabilities, rather than the scientific requirements. UK groups, such as MSSL, have provided an important bridge to industry in this respect by taking a science instrument systems view (i.e. demonstrating an understanding of the relationship between science performance and technical design including the appreciation of spacecraft system level issues such jitter, mission operations etc.).

ESA faces a dilemma in the creation of credible Payload Definition Documents (PDD) for missions where ESA takes a central scientific role. UK University groups and UK Establishments are well placed to proactively help ESA with PDD developments and of course the phase A studies themselves, by providing critical assessment of such documents and recommending area of technological preparation / risk mitigation.

To be in a position to provide the science-to-technology bridge requires investment in research, systems studies and laboratory experimentation, so as to be in a position to offer support at a time when either ESA or Industry need it yet are not immediately in a position to pay for it entirely. *A key part of the Exoplanet strategy therefore includes long-term technical support for the DARWIN program, to provide an interface to industry, and to help gain the maximum return to the UK industrial and technical base.*

3 The community

There is great UK scientific and public interest in Exoplanets and the field has received strong institutional backing in recent university appointments and strategic research emphasis. The Exoplanet research community is robust and vibrant in a number of key areas where the UK is showing world leadership. The response to our survey demonstrates a great interest in the scientific and technical programmes that will be needed in preparation for the DARWIN mission, and the strength of the response demonstrates a UK community whose members see important roles for themselves in working on the scientific and technical challenges of Exoplanet research. We believe that funding for this scientific area will, in turn, help UK industry to invest time and effort in the required technological developments.

UK has membership in key organisations and access to key facilities and programmes such as ESO, Gemini, ESA, OPTICON, etc and leading expertise in some areas of Exoplanet science, particularly the theory of planet formation and early evolution; solar system studies; state-of-the-art instrument building; e-science, and has internationally competitive observational programmes. The UK has an outstanding heritage of developing ground-based observatory facilities (such as the recent SuperWASP), and in delivering successful ESA missions such as Cluster and XMM. The community is eager to place the UK in a position to gain significant scientific, technical and industrial return from ESA's DARWIN mission, and to be a leading player in the development of ELTs.

4 Summary and Recommendations: A Roadmap to DARWIN

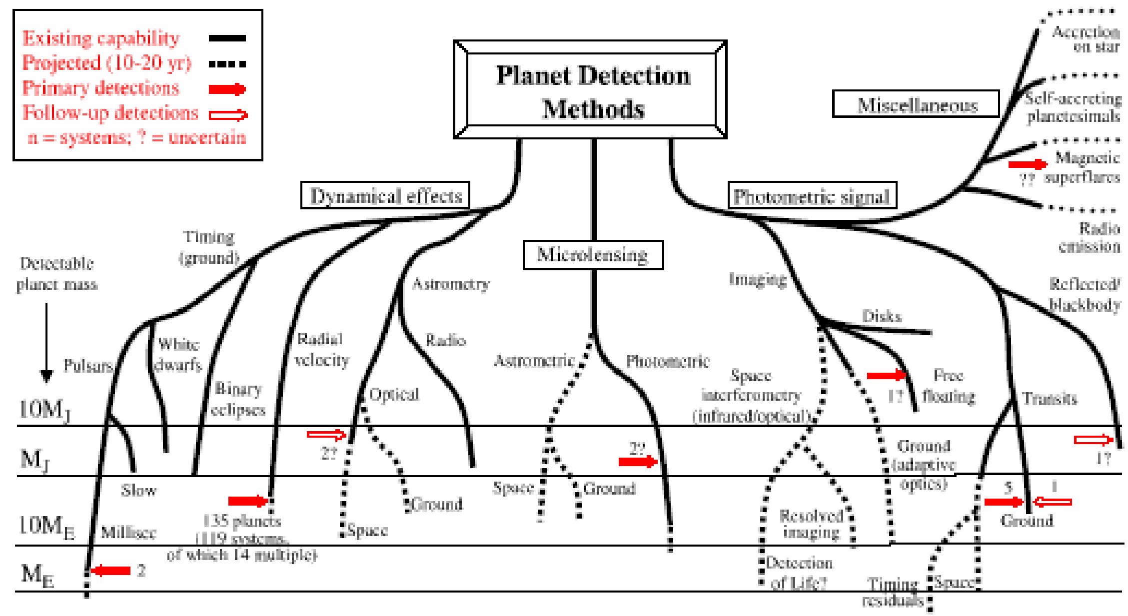
We have prepared an Exoplanet Roadmap to provide a strategy for related research within the UK to focus around, and to allow PPARC to plan for an appropriate level of support. This programme was developed during 2005 by a small group of experts and technical advisors, along with contributions and feedback from the community through a public meeting and through individual discussions.

A coherent strategy for the long-term support and development of Exoplanet science in the UK is needed promptly - there are scientific, political, educational and outreach rationales for the UK to be at the forefront of this high profile field, which has firmly captured the imagination and intellectual curiosity of the general public. The UK must rapidly become engaged in developing a leading position to ensure prominent standing in the international consortia that will form, and to optimise opportunities for juste retour and industrial return.

PPARC investment will be required in order to ensure a high degree of UK competence, development of enabling technologies, people with the appropriate skills, and a strong community interaction. For the purpose of this, it is important to identify an ultimate goal, which we set in this document as the detection and characterisation of Earth-like planets in habitable zones.

On the 10 year timescale, DARWIN is the flagship facility that will image Earth-like planets. It is the ultimate goal of this theme and must be the highest priority for the UK community. An ELT is equally important, with delivery perhaps on a longer timescale but technology development work starting early. The debate remains to be held as to the extent to which one ELT should be designed specifically for Exoplanet studies rather than as a multi-purpose facility open to flexible exploitation.

The figure below is taken from the ESA/ESO Exoplanet report referenced earlier: it shows the projected exoplanetary masses that should be detectable by different techniques.



Taking this diagram as a basis for potential discoveries, we set out a UK strategy for 2006 – 2015, the ten years leading up to the DARWIN mission. The strategy includes recommendations for all strands of the UK's Exoplanet research: surveys by ground- and space-based instrumentation, theory and modelling and laboratory-based studies. Our recommended programme provides seven key elements that will:

1. Maintain strong national visibility in support of Exoplanet studies
2. Provide operational support for our unique current world leading positions in transit studies and microlensing
3. Support infrastructure for different communities (observational, instrumentation, theory and laboratory-based analysts) to collaborate effectively.
4. Develop at least one next generation ground-based instrument
5. Enable key critical technology skills that will facilitate future leadership opportunities and engage industrial support.
6. Maximise juste retour for UK industry
7. Achieve our top level goal to hold a leading position in the first detection of a biomarker signature of an Earth-like extra-solar planet

These seven goals will be achieved through a strategy that combines the UK's strengths in the different fields that comprise Exoplanet research. We make the following recommendations in order to deliver that strategy. The recommendations are grouped; where possible, approximate costings are given for each recommendation. The costings table also acts as a timeline for implementation of these recommendations.

Planet searches

- Continue support of the operations phase of the SuperWASP experiment to facilitate UK leadership in bright transiting Exoplanet search through to at least 2010 (£150k yr^{-1} for 5 years)
- Maintain operational support for the AAT Planet Search programme until at least 2010, to allow the acquisition of data from long-period, massive Exoplanets. This will yield a statistical survey of Exoplanet system architectures, based on current AAT archival material and will constrain Jupiter- and Saturn-sized objects around the brightest solar-

type stars, as well as planets down to about 5 Earth masses in short period orbits. (£90k yr^{-1} for 5 years)

- Support the PRVS instrument on Gemini (North), simultaneously optimising 8m telescope opportunities and facilitating the UK lead in IR RV studies of low mass stars. The total cost is ~$6M, the UK contribution of which will already be met provided PPARC buys in to the results of the 'Aspen process'.
- Explore and negotiate towards an entry strategy that would allow the UK to play a real role in the science programmes of the new global telescope network being developed under the Las Cumbres Observatory flag. This is a strategic opportunity for prominent UK involvement in a major new global facility. If negotiations fail, then to fund an enhanced network of 8 x 1 m ground based telescopes for microlensing observations.
- Support the technical and scientific participation in the ESA-ESO GENIE science programme as a precursor to DARWIN by providing staff to facilitate operation and data collection at the VLTI site, and the analysis and reduction of data. (1 Scientific and Support scientist who would become involved in the collection and reduction of data for 5 years (2007 – 2012)

Science Exploitation

- Provide support for a Programme Coordinator, ramping up to a full time position by 2009, to support and co-ordinate development of the technologies, and to stimulate coherence of the skills in the science community.
- Establish an (initially) virtual DARWIN Integrated Science Centre (DISC) as a point of community contact. This (through the Exoplanet Project Manager) will facilitate and co-ordinate science exploitation activities, including:
    - A targeted Visiting Fellowship programme aimed at bringing a small number of experts into UK groups for medium term visits. This will help to build and develop UK academic and industrial competences
    - A series of Science and Technology Focus Meetings to develop UK strengths in the interdisciplinary areas covered in this document. As well as enabling discussion and exchange of information, this will develop coherence and a central vision and inertia within the community
- Provide support for targeted Ph.D. projects in Exoplanet research, at a rate of 5 per year for at least the next 10 years. Provide support for PDRAs in Exoplanet research at a rate of at least 5 per year for the next 10 years from 2006 - 2015. This will maintain and develop a community of young research staff with the key skills required to ensure continuity in research projects over the 10 years leading up to DARWIN.
- Provide stable and continuous investment in HPC (High Performance Computing) facilities over the next 10 years to support the theory and modelling community, and to develop a programme modelling spectroscopic signatures of biomarkers in Exoplanets. Investment needed is 250K in 2006, 2009, 2012, 2015 for HPC Hardware, and £100K per year FEC costs for manpower. This should come out of the existing HPC budget, so is not new money – but requires AAP/Science Committee prioritisation.
- Support for a UK GAIA Data Centre (will form a separate bid to PPRP – not costed)

Technology Development

- Develop end-to-end systems modelling to allow optimisation of the science capability for both the DARWIN and the ELT systems.
    - Focus on key technologies that are of strategic interest to the UK industrial and technology base, particularly formation flying, optics, materials development, fast low noise detectors

- Fund or support a major UK laboratory facility as a test-bed for ultra-high quality imaging, coronography, or image quality evaluation techniques.
    - Aimed at giving the UK a leadership position in development of ESA's DARWIN mission (short term) and future ELTs (medium term), and interfacing directly with UK Industry
- Support a series of Technology Focus Meetings
    - identify UK strengths in the technology areas relevant to Exoplanet research; establish a more detailed route for the most promising areas of development

Beyond DARWIN

- Plan for full engagement in ESA's Cosmic Visions 2020 Far-IR observatory mission (FIRM), and the Japanese SPICA mission (4 m cooled space observatory 100 times more sensitive than JWST - likely to be in association with ESA, and currently in a UK led Phase A study through RAL/Cardiff)

5 Cost of the Road Map

The table below gives an approximate costing for the proposed road map. Most of the requested funds are for staff costs (taken as £100k yr^{-1} to allow for fEC) and costs associated with purchase of telescope time (for AAPS). Many of these costs are already in PPARC's budgetary plans, such as the PRVS costs, which is for second-generation Gemini instrumentation to which the UK is already committed.

The cost to PPARC by Financial Year of the strategy is as follows *a) <u>New money</u>*:

Project (costs in £k)	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	**Total**
Planet Searches											
SuperWasp	150	150	150	150	150						750
AAPS	90	90	90	90	90						450
GENIE		100	100	100	100	100	100				600
Robotic Telescopes	1000	2000	1000	100	100	100	100	100	100	100	4700
Science Exploitation											0
Project Manager	20	30	50	100	100	100	100	100	100	100	800
Science focus meetings	15	15	20	20	25	25	25	25	30	30	230
Visiting Fellowships	50	53	55	58	61	65	68	70	73	75	628
Technology											0
Systems modelling	100	100	100	100	100	100					600
ELT EU FP7 matching finds			80	140	140	140	140	140	140	80	1000
Laboratory test-bed		50	100	450	100	100	100	100			1000
Technology focus meetings	15	15	20	20	25	25	25	25	30	30	230
Total	**440**	**603**	**765**	**1228**	**891**	**655**	**558**	**460**	**373**	**315**	**6288**
Total with Robotic Array	**1440**	**2603**	**1765**	**1328**	**991**	**755**	**658**	**560**	**473**	**415**	**10988**

b) *<u>by recommending support for money that should be funded by other programmes</u>*:

Project (costs in £k)	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	**Total**
Planet Searches											
PRVS				1100	100	100	100	100	100		**1600**
Science Exploitation											
Visiting Fellowships	30	30	30	30	30	30	30	30	30	30	**300**
Ph.D. students	100	100	100	100	100	100	100	100	100	100	**1000**
PDRAs	500	500	500	500	500	500	500	500	500	500	**5000**
HPC facilities	350	100	100	350	100	100	350	100	100	350	**2000**
Technology development											
EU FP7	?	?	?	?	?	?	?	?	?	?	?
Total	**980**	**730**	**730**	**2080**	**830**	**830**	**1080**	**830**	**830**	**980**	**9900**

6 Authorship of this document

This document has been compiled at PPARCs request to provide a plan for the Astronomy Advisory Panel. The report includes inputs from a wide range of UK scientists and industrial companies, and we acknowledge the considerable community input that has characterised the outcome of this report. Much of the collation and organisational work was carried out by Matt Burleigh (Leicester), Andrew Collier Cameron (St Andrews), Monica Grady (Open University), Keith Horne (St Andrews), Hugh Jones (Hertfordshire), Andy Longmore (UK ATC), Richard Nelson (QMUL) and Glenn White (Open University, Chairman), and the programme was critically reviewed by Mark McCaughrean. Helpful contributions are also acknowledged from Alan Smith (MSSL). The attendance and presentations at the Exoplanet Forum Community meeting demonstrated the wide platform of support from within the community, and involved a change of venue as the attendance was more than double our initial expectations. The present document has only just been made publicly available for comment (9th November 2005), and we will collate feedback from the community as these are communicated back to us. Helpful support from Colin Vincent and Simon Berry is also acknowledged.

7 Terms of Reference of The PPARC Exoplanet Forum Working Group

For this purpose, Exoplanet science is taken to be the discovery and characterisation of planets outside the Solar System. It is meant to be inclusive of all observational areas and programmes, and to include instrumentation, facilities and space missions necessary to support these, as well as relevant areas of astrobiology and planetary science.

- To develop a roadmap for UK Exoplanet science that lies within PPARC's portfolio of interests, extending from now through to the ESA DARWIN space mission
- To facilitate the exchange of information and collaboration between the various UK groups interested in Exoplanet science, astrobiology and planet science
- To establish what the scientific priorities of the UK community are in Exoplanet science
- To determine whether these scientific priorities can be met cost effectively within PPARC's portfolio, and to roadmap then into a realistic programme that could be fitted into the PPARC 10 year forward look
- To provide advice on these issues to PPARC through the Astronomy Advisory Panel

The policy advice and meeting organisation will be carried out by an Executive Committee with evidence being sought from experts as appropriate, and one open consultative meeting to which interested members of the community will be invited.

Appendix 1 - The UK Community

A Community Meeting organised by PPARC was held at University College, London to engage the UK Community in discussion of a UK Strategy. Almost 70 people pre-registered for the meeting, while 83 people attended in person, demonstrating the wide interest in the UK Community for involvement in the science and technology challenges for an Exoplanet Science programme. Fourteen speakers from 14 different ‘establishments’ (both academic and commercial) gave summaries of 22 projects describing their work or interest in technology and data analysis related areas. The work presented fell into several broad categories: use of existing facilities; building new facilities/instruments; technology development; test-beds for new technology; astrophysical modelling; data processing & interpretation. A list of the pre Registrants to the meeting is shown below, emphasising the wide community support.

Exoplanet Community Meeting Attendees at University College, London			
Christian Name	Surname	Email	Affiliation
Ian	Stevens	irs@star.sr.bham.ac.uk	Birmingham
Steven	Spreckley	sas@star.sr.bham.ac.uk	Birmingham
Simon	Hodgkin	sth@ast.cam.ac.uk	Cambridge Astronomical Survey Unit
Derek	Ward-Thompson	spxdw@astro.cf.ac.uk	Cardiff
Ant	Whitworth	A.Whitworth@astro.cf.ac.uk	Cardiff
Dimitris	Stamatellos	D.Stamatellos@astro.cf.ac.uk	Cardiff
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Richard	Wilson	r.w.wilson@durham.ac.uk	Durham
Ronan	Wall	ronan.wall@astrium.eads.net	EADS Astrium
Mark	McCaughrean	mjm@astro.ex.ac.uk	Exeter
Martin	Hendry	martin@astro.gla.ac.uk	Glasgow
Kirsty	Selway	kirsty@astro.gla.ac.uk	Glasgow
James	Jenkins	jsj@star.herts.ac.uk	Hertfordshire
Phil	Lucas	pwl@star.herts.ac.uk	Hertfordshire
Hugh	Jones	hraj@star.herts.ac.uk	Hertfordshire
Jim	Hough	jhh@star.herts.ac.uk	Hertfordshire
Alan	McCall	a.mccall@herts.ac.uk	Hertfordshire
Jonathan	Irwin	jmi@ast.cam.ac.uk	IOA Cambridge
Andy	Adamson	adamson@jach.hawaii.edu	JACH Hawaii
Gary	Davis	g.davis@jach.hawaii.edu	JACH Hawaii
Coel	Hellier	ch@astro.keele.ac.uk	Keele
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Exoplanet Community Meeting Attendees at University College, London			
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Martin	Burgdorf	mjb@astro.livjm.ac.uk	Liverpool JMU
Mike	Bode	mfb@astro.livjm.ac.uk	Liverpool JMU
Gary	Fuller	G.Fuller@manchester.ac.uk	Manchester
Tom	Millar	Tom.Millar@manchester.ac.uk	Manchester
John	Richer	jsr@mrao.cam.ac.uk	MRAO
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Dave	Walton	dmw@mssl.ucl.ac.uk	MSSL
Gavin	Ramsay	gtbr@mssl.ucl.ac.uk	MSSL
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Patrick	Irwin	irwin@atm.ox.ac.uk	Oxford AOPP
Graeme	Watt	greame.watt@pparc.ac.uk	PPARC
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Richard	Blott	rjblott@qinetiq.com	QinetiQ
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Elizabeth	Platt	E.J.Platt@qmul.ac.uk	QMUL
Richard	Donnison	r.donnison@qmul.ac.uk	QMUL
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Richard	Nelson	r.p.nelson@qmul.ac.uk	Queen Mary
Brian	Ellison	b.n.ellison@rl.ac.uk	RAL
Bruce	Swinyard	b.m.swinyard@rl.ac.uk	RAL
Sarah	Dunkin	s.k.dunkin@rl.ac.uk	RAL
Colin	Cunningham	crc@roe.ac.uk	ROE
Andy	Longmore	ajl@roe.ac.uk	ROE

Exoplanet Community Meeting Attendees at University College, London			
Christian Name	Surname	Email	Affiliation
Mark	Wyatt	wyatt@roe.ac.uk	ROE
Bill	Dent	dent@roe.ac.uk	ROE
Andrew	Collier Cameron	acc4@st-and.ac.uk	St Andrews
Keith	Horne	kdh1@st-and.ac.uk	St Andrews
Jane	Greaves	jsg5@st-andrews.ac.uk	St Andrews
Antonio	Hales	ahales@star.ucl.ac.uk	UCL
Janet	Bowey	jeb@star.ucl.ac.uk	UCL
Serena	Viti	sv@star.ucl.ac.uk	UCL
Martin	Andrews	mandrews@star.ucl.ac.uk	UCL
Steve	Miller	s.miller@ucl.ac.uk	UCL

Talks were given at the meeting by

Talks		
First Name	Surname	Title
Dave	Walton	Demonstration space-based planet-finding focal plane developed at MSSL
Matt	Burleigh	Investigating the ultimate fate of solar systems
Keith	Horne	REX
Andrew	Norton	SuperWASP
Janet	Bowey	Spatially resolved Mid-infrared imaging and spectroscopy of T Tauri disks
Janet	Bowey	Laboratory studies of terrestrial minerals and their application to astronomical environments: planets are giant dust grains!
Tim	Naylor	Crucial Technology for understanding Exoplanets - eSTAR
Fraser	Clarke	exoPlanets at Oxford; research and instrumentation
Colin	Cunningham	Observing Exoplanets with ELTs
Mark	McCaughrean	Putting the UK on the Exoplanet Roadmap
Martin	Burgdorf	Exoplanet Detection with RoboNet
John	Richer	ALMA - the exoplanet opportunities
Bruce	Swinyard	SPICA opportunities in extrasolar planet research
Hugh	Jones	Ground base observational opportunities
Ian	Stevens	Exoplanet Research at the University of Birmingham
David	Buscher	Aperture synthesis imaging of exoplanets and planetary formation
Ronan	Wall	Exoplanet Mission capabilities in Astrium
Peter	Sarre	Herbig AeBe stars, Diamonds in Disks, and the future role of the South African Large Telescope, SALT

Talks		
First Name	Surname	Title
Serena	Viti	Molecules in Exoplanet Atmospheres
Andrew	Collier Cameron	Atmospheric modelling
Andy	Longmore	Technologies for Exoplanet studies
Monica	Grady	Exoplanets and Astrobiology
Richard	Nelson	Planet Formation and evolution Theory
Mark	Wyatt	Debris Discs
Glenn	White	Overview talk

Appendix 2 - UK Groups and Companies with relevant Technology capabilities

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Although not intended as a complete list, the list of UK relevant technology companies illustrate the range of resource available. It is drawn up from companies who have already been involved in manufacture, design or consultancy for astronomical instruments, telescopes or technology development. The companies range from industry giants to small spin-off companies and consultancies. Particularly for the former we only list one or two example areas where they have relevant specialist expertise. PPARC is organising a meeting on 13th December 2005 under the KITE Club umbrella to bring together the industrial and academic groups interested in starting to develop DARWIN related technologies.

Industry (major and small companies, consultancies)

- Arnetek Taylor Hobson (Leicester) – optical metrology;
- Barr & Stroud Ltd (Glasgow) - filters, coatings, optical instrument engineering;
- Cobham Composites Ltd () – fabrication of carbon fibre composites
- Cranfield Precision (Bedfordshire) – high precision machine tools;
- EADS Astrium - Space technologies, formation flying, micro-propulsion, integrated systems, systems engineering, control systems; project management
- E2V – low noise, high speed optical detector development
- FASE (Fisher Astronomical Systems Engineering) – mechanical modelling, finite element analysis
- Lambda Photometrics Ltd () – Precision Actuator
- Nallatech Ltd (Glasgow, Bristol) – FPGA parallel computing
- Optical Surfaces (Surrey) – manufacture of precision surface optics;
- Quality Laser Optics Ltd (Isle of Man) - ;
- Qinetiq (Farnborough) - 3D (wavelength-discriminatory) IR detector development
- Renishaw Ltd (Gloucestershire): metrology
- Selex (formerly BAE Systems) - electro optical systems, electronics control systems.
- Spanoptic (Glenrothes, Fife) - MRF technology, precision lenses, mirrors, flats and prisms;
- Scalar Technologies (Livingston, W.Lothian) – optical thin-film metrology
- Sira (Kent) – control systems design, systems modelling
- Solartron Metrology (Bognor Regis) - precision dimensional measurement and position measurement transducers;
- Surrey Satellite Technology (Guildford) – Mico and nano satellites, Constellation Control, Metrology. Low cost mission development
- Thales Optics (North Wales) - Ultra-precision machining
- Zeeko (Oxfordshire) – precision surface machining;

Academic & Establishment

- University of Birmingham: algorithms for automatic light-curve classification, precision control of space-craft.
- MRAO, University of Cambridge: R&D for multi-telescope optical/IR interferometry, 3D detector development
- CCLRC (RAL): Spacecraft and instrumentation design and construction, project management, telemetry and ground station systems, Control Centre functions, Data Processing infrastructure

- University of Durham: Extreme AO Simulations, high-order AO test-bed; AO processing and real-time control platforms, ultra-high-quality optics for image slicers
- University of Edinburgh (includes Scottish Micro-electronics Centre): microelectronics manufacture, lithography, potential for mask manufacture?
- Heriot Watt University (Edinburgh): innovative optical design, spin-off
- MSSL: simulations for radial velocity measurements (with Gaia), lab tests of low noise detectors, lab tests of high-stability imaging
- Open University: design studies of the GENIE and DARWIN configurations, partners in the SALT consortium
- University of Nottingham: partners in SALT high-resolution spectrometer
- Optical Science Laboratories (UCL, London) - research in ultra-precision surface manufacture;
- University of Oxford: ultra-high-quality optics for image slicers
- St Andrews University: RoboNet-1 and REX leadership: ground-based facilities for planets searches via transits and microlensing. (UK and international consortia).
- UKIRT / UKATC: IR radial velocity spectrometer concept for UKIRT
- UK ATC: ELT instrument technology development programme management, work package participation; astronomical technologies, systems engineering, instrument design and engineering.
- University College, London: large adaptive mirrors, precision surfaces

Projects and Funded Studies

- OMAM (Optical Metrology & Manufacture consortium, involving UK ATC, Selex, NPL, Scalar Technologies, Zeeko, UCL, Heriot Watt)
- OPTICON JRAs: Adaptive Optics; Detectors for Adaptive Optics; Smart Focal Planes.
- OTPICON FP6 ELT studies
- OPTICON Key Technologies Network
- LOMS (Large Optics Manufacturing Study)
- MASLOS (Metrology Assessment Study for LargeOptical Surfaces);
- Coordinated involvement of regional and national optics clusters such as the Scottish Optoelectronics Association, Photonics Cluster UK and the Smart Optics Faraday Partnership.
- Cranfield University and University College London with a proposed laboratory at the new OpTIC Technium in North Wales: proposed optical ‘centre of excellence’.

Appendix 3 - Acronyms and Glossary

AAPS	Anglo-Australian Planet Search
ALMA	Atacama Large Millimeter Array (limited science operations ~ 2009)
COROT	COnvection ROtation and planetary Transits
Cosmic Vision	ESA long term Space Mission framework
DARWIN	Nulling Interferometer Mission (ESA; projected launch 2015)
ELT	Extremely Large Telescope (2020+)
EPICS	Extra-solar Planet Imaging Camera and Spectrometer (proposed ELT instrument)
ESA	European Space Agency
ESO	European Southern Observatory
FIRSI	Far-Infrared and Submillimeter Interferometer
GENIE	Ground-Based European Nulling Interferometer Experiment (a collaborative ESO-ESA project that is a technology test for DARWIN)
HERSCHEL	ESA 3.5 m space observatory (projected launch 2007+)
HPC	High Performance Computing
HST	Hubble Space Telescope (in orbit)
OGLE	Optical Gravitational Lensing Experiment
JWST	James Webb Space Telescope, NASA mission (projected launch 2013+)
Keck-I	Keck Interferometer (commissioning under way)
LBTI	Large Binocular Telescope Interferometer
LUVO	Large UV/optical Observatory
MIRI	Mid-Infra-Red Instrument for HERSCHEL (under development)
NIRSpec	Near-Infra Red Spectrograph
PRVS	Precision Radial Velocity Spectrometer (proposed GEMINI instrument)
SAAO	South African Astronomical Observatory
SIM	Space Interferometry Mission – PlanetQuest (undergoing studies)
SOFIA	Stratospheric Observatory for Infrared Astronomy (in commissioning)
Spitzer	NASA IR mission (operational)
TPF-C	Terrestrial Planet Finder Coronagraph (NASA; projected launch 2014++)
TPF-I	Terrestrial Planet Finder Interferometer (NASA; projected launch 2020++)
UCLES	University College London Echelle Spectrograph
VLTI	Very Large Telescope Interferometer
WASP	Wide Angle Search for Planets
WISE	Wide-field Infrared Survey Explorer
XMM-Newton	ESA X-ray observatory (currently operational)