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EXOPLANET SCIENCE REVIEW
PANEL REPORT 2015

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Executive summary

There are few questions more scientifically- and sociologically-fundamental than whether or not the Earth is a unique environment in the Universe. For most of human history attempts to answer this question have been limited to studies of environments within our own Solar System. Today we are on the brink of being able to answer the question directly by determining the detailed properties of exoplanets – planets orbiting stars other than the Sun. Following the discovery of the first exoplanets, found just twenty years ago, there are now more than one thousand confirmed planets, and thousands of candidates, exoplanets ranging from giant planets larger than Jupiter to smaller Earth-sized objects. We now know that the Solar System is far from being the archetype for all planetary systems; indeed the complexity and diversity of exoplanetary systems and how they change over time has been a revelation. The UK has been strongly involved in exoplanet research since the early days, leveraging its expertise in astronomy and solar system science, contributing to studies ranging from the discovery of planets and determination of their sizes and masses, to detection of molecules in exoplanetary atmospheres, through to the development of theoretical models of planetary atmospheres/interiors and the formation and evolution of planetary systems.

In 2007 STFC commissioned a report (McCaughrean 2007) into the state of the UK exoplanet community and how it could grow and develop at a time when, in the words of the 2007 report, the community suffered from “a lack of coherent ambition, strategy, planning, and funding”. In 2014 STFC convened a new science review panel to review the UK exoplanet science landscape in order to “develop a coordinated strategy for UK involvement in exoplanet research that could enhance UK leadership in this area”. In striking contrast to the situation a decade ago, today the UK exoplanet science community is one of the largest and most successful in the world, involved in a broad range of observational and theoretical projects. These include several that address the recommendations of the 2007 report and form part of the funded roadmap of European exoplanet facilities. Some of these projects have not been funded directly by STFC or UKSA but rather have attracted external funding, such as from University consortia or the EU. It could be argued that the UK community has thrived despite funding constraints, but the view of the UK exoplanet community, strongly supported by the review panel, is that the time has now come for UK funding agencies to take the difficult but essential steps in order to adequately support one of the most important areas of astronomy.

This report outlines a coordinated set of strategic goals and provides a set of recommendations to enhance UK leadership in exoplanet research. The recommendations are informed by current UK leadership roles and take into account the many changes that have occurred over the last decade. This is a fast evolving area of astronomy, but clear pathways exist for the UK community to thrive and lead.

The panel proposes four main aims for the UK community:

Aim 1: Support of the Transit Roadmap. With the selection of the ESA M3 PLATO mission, Europe now has an exoplanet roadmap that stretches into the 2030’s. The backbone of this is transit detections and their applications (e.g. atmospheric studies). Throughout this period we see the science moving towards understanding the characteristics and evolution of terrestrial planet systems.

Aim 2: Develop a better understanding of Planetary Atmospheres through observations and theoretical research. Around the transit roadmap are common user facilities that have spectroscopic instruments capable of detecting planetary atmosphere signatures.

Aim 3: Understanding the structure of disks and the formation and evolution of planetary systems. Beyond detecting planets and understanding their physical properties (e.g. bulk compositions, atmospheric dynamics and chemistry), a major science goal is to understand planet formation and planetary system evolution.

Aim 4: Determine the frequency, mass distribution and origins of orphan and cool planets.

To support these generic aims we make a series of seventeen specific recommendations:

R1 - Support for exoplanet science should be awarded to projects of the highest academic excellence. This should occur over the entire breadth of the research area.
R2 – Provide long-term stable funding of HPC through DiRAC and smaller local facilities, and fund PDRAs through the grants line in support of the highest rated theoretical research. We recommend that support be maintained for both fundamental theory and for modeling aimed at interpreting observations.

R3 – The funded transit roadmap should be adequately resourced. Finding transiting planets is the bedrock of the UK programme due to existing leadership roles and the selection of PLATO.

R4 – Support transit experiments by ensuring adequate Radial Velocity facilities are available to the entire UK community. This is vital to exploit the transiting planet discoveries.

R5 - The UK should continue to support the exploitation of Hubble Space Telescope data for the characterisation of planetary atmospheres until the James Webb Space Telescope becomes available.

R6 - Encourage ESO to bring the CRIRES+ instrument online as soon as possible.

R7 - The UK should explore the possibilities in the near term of an optimised instrument(s) designed for atmospheric studies. If we are to better understand exoplanet atmospheres we require access to stable, well designed instruments.

R8 - Support the exploitation of the SPHERE and GPI instruments. Larger orbital radius planets beyond the range of the transiting planet facilities can be studied using imaging and spectroscopic techniques.

R9 - Support the development of European Extremely Large Telescope (E-ELT) instruments specifically for exoplanet science (e.g. METIS, HIRES, PCS/EPICS etc.).

R10 – Support the exploitation of Hubble Space Telescope, Very Large Telescope, Very Large Telescope Interferometer, William Herschel Telescope, Atacama Large Millimetre/sub-millimetre Array, James Webb Space Telescope and European Extremely Large Telescope and associated modelling in studies of planetary atmospheres, protoplanetary discs, debris discs and metal-polluted white dwarfs. This includes support for radiative transfer models and line-lists, accurate atmospheric and interior models, planet formation, chemical/cloud/dust models, data analysis, numerical simulations and other relevant fundamental physics.

R11 - Support the proposed Euclid microlensing survey to produce statistics on low mass planets at mostly long periods. While PLATO will well constrain the rate of habitable-zone planets for solar type stars, going beyond the habitable zone requires microlensing surveys. The Euclid survey provides an efficient way to achieve this goal.

R12 – Support the exploitation of data from the Gaia mission leading to the characterisation of exoplanets and their orbits, and to an improved understanding of the physics of planet host stars

R13 – Continue support for PLATO during its full operational phase (2024-2030) including the 3-year wind-down period (2030-2033). This includes theoretical support for interpreting the main results from PLATO.

R14 – Increase support for Atmospheric Facilities in the post 2025 era. This includes support for any future ESA missions.

R15 – Support technology development for future space projects. These could include wave front control systems, achromatic coronagraphs and IR detectors

R16 – Examine the options for funding the development of the European Extremely Large Telescope (PCS/EPICS) and Planet Formation Imager as a means of securing future UK leadership in the exploitation of these next-generation direct imaging facilities.

R17 – Support future ESA missions that have a significant exoplanet science component and UK participation at an early stage sufficient to establish UK leadership.
This report presents the findings of the Science and Technology Facilities Council (STFC) Exoplanet Science Review Panel (EPRP). The panel was constituted in 2014 to undertake (a) a review of the state of exoplanet research within the UK; (b) place UK exoplanet research in an international context; and (c) recommend a coordinated strategy for future UK involvement in the field over the next several decades by both STFC and the UK Space Agency (UKSA). The report builds on past national and international reviews and takes into account the substantial growth in exoplanet research within the UK, particularly within the last decade. During 2014-15 the review panel consulted the UK astronomical community, including observers, theorists and instrumentists. We outline likely future investment opportunities and make recommendations as to both near-term (5-10 year) and mid- to long-term (10-30 year) timescales.

The report is structured as follows:

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Section 3: State of the art of the field and the international context
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1. Background and historical context

It is only ~20 years (one generation) since the long-sought goal of finding planets orbiting other stars was finally realised. While members of the UK theoretical community have been involved in exoplanet work since before the first discoveries, it was only with the formation of the Anglo Australian Observatory Planet Search (AAO-PS) that the UK became involved in observational searches for planets. This exploited perturbations in the radial velocity of a star as an unseen companion orbited its parent star. Along with the HARPS (High Accuracy Radial velocity Planet Searcher) surveys, AAO-PS has been one of the most prolific radial velocity (RV) discovery projects. Another extremely successful technique for the detection of exoplanets is by detecting temporary but repeatable drops in the light from a distant star when an exoplanet moves across the disc of the star: known as a transit. In the area of ground-based transit detection, the UK has led the world since 2005 when the SuperWASP facilities (La Palma and SAAO) started routine operations (WASP is the Wide Angle Search for Planets). When WASP-1b and WASP-2b were announced in 2007, there were just 14 transiting planets known. The SuperWASP planet survey total now amounts to nearly 150 planets for which radii and masses (and hence bulk densities) are known, representing nearly half of the known sample. Transit searches remain the only route to determine planetary radius (and orbital inclination) with any accuracy. When complemented with masses derived from radial velocity measurements an accurate estimate of the planetary bulk density is possible, which can then be compared with theoretical planetary interior structure models. Transits are also essential for being able to probe the atmosphere of an exoplanet.

CoRoT was launched in December 2006 and was the first space-based transit experiment. This was followed by the more ambitious Kepler mission in 2009. Together these missions have found the first terrestrial-mass exoplanets, while Kepler data has also totally transformed our knowledge of multiple planet systems (already known from the HARPS RV surveys) and the size distribution of exoplanets. While the UK exoplanet community has not been well placed in these surveys, as they originated before the community was well organised, our asteroseismologists and stellar astrophysicists have been central in efforts to characterise the host stars.

The limited fields-of-view of CoRoT and Kepler, and their limited observational strategies (especially for Kepler), have made follow-up RV observations challenging. None-the-less some individuals in the UK exoplanet community have become involved in the Kepler follow-up campaign thanks to institutional involvement in HARPS North. Considering the thousands of planetary candidates these missions have produced, relatively few have directly measured masses (the vast majority of these have been found through indirect techniques and are of relatively low accuracy).
While the UK has continued to operate and exploit the SuperWASP surveys, we have also developed a new facility, the Next Generation Transit Survey or NGTS, which was designed to exploit planetary parameter space not occupied by CoRoT or Kepler observations. NGTS is designed to obtain photometry at the limit of that possible from the ground and is driven by the need to obtain bright examples of Neptune and super-Earth sized planets to enable detailed follow-up observations. It is currently undergoing commissioning at Paranal, ESO.

The WASP and NGTS developments have led to the UK having significant roles in CHEOPS (ESA S1 mission, due for launch in 2017) and PLATO (ESA M3 mission, due for launch in 2024). CHEOPS is a pointed mission, looking primarily at known low-mass radial velocity planets of which maybe 10% can be expected to transit (but which are not detectable from the ground). CHEOPS is a Swiss-led mission but the UK is well placed through the long-standing WASP and NGTS collaborations. PLATO will be transformative in extending our knowledge of the bulk properties of terrestrial planets not least because of its concentration on bright stars (the faint end of the PLATO stellar sample used in exoplanet work corresponds to the bright end for Kepler). The UK is well placed both technologically and scientifically in PLATO to fully exploit this mission.

In the past years the UK has been at the forefront of exoplanet/brown-dwarf atmosphere characterisation and theoretical/observational magnetospheric studies (e.g. 6 ERC grants + other prestigious awards), with a growing number of institutes and scientists contributing to this field. While planetary atmosphere spectroscopy is challenging as the atmospheric signals are very small, pioneering results from UK scientists with Hubble, Spitzer and number of institutes and scientists contributing to this field. While planetary atmosphere spectroscopy is challenging as the atmospheric signals are very small, pioneering results from UK scientists with Hubble, Spitzer and ground-based instruments have proven that it is possible using both transit and direct imaging techniques. The UK is currently a world-leader in atmospheric data analysis with statistical techniques able to remove instrumental systematics and stellar activity, spectral retrieval modeling, atmospheric dynamics and interior modeling, theoretical line-lists calculations, and modeling the formation of clouds and hazes in planetary atmospheres. The UK is also at the forefront of designing future space- and ground-based instruments for atmospheric characterisation. It is also worth noting that WASP planets remain amongst the best targets for atmospheric studies.

Microlensing techniques have opened up a new parameter space for long period, low mass planets. It has suffered in the UK due to a lack of suitable and dedicated resources. In the surveys that have been ongoing, UK scientists have been instrumental in organizing the observations and the modeling of the light curves. One of the biggest discoveries coming from this area is the significant population of orphan planets (planetary-mass objects with no parent star).

In space the Gaia astrometry mission has now entered routine operations. At the end of its five-year baseline mission it is likely to discover thousands of massive planets in the solar neighborhood. These astrometric orbits when complemented by ground-based radial velocity observations will enable absolute planetary masses to be obtained (not just lower limits as obtained from radial velocity studies alone). Gaia data for eclipsing binary stars can be used to test and calibrate the next generation of stellar models that are now being developed in response to the need to better understand how the properties of planet host stars affect the formation and properties of the planets that orbit them.

With the advent of SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research instrument) at the Very Large Telescope and GPI (Gemini Planet Imager) at Gemini South we are likely to see a major step forward in numbers of directly imaged planets. These dedicated facilities are most likely to discover populations of long period, young (hot) gas giants; important targets with which to test atmospheric models. This was an area identified during the last STFC exoplanet review (McCaughearan 2007) as important, but one in which involvement by the UK was lacking. Since then a small number of institutes have developed groups and made key appointments to fill this void.

Since before the first exoplanet discoveries the UK has had a strong theoretical presence in this field. This was in the areas of discs and planet formation, but over the past ten years the UK theory community has increased in size and has broadened its research base so that it can now claim international leadership in diverse activities such as planetary system formation and dynamical evolution, protoplanetary and debris discs, planetary interior modeling and atmospheric physics. Investments in HPC have played a key role in allowing UK theorists to maintain and increase their international competitiveness.

The UK has led both observational and theoretical studies of the asteroid and Kuiper belts of nearby stars (collectively called debris disks). As integral components of exoplanet systems, observational characterisation of debris disks has provided valuable information on the architecture of the underlying planetary system (e.g., disk structure has been used as an indirect exoplanet detection technique), and theoretical modeling has constrained the formation and dynamical evolution of the systems.
More recently, UK astronomers have led the way in understanding the final demise of some exoplanetary systems through the study of what is thought to be accreted (terrestrial) planet material onto the otherwise pristine atmospheres of white dwarfs. Along with observations of fragmenting and evaporating transiting planets these techniques offer our first attempts to directly measure the internal composition of some types of exoplanets.

For the first time, there is now a European roadmap of funded facilities stretching over the next 10-15 years or so – see Figure 1. While many of these facilities are general purpose (e.g. the Square Kilometer Array, James Webb Space Telescope, European Extremely Large Telescope) central to the roadmap is the use of instruments designed specifically for transit discovery and their utilization for both bulk atmospheric and internal characterisation. The UK has world-leading research groups in these areas with high-level roles in many of these projects and so is well placed to play a leading role in the roadmap.

Over the next few years the UK-led WASP Project will remain the most prolific ground-based producer of large planets, supplying planets that are well suited for study with current spectroscopic instrumentation both for internal and atmospheric studies.

From space the re-tasked Kepler spacecraft has entered a new phase – the K2 surveys. By an ingenious use of the crippled spacecraft it is now possible to obtain time series of parts of the ecliptic for as long as ~80 days. While the data are not comparable to the original mission (neither in duration or overall accuracy), it is reaching unprecedented levels of accuracy for the chosen fields resulting in new discoveries. Despite this the original problems associated with Kepler planets remain – the bulk of the stars (and their likely small, low mass, planets) are challenging objects for detailed spectroscopic examination with our current crop of spectrographs. Nonetheless K2 is starting to find (at the time of writing Kepler is observing its second K2 field) multiplanet systems of a few earth radii each.

Also included in Figure 1 are the radial velocity instruments required to exploit the transit facilities. Stabilised spectrographs, for example HARPS North, SOPHIE and VLT-ESPRESSO, are needed for determining the planetary mass and, when combined with the radius, the planetary bulk density. Also likely to be available to the UK (at least through collaboration) are IR stabilized spectrographs on 4m sized telescopes such as CARMENES (Calar Alto) which will be used for terrestrial planet searches around M-dwarfs. Gaia is expected to discover thousands of new planets through astrometry and promises to refine our knowledge of the stars in the Galaxy.

Warm Spitzer, Hubble Space Telescope, James Webb Space Telescope, SPHERE, and GPI will all contribute to the atmospheric characterisation of transiting and imaged planets. The Atacama Large Millimetre/sub-millimetre Array and James Webb Space Telescope will be critical for protoplanetary and debris disk studies. In the next decade the European Extremely Large Telescope is likely to contribute to many exoplanet areas through the METIS (atmospheric studies, direct imaging, disks) and HIRES (radial velocity and atmospheric work) instruments, but selection of the final instrumentation for the telescope is still to occur.

2. Overview of exoplanet research in the UK

2.1 General overview of the UK exoplanet community standing and reputation.

The McCaughrean (2007) report noted that, although the UK had a high degree of involvement in the exoplanet field, it lagged significantly behind the US, Switzerland, France and Germany – and, as such, was not perceived as a leader in exoplanet research. Several reasons for this were opined, which included a lack of coherent planning and investment, leaving the UK community unable to compete for key leadership roles. An overall impression of the activity and development of the UK exoplanet community can be forged by inspecting the rate of exoplanet-related publications with UK affiliated authors. These totals, benchmarked against other countries, are shown in Figure 2 for the last decade. This clearly underlines the rapid growth that the exoplanet field has seen on the global stage over the last decade. It also supports the opinion of the 2007 report that the UK was trailing its main competitors at that time, with an apparent 2 to 3 year lag behind its rivals. Fast-forward to the present day and there is evidence that the UK has not only caught up with its main European competitors, but that it may have recently overtaken them. This emergence of exoplanetary astronomy with a leading UK contribution was also noted in the REF 2014 exercise.

2.2 UK highlights, high-visibility projects, and leadership roles

Both the UK community and the global scene have evolved rapidly since 2007, as clearly illustrated in Figure 2. The following represents a more in-depth look at a selection of UK highlights (rather than an exhaustive list) linked
to some of the areas specified in the scientific agenda laid down by the McCaughrean (2007) report. This demonstrates the world-leading quality and depth that the UK community has developed – and shows that some of the science goals recommended in 2007 have been achieved, despite a challenging economic environment.

![A timeline of exoplanet facilities](image)

**Figure 1: A timeline of exoplanet relevant facilities.** Central to this are those specifically designed for transit discovery: SWASP, K2, NGTS, CHEOPS (ESA), TESS (NASA) and PLATO (ESA). Other ground-based facilities (e.g. HARPS and VLT-ESPRESSO) will complement these discoveries by determining the planetary mass and density. Gaia is expected to discover thousands of new planets and refine our knowledge of the stars in our galaxy. ALMA and JWST will be pivotal for studies of planetary and debris disks. Warm-Spitzer, Hubble, SPHERE, GPI and later on JWST will contribute to atmospheric characterization. In the next decade the E-ELT will contribute too many exoplanet areas (in particular RV, atmospheric and disks characterization, direct imaging).

**Radial velocities:**

The McCaughrean (2007) report stressed a future need to secure access to (as well as encourage the development of) high-precision spectrographs such as at the AAT (UCLES), Gemini-N (e.g. PRVS), WHT (e.g. HARPS-N), as well as UKIRT for the purposes of obtaining planetary mass and bulk density measurements. Clearly, the landscape regarding the provision of facilities has changed dramatically in the intervening period, with the UK only retaining access to HARPS at the ESO 3.6m (see Table 1). It has also led to highly successful follow-up campaigns (largely of WASP planets) using SOPHIE at the OHP and FIES at the NOT obtained primarily through access provided by OPTICON. In addition to measuring planetary masses, UK groups have been at the heart of several other RV programmes. For example, UK authors have led publications on more than 25% of all the planets with currently measured spin-orbit alignment angles and, as a result, can claim world leadership in observations probing the migration and evolution of exoplanets.

A number of UK institutes are also privately funded members of the HARPS-N consortium. This instrument (mounted on the TNG) was partly built by the UKATC. The pioneering HARPS-N follow-up of Kepler-78b (Pepe et al. 2013) demonstrates the scientific impact that access to such facilities can have, as highlighted in an impact case study by STFC. UK HARPS-N consortium members, alongside EU and US partners, were able to determine the mass of this Earth-sized planet (the smallest transiting planet to ever have had such a measurement) – revealing that it probably has an Earth-like iron/rock composition.
Within the context of planetary mass measurements, UK groups also play internationally-leading roles in developing innovative methods for modeling and reducing the impact of quasi-periodic RV variations caused by surface inhomogeneities (such as starspots and convective motions) on the surfaces of stars. Understanding and mitigating the effects of these astrophysical noise sources is of fundamental importance, since it is astrophysical noise that will set the fundamental barrier to the ultimate RV precision attainable, not technological capability. This is a research topic that, in recent years, has become increasingly prominent in both the literature and science discussions regarding the RV follow-up of extrasolar planets. Building on its long heritage as world-leaders in pioneering stellar activity research – the UK is ideally positioned to lead the way in this area, which will only become more important as the highly-prized smaller (lower-mass) terrestrial planets are uncovered by future transit surveys (see Section 3.3).

**Transiting planets:**

The WASP experiment has been a particular UK success story, and has now found >150 transiting exoplanets – and the discovery rate is still increasing. Due to the brightness of the host stars that WASP surveys \( V = 9 - 13 \), compared to Kepler targets that are typically \( V = 13 - 16 \), WASP has also provided prominent targets for the global exoplanet bulk and atmospheric characterisation community. Indeed, atmospheric characterisation papers based on WASP planets are more prolific than for planets from any other survey, including Kepler. Of the 39 planets for which 1 or more follow-up secondary eclipses are available, WASP planets account for 15 (more than double that of the next survey). The same can be said for transmission spectroscopy and dayside emission spectroscopy, where WASP discoveries account for \( \sim 32\% \) and \( 50\% \) of planets targeted for detailed follow-up with these methods, respectively (Bailey 2014). It is also worth noting that, unlike the space based projects, WASP planets are only published when a direct mass determination (from radial velocity studies) is available. The ability to spectroscopically follow-up WASP planets has led to many advances such as identifying planet scattering as one of the prominent migration mechanisms through which hot-Jupiters may be produced. Over and above this, one of the real successes of the WASP project has been to dramatically enlarge the UK Exoplanet community – either launching or consolidating 5 exoplanet groups.

A number of UK institutions initiated the Next Generation Transit Survey (NGTS) for which the UK retains leadership. NGTS builds on the experience and heritage of the WASP project and will take survey photometric precision to unprecedented levels. The design goal is to reach routine transit detection at the 0.1-0.2\% level sufficient for Neptune and super-Earth sized planet detection around relatively bright stars. NGTS is currently undergoing final commissioning at Cerro Paranal and the first survey is expected to start within a couple of months (at time of writing). Simulations show an expected yield of \( \sim 40 \) super-Earths and several hundred Neptune-sized planets around bright host stars – making these prime targets for future detailed follow-up. While these goals can be partly reached through the present HARPS-N instruments, the deployment of ESPRESSO at the VLT will be needed for confirmation of the majority of these objects. NGTS data will be made available to the entire UK community after a short propriety period (primarily for data verification purposes) facilitating many other exoplanet projects in the UK.

The expertise that these projects have nurtured has also been crucial in enabling UK scientists to achieve prominent roles in a number of other transiting planet discovery missions. These roles include members of the Mission Consortium Board and Science Advisory Team for both the ESA CHEOPS and PLATO missions.

**Atmospheric characterisation:**

Atmospheric characterisation research itself has matured within the UK, and now covers a variety of aspects including both theoretical and observational work. From the observational standpoint, the UK is highly active. Nearly 46\% of the Na transmission spectroscopy detection papers published since 2007 have been led by UK-based researchers, who also account for a further \( \sim 24\% \) of transmission spectroscopy papers at other wavelengths (see Bailey 2014). The first detections of water vapour, methane, carbon dioxide, potassium, and hazes were led or co-authored by UK scientists (with a total of over 1,000 citations for the corresponding papers). In addition, the UK is the world leader in line-list calculations used for exoplanet spectroscopy.

Prestigious awards for exoplanet atmospheres research include 6 ERC grants (3 senior, 1 consolidator, 2 starting) a Royal Society Wolfson Research Merit Award, an Institute of Physics Moseley Medal, and a NASA Group Achievement Award. Furthermore, UK scientists have forged leadership roles in several high visibility projects. Recent examples include the UK PI of the ESA-M3 mission candidate Exoplanet Characterisation Observatory (ECHO), UK PI of the ESA-M4 ARIEL mission candidate, as well as PI of the Large HST programme “An Optical Transmission Spectral Survey of hot-Jupiter Exoplanetary Atmospheres” – the first large HST programme awarded to a UK PI.
Microlensing:
Microlensing explores a parameter space encompassing low mass, long period systems (or cold-Earths). Prior to the end of 2007, only 4 planets had been discovered via the gravitational microlensing method, including the (UK-led) first microlens planet discovery (Bond et al. 2004). Since then, that number has risen to 34 planets in 32 planetary systems, including significant UK involvement in the first rock/ice microlens planet discovery (Beaulieu et al. 2006), the first 2-planet system discovered by microlensing (Gaudi et al. 2008), and the determination of the power-law mass function of cool planets (Cassan et al. 2012).

UK researchers have also taken a number of prominent lead roles in observational microlensing programmes. These include PI of Artemis; co-PI and science coordinator of MiNDSTEp; co-leader of the PLANET team, and PI of the RoboNet microlens planet search (from 2002-2013). Indeed, the UK-led RoboNet project initially developed robotic microlensing planet search capabilities using three UK-built 2-m Robotic Telescopes (Liverpool Telescope, Faulkes North and Faulkes South). Since 2014, RoboNet has been using the LCOGT network, which currently consists of nine 1-m telescopes. This significant involvement has attracted substantial funding, including a £2.8M SUPA2 grant for 3 robotic telescopes to link to the LCOGT network, a $1M Qatar National Research Fund (QNRF) grant, as well as support to individual researchers via Royal Society University Research and STFC Advanced Fellowships.

Direct detection:
The McCaughrean (2007) report highlighted the need for the UK to reinvigorate its involvement in direct imaging, and that the mid- to long-term ambitions of the UK and world-wide communities in this field clearly involved direct imaging of exoplanets. Without any institutional involvement in SPHERE (VLT) or GPI (Gemini-S) developments in this area had largely passed unnoticed. While the UK direct imaging community is still small, since 2007 a number of institutions have invested in permanent positions in this area – successfully attracting former Sagan/NSF postdoctoral and Hubble Fellows to their ranks. Furthermore, we have seen the development of hardware groups specializing in AO imaging of exoplanets on large telescopes (e.g. Oxford). This has, for example, led to significant UK involvement in the construction of the E-ELT HARMONI instrument – including a UK PI who heads this project. This first-light spectrograph will enable characterisation of known directly imaged planets and, through its participation with HARMONI, the community is well placed to lead the future development of PCS-EPICS for the E-ELT (a second-generation instrument for the E-ELT dedicated to the direct imaging of exoplanets).

Figure 2: Number of refereed publications with affiliated authors from the USA, France, Germany, UK, Switzerland and Italy over the period 2005-2014 that contain the words “exoplanet” and/or “extrasolar” in the abstract and/or title. Over the last ten years UK activity in the exoplanet area has caught up with and now exceeds that of several comparator countries.
UK researchers also currently hold a number of notable roles in this area. These include leadership of the largest exoplanet direct imaging campaign to date at the Keck Observatory (covering roughly 300 stars over 25 Keck nights), membership of the SPHERE GTO team, and leadership of several ongoing SPHERE programs on the VLT. UK researchers are also at the forefront of searches for variability due to clouds on both young exoplanet companions and free-floating planetary mass objects.

**Theory and modeling:**
Significant advances have been made in understanding theoretically the formation, evolution, and observed properties of exoplanets as well as in the modeling of their atmospheres, magnetospheres and interiors. For example, UK researchers have constructed sophisticated interior models of giant planets that are now the “industry standard”. Atmospheric dynamics calculations undertaken by UK researchers have been instrumental in interpreting the observed time dependent emission from hot Jupiters such as Upsilon Andromeda b. UK theorists have played the lead role in investigating planet formation in binary star systems (e.g. Pierens & Nelson, 2008), leading to specific predictions that were later confirmed by the discovery of the circumbinary planetary systems Kepler 16, 34, 35, and 47 in 2011 and 2012. Considerable progress has also been made in understanding the evolution of planets through the gravitational instability of protoplanetary discs – indicating that the gravitational instability model of planet formation as originally conceived is substantially less viable than was understood before 2007 (e.g. Baruteau et al. 2011; Cha & Nayakshin 2011). Other areas of appreciable progress driven by UK scientists include disc-planet interactions and planet migration (e.g. Paardekooper et al. 2011), as well as the theoretical understanding of tidal interactions between stars and short-period planets (Ogilvie, 2014) – essential for understanding the formation of inclined hot-Jupiters and the long-term dynamical evolution of the Kepler compact multi planet systems. In addition to this, UK researchers are the world leaders in the calculation of molecular line lists that are vital for interpreting spectroscopic observations of exoplanetary atmospheres.

**Debris discs:**
Debris discs provide important information about the architectures and dynamics of planetary systems. Herschel, JCMT, WISE, Spitzer and IR-interferometry have driven significant advances in debris discs in recent years. U.K. researchers have had major involvement in the DEBRIS Herschel Key Programme, provided leadership of the SONS JCMT Legacy survey, and have played major roles in the reanalysis of Spitzer and WISE data. Herschel has provided accurate far-IR fluxes, new discs and resolved images in ~ 50% of cases. WISE observations have demonstrated that numerous main-sequence stars have hot dust within 10 AU, coinciding with the expected locations of planetary systems, a result that is supported by IR-interferometry. UK researchers are PI’s on several ALMA programmes, and co-I on many more, and have led developments in theoretical modelling. In particular, advances have been made in understanding how debris populations evolve within planetary systems using increasingly sophisticated with N-body codes that include collisional evolution.

**Further developments not foreseen in 2007:**
Finally, the UK has seen the establishment of a number of other novel exoplanet-related areas not envisaged in 2007. These areas include the study of polluted white dwarfs, disintegrating planets, as well as research into circumbinary planets (via transits and timing), amongst others. The dynamic and rapidly evolving field emphasizes the need for a flexible funding system to enable the community to respond to new opportunities and ideas when and as they arise.

**Community building:**
The McCaughrean (2007) report also made reference to community building and over the last few years this has begun in earnest as the UK Exoplanet Community has organised annual meetings. A draft of this report was presented at the 2015 Community meeting held at Warwick University where some 131 participants were registered.
3. State of the art of the field and the international context

3.1 Transit surveys and discovery missions

Transit observations remain the only way to measure the planetary radius in a reliable (and pretty much model independent) way. However, as the transit probability drops off sharply with increasing period it becomes less efficient. Nonetheless it remains a proven technique for producing planets that can be characterised. Transiting planets have led to many of the discoveries in exoplanets over recent years and we expect this to continue for the foreseeable future – especially for small, habitable zone planets that are almost inaccessible by any other technique. These bodies cannot be characterised by any other means.

The SuperWASP project remains the most prolific discovery machine despite a drastic reduction in support since 2012. In particular in 2011-12 the cameras underwent a series of upgrades enabling SuperWASP-S to be sensitive to much brighter stars (the southern skies have not been surveyed at these brightness levels and we expect several high value transiting planets) and SuperWASP-N to be sensitive to much smaller (Neptune sized) and longer period planets (potentially up to 30 days). Until NASA’s TESS mission flies, we expect that WASP will continue to be the dominant facility used to detect large planets suitable for detailed follow-up by the exoplanet community.

The push to smaller planets can be achieved by targeting smaller stars (M-dwarfs) or by reaching greater photometric precisions. The NGTS experiment uses new CCD technology to target red objects and will become a rich source of small transiting planets in the southern sky (Figure 3). While UK led (and STFC supported), several other European institutes have partnered the project (Berlin, DLR, University of Geneva). The science goals for NGTS are the routine detection of super-Earths and Neptune sized planets to be used for bulk density and planetary atmosphere studies. NGTS is a real breakthrough facility as this level of performance has never been achieved by a ground-based survey. The NGTS instruments have already demonstrated photometric performance at the scintillation level for the site. Data from NGTS will be made available to the entire ESO community after a short proprietary period.

A similar aim is realized by the Belgium led SPECULOOS experiment with some UK involvement. This funded project is a small group of 1m aperture telescopes optimized to work at ~900nm with the science aim of looking for transits around ultra-cool dwarfs. For these objects the habitable zone is at periods of weeks and given that some observations predict an enhanced planet frequency then there is some chance of detecting small (tidally locked) rocky planets in these systems.

In the drive towards smaller planets, the highest photometric accuracies will ultimately be achieved by space-based platforms. Over the next decade there are 3 selected missions that will transform our knowledge of transiting planets as they are all designed to study much brighter stars than CoRoT or Kepler. These missions are:

i) TESS (NASA) – the Transiting Exoplanet Survey Satellite. This is due for launch (2017) with the aim of detecting and characterizing ~50 planetary systems (planets down to super-Earth sized) around bright and nearby M-stars. In addition TESS is tasked with providing quality targets for atmospheric characterisation with the JWST. TESS will be launched into a highly eccentric orbit and will spend most of its time near the moon and away from the Earth’s glare. This ingenious orbit will enable TESS to survey almost the entire sky during its 2 year life time primarily focusing on late type stars in the brightness range $I \sim 4 - 13^{th}$ magnitude. For a handful of the latest type M-dwarfs TESS will have some sensitivity to habitable zone Earth sized planets – but for most of the stellar population it will be sensitive to Neptune and super-Earth sized planets (its sensitivity space is similar to that of NGTS, see Figure 3). TESS can stare in any particular right ascension range for about one month and its large field of view will result in some overlap at the ecliptic poles so that a small region of sky could have up to 1 year of almost continuous coverage. The UK has no direct exoplanet role in the mission, but
will certainly be involved through the key spectroscopic observations using the HARPS/N instruments – most likely as part of large collaborations. The UK will also have leadership roles within the TESS Asteroseismic Science Consortium (TASC).

ii) CHEOPS (ESA) – the Swiss Exoplanet Survey Satellite. To be launched in 2018 this is ESA’s first S mission. Its main purpose is to observe planets already discovered through radial velocity surveys of which a fraction maybe expected to transit their host stars. It is expected that a few dozen objects will be characterized in this way. In addition, CHEOPS will also observe the smallest planets found from other photometric discovery missions such as NGTS and TESS. These missions will have limited time on sky and are likely to detect many single transit events that, when combined with RV spectroscopy, will give approximate periods. High precision CHEOPS observations would be needed to understand their bulk properties and aid the JWST atmosphere observations. The history of this mission can be traced back to discussions between the UK-WASP and Swiss teams as a way to follow-up the smallest WASP planets. Consequently, while our direct exposure is limited to just a few individuals we still have some influence within the mission. It’s also important to remember that 20% of the science time is available to ESA countries, giving the UK community an additional channel through which it may yield scientific benefits from the mission.

iii) PLATO (ESA) – the PLAnetary Transits and Oscillations mission. PLATO was selected as the M3 mission by the ESA advisory structure in February 2014 with an expected launch date in 2024. Its mission goals are primarily concerned with large-scale characterisation of terrestrial planets with periods up to those of planets orbiting within the habitable zones of sun-like stars. PLATO will characterise several thousands of planets, which will be used to aid our understanding of the important processes in planet building and evolution (it is the only source of habitable zone terrestrial planets with solar like host stars on the horizon). PLATO will also use asteroseismology to test and improve accurate internal models of host stars enabling their ages to be derived with some accuracy. The final data product from PLATO will be a large database of system parameters. The UK is extremely well placed in this mission with important leadership roles in the Science (both exoplanet and asteroseismology areas) and technology areas of the project. The UK is one of the founding members of PLATO and as such exerts real influence at all levels within the mission.

Asteroseismology has a central role to play in the PLATO and TESS missions in characterising bright planet-hosting Sun-like stars. These missions will increase by more than two orders of magnitude the number of Sun-like stars with high-quality asteroseismic data. Crucially, and most notably for PLATO, the data will make possible detailed statistical and ensemble studies of the internal structure, dynamics and physics of thousands of solar-type stars, where the current data are only now providing a first glimpse of what is possible from results on a much smaller target sample. There is also huge potential for applications to population studies of the local solar neighbourhood. These results will lead to significant advances in our understanding of convection, mixing and other transport processes in stellar interiors. This has important implications for the characterisation work, since it will then be possible to provide much more robust age estimates that are less susceptible to uncertainties associated with the assumed input physics. There is significant scope to further reduce the uncertainties due to missing physics in stellar models using detailed follow-up observations for eclipsing binary stars discovered by transit surveys.

For high value targets the JWST will also be used to obtain multi-waveband photometry during transits (and occultations) with similar aims to the Spitzer programmes.

3.2 Atmospheric characterisation
For planets transiting in front of their parent stars – of which some 1100 are known today – the simplest observables are the planetary radius and, when combined with radial velocity measurements, the mass. Mass and radius allow the estimation of the planetary bulk density. While the density is an important parameter, on its own it cannot be used to discriminate the different classes of exoplanets that we are seeing (Valencia et al., 2013; Adams et al., 2008). To do this requires additional information; the other key observables for planets are the chemical compositions and states of their atmospheres (see Figure 4). Knowing what atmospheres are made of is essential to clarify, for instance, whether a planet was born in the orbit it is observed in or whether it has migrated a long way. It is also critical to our understanding of chemical evolution, global circulation, and the role played by stellar radiation on escape processes. Finally, some have claimed that the atmospheric composition is the only direct
observable to investigate planetary habitability (Lovelock, 1979), although in-situ exploration is obviously also extremely valuable.

To date, two classes of methods can be used to probe exoplanetary atmospheres: combined light spectroscopy and angular resolved spectroscopy.

**Combined light spectroscopy**

Combined light spectroscopy allows us to measure atmospheric signals from the exoplanet at levels of ~$10^{-4}$ relative to the star. High-quality angular resolution is not required as the signals from the star and from the planet are differentiated using knowledge of the planetary ephemerides. Various techniques can be used, all of which are very sensitive to planets that orbit relatively close to their star. These techniques are:

- Transit spectroscopy, (e.g. Brown, 2001).
- Eclipse spectroscopy, (e.g. Grillmair et al., 2008).
- Eclipse mapping, (e.g. Majeau et al., 2012).
- Phase-curves, (e.g. Knutson et al., 2007; Harrington et al., 2006).
- Time series of narrow spectral bands, (e.g. Apai et al., 2013).
- High-dispersion spectroscopy (e.g. Snellen et al., 2010).

Over the past decade, pioneering results have been obtained using combined-light spectroscopy with Hubble, Spitzer, and ground-based facilities, enabling the detection of a few of the most abundant ionic, atomic and molecular species, as well as setting constraints on the planet’s thermal structure. UV observations from space, with HST/STIS-COS, have unveiled a population of ions and radicals wrapping the planet like a blanket and partially occulting the star. These observations are suggestive of escape processes. Repeated measurements in the visible range of alkali metals on other planets have been reported in the literature, from both space and the ground (e.g. Charbonneau et al., 2002; Redfield et al. 2008; Sing et al. 2011).

Hazes or clouds of currently unknown composition appear to affect the transparency of some of the observed atmospheres in the visible/NIR spectral range. The IR range offers the possibility of probing the neutral atmospheres of exoplanets and their thermal properties. On a large scale, the IR transit and eclipse spectra of hot-Jupiters seem to be dominated by the signature of water vapour. Similarly, the atmosphere of the hot-Neptune HAT-P-11b appears to be water-rich (Fraine et al., 2014). Other molecules (CO, CH$_4$, CO$_2$...) have also been suggested as being present in some exoplanetary atmospheres. The analysis of the transit spectra for the 6.5 M$_{\text{Earth}}$ super-Earth GJ 1214b has oscillated between a metal-rich or a cloudy atmosphere. In addition, UK-led studies have also examined the influence of the surrounding magnetospheric environments of exoplanets and their effects on transit shapes and depths (e.g., Nichols et al., 2015).

Despite these early successes, current data are rather sparse, i.e. there is not enough wavelength coverage and most of the time the observations are not recorded simultaneously. Notice that an absolute calibration at the level of $10^{-4}$ is not guaranteed by current instruments, as none were designed for precision spectrophotometry, and therefore caution is needed when one combines multiple datasets at different wavelengths that were not recorded simultaneously. The degeneracy of solutions embedded in the current transit observations prevents precise estimation of the elemental abundances of the planets analysed. The rather unique requirements of high precision exoplanet transit spectroscopy require a novel part of instrumentation parameter space that has yet to be developed. New and better data from dedicated instruments are needed for this purpose.

**Angular resolved spectroscopy**

These investigations involve the use of high contrast imaging to minimize the light from the host star and to detect directly the light from the exoplanet (e.g. Barman et al., 2011). These techniques target planets at larger separation from the stars, a domain that is unsuited to transit surveys.
The advantage of transiting planets is that the planetary size and the mass are known. Direct imaging or combined light observations of non-transiting planets suffer from the lack of knowledge of the planetary radius and often the mass. When the mass and the radius are not known, model estimates need to be invoked, increasing the source of degeneracy in the interpretation of the results.

In parallel with combined light studies, the first spectra of hot, young super-Jupiters at large separations from their host stars have been observed in recent years through direct imaging (e.g. Bonnefoy et al., 2013; Konopacky et al., 2013). Spectroscopy in the wavelength range of YJHK-band will start soon with dedicated instruments on VLT (SPHERE), Gemini (GPI), and Subaru (SCExAO).

The next decade: JWST & dedicated instruments for atmospheric characterisation from space and the ground

Thousands of (mostly transiting) planets around bright sources will be discovered by current (WASP, HAT-NET, HARPS etc.) and new facilities from space (Gaia, TESS, CHEOPS, PLATO) and the ground (NGTS, ESPRESSO, etc.). The brightest of these planets will be ideal targets for atmospheric characterisation through combined-light spectroscopy. Indeed it is the atmospheric characterisation requirements that have been driving the detection of bright planetary host stars from the transit experiments.

Later this decade (late 2017) the CRIRES+ instrument at the VLT will be commissioned. This is a development of the original CRIRES instrument enabling a factor of ten increase in simultaneous wavelength coverage onto an extended focal plane as well as a new polarimetric mode. The CRIRES instrument itself was responsible for many pioneering atmosphere observations (e.g. CO direct detection, Brogi et al Nature 2012) and the new instrument will enhance this capability hugely.

Spectroscopy in the wavelength range of YJHK-band with dedicated instruments on VLT (SPHERE), Gemini (GPI), as well as Subaru (SCExAO) will provide spectra for a few tens of hot, young, gaseous planets situated at large separations from their host star. The comparison of the chemical composition of these young gaseous objects to the composition of their migrated siblings probed through transits will be of great help to understand the role played by formation location, migration and by extreme irradiation of gaseous planets.

In the next decade, JWST will revolutionise our knowledge of the physical properties of a wide variety of exoplanets, making numerous different types of observations. It has an equivalent telescope diameter of 5.8 m, and this infrared focused multipurpose observatory will orbit around L2, providing a highly stable thermal environment, ideal for transit observations. The four main instruments on JWST (NIRISS, NIRCAM, NIRSPEC, MIRI) are all conducive to exoplanet observations. The mid-infrared MIRI instrument is an international project combining the talents of a consortium of European partners including the UK ATC (UK co-PI). JWST will provide spectra from R~100 to 3000 at wavelengths between 0.7 and 28 \( \mu \) m. Such capabilities are far beyond the current capabilities of the Hubble Space Telescope (R~100 at 0.3 to 1.7 \( \mu \) m) and will cover many important molecular species that are largely inaccessible such as CH\(_4\) and CO. With this capability, JWST spectroscopy will investigate planetary atmospheres to determine atomic and molecular compositions, probe vertical and horizontal structure, and follow the atmospheric dynamics of giant planets, Neptune-sized and super-Earth exoplanets, the most challenging being temperate super-Earths around M-dwarfs. JWST is a limited lifetime mission (5 year baseline), and there are options for facilities with additional capabilities (section 4.2) that can highly complement and enhance exoplanet atmospheric characterization by observing bright targets more efficiently, and surveying exoplanets in much greater numbers.

In the next decade (~2025) the E-ELT will be commissioned. One of the instrument concepts being closely studied is an IR spectrograph called METIS. One of the science cases supporting this instrument builds on the successes of CRIRES in the area of atmosphere studies. A further planned instrument HIRES (an optical spectrograph) can also be applied to atmosphere studies.
3.3 Radial velocity exoplanet detections

Detecting exoplanets via stellar radial velocity (RV) measurements has played a dominant role in the detection and characterisation of exoplanets ever since the first exoplanet was discovered around a main sequence star in 1995. RV measurements are highly sensitive to the orbital parameters such as the period and eccentricity as well as the planetary minimum mass. With technology steadily improving (see Figure 1), RV precisions in the sub m/s regime are now possible for the quietest stars, which allows exoplanets in the Earth-mass regime at short orbital periods to be detected (see Figure 5). Running parallel to improvements in instrumental capabilities, several UK groups are leading efforts to understand and mitigate the effects of astrophysical noise (such as star-spots and convective blue-shifts) that can impact RV measurements at the 1 m s\(^{-1}\) level, even for apparently quiet stars. This work is crucial, especially as the next generation of high precision spectrographs come on-line, as it will be astrophysical noise that sets the fundamental RV noise floor that can be achieved, not technical capability. For example, future spectrographs such as ESPRESSO (VLT) and HIRES (E-ELT) will reach RV precisions better than 0.1 m s\(^{-1}\), well below the ~1 m s\(^{-1}\) variations due to astrophysical noise typically exhibited by solar-like stars. Without an understanding of astrophysical noise, and the development of techniques to remove its effects from the RV follow-up of planets, efficient confirmation via mass (and hence bulk density) measurements of terrestrial planets around even quiet stars will be significantly compromised. Thus-far techniques to combat astrophysical noise have kept pace with technological advances, but the push to 0.01 m s\(^{-1}\) precisions will undoubtedly reveal new challenges in this field. The UK is ideally positioned to take leadership in this area – building on its strong heritage in world-leading research into stellar activity. In addition, there is a considerable interdisciplinary overlap with solar physics where “sun-as-a-star” observations and/or simulations can be used to guide future methodologies and observational strategies. With the launch of missions such as PLATO and the discovery of potential transiting Earth-analogs (expected to have Doppler wobbles of amplitudes of ~0.1 m s\(^{-1}\)) on the horizon, astrophysical noise is now widely accepted by the community as a crucial limiting factor of such work. Investment in innovative new ideas and approaches will be required.

RV follow-up of transiting planet candidates is a vitally important verification method for those planets, and coupled with astrophysical noise removal techniques provides reliable mass determinations. With RV and transit measurements of an exoplanet, both the mass and radius and thus bulk density of a planet can be determined to high accuracy. With a bulk density, the basic composition of a planet can be constrained, which is particularly important for low-mass planets as compositions can vary widely. Transiting planets with RV detections are extremely valuable, as they are vital for testing theories of planetary structure in the context of planet assembly and dynamical evolution. Moreover, for small planets, transiting+RV exoplanets are the only ones for which detailed follow-up atmospheric characterisation is possible. As such, with the increasing efficiency of surveys such as WASP, CoRot, and Kepler, transits with RV measurements have now become a major exoplanet detection technique (see Figure 1). Since 2007 there have been 200 exoplanets detected by both transit and RV measurements, which represents more than an order of magnitude increase over the last eight years. Such successes and increasing sensitivity to low mass terrestrial planets have helped drive future transit missions such as PLATO and TESS as well as future RV instrumentation such as ESPRESSO on the VLT.

The HARPS instrument on the 3.6m telescope at La Silla has lead the way in RV techniques since it was installed in 2003, and it still represents the state-of-the-art in RV instrumentation. HARPS is a high resolution fibre-fed echeleon spectrograph that achieves long-term RV stability by placing the instrument in a pressure and temperature controlled vacuum tank, and precisions on the order of 1 m/s can be reached in 1 minute on an 8th magnitude star. The success of HARPS has helped lead other observatories to pursue high accuracy RV measurements, and there are now about 10 RV instruments on-line capable of 1 m/s precisions (mostly built after 2006), with an additional 3 planned over the next few years (see Table 1).

Future transit surveys, such as TESS and ESA’s PLATO (due to launch in 2024), will detect 1,000s of low mass exoplanet candidates in both the northern and southern hemispheres. PLATO’s mission objective is to find and study a large number of exoplanetary systems, with emphasis on the properties of terrestrial planets in the habitable zone around solar-like stars. Candidate planets discovered by TESS or PLATO will require RV follow-up measurements for mass confirmation, and to rule out false positives. In the case of PLATO, ESA will work alongside ESO with facilities enabling follow-up of PLATO transiting planet candidates in the south. As both TESS and PLATO will detect transits around extremely bright stars in both hemispheres, RV follow-up with precision spectrographs on small workhorse 2-4 meter class instruments in both the north and south is needed. Furthermore, measuring small terrestrial-size exoplanets via RV observations also requires long-term use of a dedicated facility. A prime example of this is highlighted by recent work on CoRot-7b, where a campaign of 26 consecutive nights was needed with HARPS to measure the planet’s mass and remove stellar activity induced signals.
Table 1: A sample of present and future high-precision Doppler velocimeters capable of 1 m/s precisions (Pepe et al. 2014). The UK community currently only has full access to ESO facilities (bold). Additionally, some UK institutions have privileged access to HARPS-N and CARMENES.

Of the facilities listed in Table 1, the UK community only has regular access to the ESO instruments in the south (HARPS and soon ESPRESSO). However, it is vital that the whole UK community has RV access to both hemispheres such that it can play a leading role in the confirmation and subsequent follow-up observations (e.g. atmospheric characterisation with JWST) from the upcoming space-based exoplanet surveys.

3.4 Direct imaging detections

At some point in the future direct imaging using adaptive optics and coronography will become the primary means of studying exoplanets. The technique has already been proven by the discovery of 4 super-Jovian planets around the 10 Myr old star HR 8799, and by confirmation of the long-suspected giant planet that orbits the star β Pictoris.
In addition to being a technique that is useful for exoplanet discovery, direct imaging opens up possibilities for spectroscopy and variability studies, providing insights into planetary atmosphere compositions, temperatures, flow structures and cloud properties. The McCaughrean (2007) report identified direct imaging as an area where the UK lacked expertise and access to the next generation of major facilities (e.g. GPI on Gemini and SPHERE on the VLT). This situation has been remedied to a large extent by a few institutions hiring experts in this area. Furthermore, UK institutions have played leading roles in developing some of the most important instruments for exoplanet imaging and angular resolved spectroscopy: MIRI on JWST (UK ATC), HARMONI and METIS for the E-ELT (Oxford and UK ATC, respectively).

SPHERE and GPI are sensitive to young (1-10 Myr) self-luminous Jovian planets orbiting beyond ~20 AU from their stars in nearby star forming regions. The recent academic appointments mentioned above mean that the UK is well positioned to play a central role in the forthcoming surveys to be carried out by these instruments. The surveys will make new discoveries, and will characterise planets through low-resolution spectroscopy. Estimates for the numbers of discoveries by SPHERE are 30-50, based on extrapolating the population of radial velocity planets.

In the near future, E-ELT instruments will improve ground based imaging. These include HARMONI, a first-light instrument that will obtain R ~ 500-3500 spectra, MICADO, which will image 1 -10 Myr planets at 10-20 AU in nearby star forming regions, and METIS, which will provide imaging in the L and M bands. Further in the future, a possible instrument with significant UK involvement will be PCS/EPICS. Essentially this will be a "SPHERE for the E-ELT", capable of imaging warm super-Earths. The launch of JWST in 2018 will bring NIRCAM + MIRI into operation as imaging instruments capable of detecting and characterising long-period planets, along with NIRISS that will provide spectra of 1-10 Myr old Jupiters.

Of relevance to the longer term aim of directly imaging Earth-like planets, the UK has the only non-US member of the Key Science Team of the NASA-funded LBTI survey HOSTS, which is aiming to characterise the exozodiacal light of the nearby stars that will be targeted in future missions to directly image exo-Earths. Even moderately bright exozodiacal dust would hinder such imaging searches, and their presence can only be determined using nulling mid-IR interferometry.

Looking further to the future (2025/2030) there is strong UK interest in the Planet Formation Imager (PFI) concept. Both the Project Scientist and Project Architect are affiliated to UK institutions. The design specifications for the PFI are to enable the direct imaging of planets forming in protoplanetary discs with resolution on the scale of the Hill sphere for Jovian planets, providing direct information on the planet formation process itself.

### 3.5 Microlensing

Microlensing surveys stare at dense stellar fields, such as towards the galactic center, and detect the gravitational lensing of individual background stars when a foreground star passes directly across the line of sight. If the lens-star hosts an orbiting planet, then light curve anomalies are induced, allowing the properties of the lens-planet system to be deduced. The first exoplanet detection via gravitational microlensing occurred in 2004, and since this time a total of 34 planets in 32 systems have been detected (there being two reported multiple systems). These planets range in mass from around an Earth mass up to objects significantly more massive than Jupiter.

Although the contribution to the total number of known exoplanets has been modest, the microlensing technique is able to detect planets in a unique region of parameter space, namely cold low-mass planets orbiting near the ice-line (as shown in Figure 6). For example, OGLE-2005-BLG-390Lb is a 5.5 Earth mass planet orbiting at ~ 2.6 AU, whose detection had significant U.K. involvement. As such, the technique has the potential to provide important information about the galactic planet population that is not accessible to other techniques.

Internationally, there are two major microlensing surveys: OGLE and MOA, operating from observatories in Chile and New Zealand. Alerts are sent out when high magnification events occur, and intense follow-up observations, necessary for planet detection and characterisation, are undertaken by a number of international consortia: RoboNet-II, MINDSTEp, PLANET, μFUN. Institutions from the U.K. (St. Andrews, Manchester, Keele and IoA Cambridge) are involved through RoboNet-II and MINDSTEp. In particular, St. Andrews participates through membership of the Las Cumbres Observatory Global Telescope (LCOGT) network, having provided funds of £2.8M for three telescopes funded by SUPA.

Achieving a major step-change in the rate of exoplanet detection through microlensing will require a space mission. The 2010 U.S. decadal survey of astronomy & astrophysics ranked WFIRST as the number one priority space-
borne observatory. WFIRST’s primary mission aims will be to study dark energy and detect planets via microlensing. The funding situation and launch date at present are uncertain, although a launch date of 2024 is suggested in the latest NASA review of WFIRST. An opportunity for a U.K.-led space-based microlensing survey (ExELS, co-P.I. Kerins, Manchester) may arise with the launch of ESA’s M2 mission EUCLID in 2020, potentially leading to the discovery of 100’s of cold exoplanets with a broad range of masses.

Figure 6: Mass versus orbital distance diagram showing the unique discovery space of ground- and space-based microlensing surveys.

3.6 Theoretical modelling (including High Performance Computing)

Theoretical modeling has played a central role in exoplanets research since the discovery of the first extrasolar planets in the mid-1990s. The initial focus was on providing formation and evolution scenarios to explain the orbits of the early discovered systems, invoking disc-driven migration to explain the short orbital periods, and planet-planet scattering to account for eccentric orbits. As the diversity and quality of observations has increased, however, theoretical research has sought to address the new challenges to our understanding of exoplanets provided by this data. Key examples include: explaining the temporal variability of thermal emission from exoplanet atmospheres through hydrodynamic modeling; accounting for the atmospheric chemical element and molecular abundances identified through spectroscopy; explaining the (surprising) fact that many hot Jupiters have orbits that are misaligned with respect to their host star spin axes; using multi-planet dynamics to account for the transit timing variations (TTVs) observed in systems of multiple systems by Kepler, and to also explain their orbital architectures through consideration of disc-planet interactions and tidal interactions with the central star. Meanwhile, theoretical modeling of stellar activity and convection is currently being used by UK groups to explore diagnostics that will enable efficient RV follow-up of low-mass planets through filtering of astrophysical noise sources.

The world-wide growth of exoplanets research has been accompanied by an expansion in the number of U.K.-based exoplanet theorists. Thirteen U.K. universities host a total of 23 permanent academic staff that have contributed significantly to research in this area. The research undertaken is diverse, reflecting the evolving and expanding nature of exoplanet science, and combines areas of historical strength with new initiatives, often based around more recent appointments. Areas of strength, where the U.K. has a clear international lead, include: protoplanetary disc modeling (including the effects of self-gravity, non-ideal MHD, radiation/photoevaporation, chemistry); disc-planet interactions and planet migration theory; planet formation theory; debris discs modeling (there being a notable synergy between observations and modeling); planetary interior models, atmosphere dynamics and cloud/haze formation; tidal dissipation theory in stars and planets; long-term planetary dynamics and N-body modeling; quantum mechanical calculations of molecular line lists. Specific examples of U.K.-based agenda-setting research include: step-changes in understanding disc-driven planetary migration; clarification of the role of gravitational instability in forming planetary systems; state-of-the-art planetary interior models and atmospheric dynamics simulations; significant advances in understanding tidal dissipation in stars and planets, with application to hot Jupiters and compact multi-planet systems; studies of planet formation in binary star systems, leading to predictions about the orbital configurations of circumbinary planets that were later confirmed through the discovery of the Kepler-16,-34,-35 and -47 systems; ab initio calculation of molecular line lists for interpreting spectroscopic observations by the ExoMol group. Major advances in our understanding of the formation and early evolution of planetary systems is expected in the coming years from increased synergy between observations and
3.7 Debris discs: theory and observations

There have been significant advances in debris discs research since 2008, driven by Herschel, JCMT, WISE, Spitzer and IR-interferometry. U.K. researchers have been at the forefront of developments through major involvement in the DEBRIS Herschel Key Programme, leadership of the SONS JCMT Legacy survey, and playing major roles in the reanalysis of Spitzer and WISE data. For example, Herschel provided accurate far-IR fluxes, new discs and resolved images in ~ 50% of cases. WISE observations have demonstrated that numerous main-sequence stars have hot dust within 10 AU, coinciding with the expected locations of planetary systems, a result that is supported by IR-interferometry. The arrival of ALMA will allow debris discs to be imaged with high resolution, and opens up a new window of imaging the distribution of optically-thin CO gas around main sequence stars (raising intriguing questions about its origins). UK researchers are PI's on several ALMA programmes, and co-I on many more. These developments have required significant advances in theory, where the UK plays a clear leading role. In particular, advances have been made in understanding how debris populations evolve within planetary systems, with N-body codes becoming increasingly advanced in simulating N-body interactions with collisional evolution.

Future developments in this area will come from JWST, continued support of JCMT, E-ELT, SPICA and possibly WFIRST (discussions about UK and broader European involvement are at an early stage, and as part of these a Sol for UK involvement has been submitted recently to the UKSA). There are also possible synergies with transit missions such as PLATO where the debris disc-planetary system connection can be explored in more depth.

3.8 Post-main sequence planetary system evolution

This area represents a new development not discussed in the McCaughrean (2007) report, and serves to illustrate the rapid and unexpected developments that are occurring in the field of exoplanets. The UK has quickly become the international leader in the study of exoplanetary system formation and post-main sequence evolution via observations of 'polluted' white dwarfs and associated dynamical modeling. There are four institutions with faculty who are actively engaged in this area, including more than a dozen PDRAs and PhD students. Since 2006, UK faculty and their teams have published nearly 40 papers in this area, including the most highly cited paper in the field and two papers for Science. Major grants and fellowships totaling over £2.5M (both STFC and ERC) are held by two UK researchers in support of themselves and PDRAs; together they have been awarded well over 200 hours of time on NASA / ESA space telescopes (e.g. Hubble, Spitzer, Herschel) representing more than a dozen programs related to exoplanetary research.

The debris is seen not only via thermal emission in the infrared, as from conventional debris discs, but also in the otherwise-pristine stellar atmosphere, which it pollutes. The fact that debris reveals its elemental composition via white dwarf atmospheres implies UK astronomers are poised to characterize the bulk composition of planetary building blocks using sensitive UV-blue spectrographs (e.g. E-ELT HIRES, HST) on the ground and in space. Associated theoretical modeling will constrain the architectures of the underlying planetary systems that are destabilized during the post-main sequence evolution, leading to the supply of terrestrial material to the central white
dwarf star through scattering and disruption. An issue of particular importance for the future characterization of the elemental abundances in polluted white dwarf atmospheres is the availability of spectroscopic instruments with wavelength coverage extending down to the UV. In the post-HST era, this capability could be provided by E-ELT HIRES if a decision was to be made that its coverage should extend to the UV cut-off. Such a decision would allow UK researchers to maintain their lead in this rapidly developing area.


Before discussing this further we must first recognize that ability to advance the subject will come from creativity, so our first recommendation is:

*R1 - Support for exoplanet science should be awarded to projects of the highest academic excellence.*

We recognize that when funding is under pressure the apparently riskiest science is first to be dropped. However, we would not be surprised if the next major advance in exoplanet studies came from an unlikely source. Exoplanet science is still in a discovery and early characterisation phase and we would be amazed if there were no more surprises to come. Hence we encourage STFC’s grant panel to support projects of the highest academic excellence over all areas of exoplanet science.

The UK has a long tradition of excellent theoretical research in disks, planet formation, and evolution. In recent years theory has moved into new areas of exoplanet-related research such as interior structures and atmospheres modeling, and is vital to our ability to interpret our data. Fundamental theoretical research will further propel the area forward, opening up new directions as it does so. These activities act as the glue that holds our research together.

*R2 – Provide long-term stable funding of HPC through DiRAC and smaller local facilities, and fund PDRAs through the grants line in support of the highest rated theoretical research. We recommend that support be maintained for both fundamental theory and for modeling aimed at interpreting observations.*

4.1 Funded and likely funded facilities

- **Aim 1: Support of the Transit Roadmap**

With the selection of the ESA M3 PLATO mission, Europe now has an exoplanet roadmap that stretches into the 2030's. The backbone of this is transit detections and their applications (e.g. to atmospheric studies). Throughout this period we see the science moving towards understanding the characteristics and evolution of terrestrial planet systems. PLATO will be the game changer here as it will be able to detect hundreds of Earth-Sun analogs that are bright enough for study with other instruments (e.g. JWST, E-ELT). It is likely that, towards the end of this period, we will be able to start targeted searches for biomarkers in the most massive terrestrial planets.

The facilities that comprise this roadmap are shown graphically in Figure 7 and given that this is fully funded this must also be considered as the highest priority.

The UK is fortunate to be well represented in this timeline with leadership roles in nearly all the photometric experiments (SuperWASP, NGTS, CHEOPS & PLATO). While both SuperWASP and NGTS were built primarily with University funding, their data is made publically available after a short propriety period (which is mostly needed in order to complete planet verification) either via MAST or the ESO archive. Currently, operations funding for SuperWASP-N and the WASP computing infrastructure is provided by Warwick University, while SuperWASP-S is supported by STFC and Keele University. STFC also supports NGTS operations. Both CHEOPS and PLATO are ESA missions to which the UK has community access. This naturally leads the panel to the following recommendation.

*R3 – The funded transit roadmap should be adequately resourced. Finding transiting planets is the bedrock of the UK programme due to existing leadership roles and the selection of PLATO.*

The issues involved here range from small amounts of hardware (e.g. computer equipment for data storage) or staff either for operational functions (e.g. database management) through to exploitation (both observationally and theoretically). To cut this support would limit our ability to exploit the roadmap, enabling our competitors to profit from the planet discoveries the UK community has worked so hard to obtain. While the SuperWASP facilities will become less competitive in their present form with the launch of TESS, NGTS will be capable of following up many of the single transit events found by TESS that are likely to be long period planets.
One of the main tasks for all transiting experiments is the provision of high quality exoplanet targets for atmospheric studies with JWST.

**R4 - Support transit experiments by ensuring adequate Radial Velocity facilities are available to the entire UK community. This is vital to exploit the transiting planet discoveries.**

Current and future transit experiments will give rise to hundreds of high quality transiting planets. Radial velocity observations are vital to confirm candidates and determine their masses (and hence densities). In the near term, SuperWASP and NGTS are well served by UK access to SOPHIE (Opticon) and HARPS (3.6m/ESO) and for super-Earths discovered by NGTS we will have access to ESPRESSO (VLT/ESO). For TESS and PLATO, southern access will be available through ESO but the UK must look for 4m telescope options in the northern hemisphere. OPTICON or private access to HARPS-N will not be sufficient. In addition, the redder stars observed by TESS (and PLATO) would benefit from access to a red sensitive spectrograph. The PLATO follow-up observations will be extensive, but to enable transformative science on terrestrial planets it is important that the UK plays its role in this. The bulk of the terrestrial planet radial velocity work from PLATO will be done with ESPRESSO at the VLT due to its superior accuracy. The 4m+HARPS instruments will be mainly concerned with short-period super-Earths. Possible options are discussed in section 4.2. Running parallel with this, the development of methods for countering the effects of stellar activity on precision RV measurements will enable efficient follow-up of the most highly prized, terrestrial-mass planets.

**Aim 2: Develop a better understanding of Planetary Atmospheres through observations and theoretical research.**

Around the transit and direct imaging roadmap are common user facilities that have spectroscopic instruments capable of detecting planetary atmosphere signatures (sec. 3.2). We note that the UK community is particularly active in this area and that understanding Solar System planets and Brown Dwarf atmospheres may be an important laboratory for understanding those of exoplanets.

In this area our near term recommendations are:

**R5 - The UK should continue to support the exploitation of HST data for the characterisation of planetary atmospheres until JWST becomes available.**

Given the current (HST, Spitzer, VLT), upcoming (JWST, E-ELT) and proposed new facilities to characterize exoplanet atmospheres, support from STFC will be needed to fund the scientific effort and activities, which are essential to model and interpret the observed exoplanet spectra. These will include e.g. radiative transfer models and line-lists, accurate atmospheric and interior models, planet formation and chemical models, data analysis techniques and numerical simulations.

**R6 - Encourage ESO to bring the CRIRES+ instrument online as soon as possible.**

The original CRIRES instrument at the VLT has been remarkably successful. CRIRES+ offers significant enhanced capability through its cross disperser and could extend the original studies to many more objects.

**R7 - The UK should explore the possibilities in the near term of an optimized instrument(s) designed for atmospheric studies. If we are to better understand exoplanet atmospheres we require access to stable, well designed instruments.**

The lessons learnt from Spitzer, Hubble and Kepler suggest that knowledge of the instrument stability and systematics are as critical as the collecting area. Another critical point is stellar activity, which often interferes with the possibility of combining measurements at different wavelengths, if recorded at different times. Simultaneous observations of a broad wavelength range are needed to address this problem. JWST, while superbly equipped for cosmological studies, may not be optimal for exoplanet atmosphere studies and more suitable options may exist (see section 4.2).

**R8 - Support the exploitation of the SPHERE and GPI instruments. Larger orbital radius planets beyond the range of the transiting planet facilities can be studied using imaging and spectroscopic techniques.**

**R9 - Support the development of E-ELT instruments specifically for exoplanet science (e.g. METIS, HIRES, PCS/EPICS etc.)**

In the longer term the E-ELT has exoplanet science as one of its main science drivers and will have instrumentation specifically to exploit this. The UK has been positioning itself to be able to contribute to this effort and we support
the development of these instruments. In this regard we note that the nearest transiting planets from PLATO could be imaged directly by the E-ELT.

**Aim 3: Understanding the structure of disks and the formation and evolution of planetary systems**
Beyond detecting planets and characterizing their physical properties (e.g. bulk compositions, atmospheric dynamics and chemistry), a major science goal is to understand planet formation and planetary system evolution. ALMA is already producing exquisite images showing structures (possibly planet-induced) in protoplanetary discs, and will provide similar capabilities for imaging debris discs. Thus we are about to obtain key data informing us about planet formation processes, and the influence of planetary systems on asteroid/Kuiper belt analogues around main sequence stars. JWST and E-ELT will also provide resolved images of discs, in addition to providing unprecedented sensitivity to circumstellar material. IR-interferometry through VLTI is already being used to characterise warm dust around main-sequence stars. Information about the long-term evolution of planetary systems during post-main sequence phases, and the mineralogy of exo-asteroids, is being provided by studies of metal-polluted white dwarfs using HST, VLT and WHT. We note that future opportunities to maintain international leadership in characterizing the bulk composition of planetary material through polluted white dwarf studies would be greatly enhanced through provision of wavelength coverage down to the UV cut-off in the E-ELT spectrograph HIRES.

**R10 – Support the exploitation of HST, VLT, VLTI, WHT, ALMA, JWST and E-ELT and associated modeling in studies of planetary atmospheres, protoplanetary discs, debris discs and metal-polluted white dwarfs. This includes support for radiative transfer models and line-lists, accurate atmospheric and interior models, planet formation, chemical/cloud/dust models, data analysis, numerical simulations and other relevant fundamental physics.**

**Aim 4: Determine the frequency and mass distribution of orphan and cool planets**
The early demise of Kepler means that our knowledge of the statistical occurrence of terrestrial planets is compromised. For example, our best estimates for eta-earth (the occurrence frequency of habitable-zone planets around solar type stars) vary from 0.1 to >>1. PLATO data will allow this to be determined with some accuracy and for a range of stellar types. However, beyond the habitable zone we have little knowledge of the terrestrial planet occurrence rate. At large distances the only hope for any kind of statistics comes from microlensing surveys. These planets are likely to have escaped significant migration and may be useful probes of planet formation beyond the snow line.
Additionally microlensing surveys have recently shown the purported existence of an enormous population of orphaned planets that cannot be detected through any other means. This population is in dispute, and represents one of the outstanding contentions in exoplanetary science.

While PLATO will well constrain the rate of habitable-zone planets for solar type stars, going beyond the habitable zone requires microlensing surveys. The Euclid survey provides an efficient and cost-effective way to achieve this goal.

Euclid is the ESA M2 mission with a launch date expected around 2020. During the first few years the dark energy core science will dominate its observations, but in the final operational phase 6 months is available for other programmes. It has been proposed that a microlensing survey of the bulge could be implemented in this phase and would be sensitive to hundreds of cool, low mass planets. As this survey is not part of the mission baseline it would need to be adopted when a call is issued for additional science proposals during 2016. This would be a highly cost-effective means of detecting a large number of exoplanets that are not accessible to other techniques, broadening the census of the galactic exoplanet population, and providing important information on the formation of planetary systems. We would expect this programme to need significant ground-based support from existing facilities.

For cool, massive planets astrometry may be the best way to obtain statistics. When combined with radial velocity observations the mass degeneracy inherent in radial velocity observations alone can be broken and true masses derived. The Gaia mission has recently entered its operational phase and during the course of its 5-year baseline expected to determine orbits for many cool gaseous planets.

R12 – Support the exploitation of data from the Gaia mission leading to the characterisation of exoplanets and their orbits.

While these data will be interesting in a statistical sense in their own right, it is likely that planetary masses will only be possible for the brightest stars due to the shortage of radial velocity instruments.

4.2 Currently studied options in the 2015-25 period

As part of our consultation the UK community submitted white papers describing areas of research and planned facilities. We do not expect this to be exhaustive nor do we have sufficient scientific and technical details to assess these concepts, which are at different levels of maturity. However, we would encourage Science Board to investigate these in more detail where they complement the programme outlined in section 4.1, but using the criteria that they must strengthen the entire UK community (otherwise they risk damaging it at this critical period).

Radial Velocity Instruments. As noted in Aim 1 the upcoming space missions and especially PLATO, will produce large numbers of terrestrial planet candidates that will require significant radial velocity support. Observations from ESO will comprise the bulk of this effort with access to maybe 70% of the candidates – utilizing ESPRESSO/VLT for the long period/habitable zone planets. The northern long stare field of PLATO will only be partially observable by ESO instruments and so we need to consider other instruments to get to the remaining targets. Options that we are aware of include:

1) THE@INT. A private consortium is proposing to bring a HARPS clone to the INT for a programme centred on habitable zone planet detection. This programme has a 10-year duration. To be useful to PLATO follow-up, significant time (>75%) would need to be made available to the UK Community and PLATO Consortium. It will be useful for filtering out astrophysical mimics from the PLATO Candidates and for confirming terrestrial planets in short period orbits (similar to Kepler-78) but extremely inefficient and not practical for habitable zone terrestrial planets.

2) HARPS-N/TNG. This instrument has a proven ability and will further improve when its laser comb is deployed. While difficult, its potential was demonstrated in the case of Kepler-78b, which is roughly earth-sized (1.2x Earth’s radius) and 1.7 times more massive. With an orbital period of just 8 hours, the amplitude of the reflex motion is just large enough to be detected with this facility. In the case of PLATO, the situation will be vastly improved as the hosts could be 100x brighter. During the instrument construction a small number of UK institutions were able to buy into the HARPS-N project and have joined in the exploitation of Kepler planets with that instrument. More general UK-wide access would be valuable in preparing the community for the opportunities that are coming.
3) As the mass determination of habitable zone/long period terrestrial planets will need the capabilities and light gathering power of ESPRESSO/VLT, members of the PLATO Consortium have started enquiries regarding the possibility of a similar instrument in the Northern Hemisphere. While at an early stage discussions are now underway about an ESPRESSO clone for the GTC. It is important the UK is part of this discussion. We would encourage Science Board to be proactive in preparation for the science bonanza that is coming.

4) CARMENES. This is a stabilized IR+optical spectrograph that will soon be deployed at the 3.6m at Calar Alto. It is designed for terrestrial planet searches around M dwarfs (this area was highlighted in successive UK Exoplanet Reports and was close to realization on several occasions, finally falling foul of the UK IRT withdrawal). While CARMENES is already a funded project, opportunities may arise for further community involvement and exploitation. Note that PLATO and TESS have M dwarf transiting habitable zone terrestrial planets as their science drivers and there is a clear shortage of radial velocity facilities sensitive to these stars as the bulk of usable spectrographs work at optical wavelengths where these stars are faint.

5) The proposal for a Photonic Spectrograph for the ESO-NTT (PSTT) has been shortlisted as part of the recent call for instrumentation. It is a novel instrument employing, for example, waveguides— and hence provides an excellent opportunity for technology development that could also be deployed on a large telescope at some future time. Similar to CARMENES in its aims, this spectrograph operates in the IR and will enable efficient planet detection around late-type M-dwarfs (0.07 – 0.4 Solar masses). Current predictions suggest that eta-earth may peak at these spectral types.

**Instruments purposed for atmospheric work (Aim 2).** The review received details of two instruments optimized for this science. These concepts are:

1) **Twinkle:** this is a dedicated UK space mission for combined-light VIS-IR spectroscopy (with a wavelength coverage from 0.5-5 µm, and a resolving power ~ 300). It consists of a 50 cm telescope in a Sun-synchronous orbit. The mission is based on a Surrey Satellite Technology platform, and has a proposed lifetime of 5-7 years with Phase-A/B1 ending in December 2015, and a planned launch towards the end of 2018. The Twinkle consortium includes twenty UK universities/industrial partners. Twinkle will spectroscopically observe over one hundred hot- and warm- Jupiters, Neptunes, and super-Earths – searching for molecules and weather patterns. No request for financial support to build and launch the satellite will be sent to STFC, but STFC will be asked to support the post-launch related scientific activities through the standard peer-review process.

2) **Exoplanet Multi-Object Spectrograph** (ExoMOS): the ExoMOS instrument is a purpose-built UK-led international effort, designed specifically to perform high precision transit spectrophotometry of exoplanets in the optical and near infrared. The concept was proposed as part of the recent call for new instruments at the NTT (but could also be located elsewhere) and has been shortlisted for further study. First light could be achieved in 2019. It has two primary science goals: a statistical survey of hot Jupiter atmospheres and reconnaissance spectroscopy of newly discovered super-Earths and hot Neptunes around the bright targets discovered by NGTS, TESS and PLATO. ExoMOS will need STFC financial support for construction.

Smaller scale projects contributing to this area and submitted to the attention of the panel include balloon experiments and an optical multiband 1-m class telescope (Rayleigh Atmosphere Machine (RAM) concept).

**Direct Imaging.** Direct imaging of exoplanets remains one of the most challenging areas of technology development and is driving many of the E-ELT science cases. We understand that there is UK involvement in the instruments HARMONI, MICADO, METIS, and PCS-EPICS, and possible interest in becoming involved with HIRES, all of which have applications in exoplanet detection and characterisation.

**Instruments proposed for ground based microlensing surveys (Aim 4).** GravityCAM has been proposed as a way of realizing some of the aims of microlensing from the ground. Composed of 100 EMCCD’s it will allow “lucky imaging” (high resolution imaging) over an extended field allowing the identification of lower amplitude lens events. This was originally submitted to the ESO NTT instrument competition, but was not selected as its concept was not sufficiently advanced at that time.
5. Medium to long-term strategic goals and developments

5.1 Medium term (2025-2035)

Unsurprisingly, facilities for this period are still under investigation but it is important that Science Board is aware of these as (in some cases) decisions will need to be made in the next few years (e.g. ESA M4). While these facilities are often international in nature, Science Board should be aware of how they fit into the (current) UK community and while a review should be conducted prior to a decision point, their strategic importance to our community reassessed.

It is also worth summarizing where we expect to be at this time: the transit roadmap will be reaching a climax with the first candidates coming from PLATO. Scientifically we will have a much better idea of the diversity of small planets as well as a much better understanding of the processes of planet formation and evolution. The era of comparative planetology will be in full swing. Atmospheric work would have advanced due to the availability of bright candidates from ground-based photometric surveys and TESS (as well as PLATO). JWST observations will have become available on the most interesting of planets.

Given the timescales of this roadmap both Aims 1 and 2 will be on-going during this period. PLATO was approved by the ESA SPC as the “ultimate” transit survey and, while we do not envisage further new developments in this area, consolidation and exploitation of the transit roadmap until the end of the PLATO mission will be vital. The baseline mission for PLATO is of 6.5 years duration with a further 3 years identified to complete the follow-up observations.

R13 – Continued support for PLATO during its full operational phase (2024-2030) including the 3-year wind-down period (2030-2033). This includes theoretical support for interpreting the main results from PLATO.

However, during this period we also expect increasing support in atmosphere characterisation (Aim 2), primarily through new facilities.

R14 – Increase support for Atmospheric Facilities in the post 2025 era. This includes support for any future ESA missions.

A few tens of planets will be observed with E-ELT (METIS, HIRES, HARMONI) in great detail, both through combined-light (especially high-dispersion spectroscopy) and direct imaging instruments. With a ~30m telescope extremely high spectral resolution over a narrow spectral range will be obtainable from the ground, with a signal-to-noise ratio increase of up to an order of magnitude compared with the VLT. Terrestrial planets in the habitable zone of M-dwarfs might be observable, but Earth-twins are expected to be too challenging (Snellen et al., 2014).

Efforts to characterise the atmospheres of exoplanets should span the entire parameter space, from giants to rocky planets, from hot, close in planets, to the cooler ones at large distances that are analogous to what is found in our solar system. Most importantly, to address the questions of formation and evolution of exoplanets we need to be able to observe a sample that is at least an order of magnitude larger than what can be obtained with the JWST and the E-ELT, and therefore a dedicated telescope from space is needed.

It is difficult for us to influence the ESA selection process. However, for the ESA M4 competition the UK leads the ARIEL concept. This instrument is a development from EChO (M3 candidate) and will perform visible and IR combined-light spectroscopy of a large sample (500-1,000) of warm and hot planets (from giants to super-Earths). Such a mission would trade lower spectral resolution (~ 100-300) in order to obtain broad, simultaneous wavelength coverage (~ 0.5-8 µm), with extremely high spectral resolution over a narrow spectral range obtainable with the E-ELT from the ground. The two configurations are highly complementary.

The increased budget of an L-class mission would enable wavelength coverage to mid-IR favouring the inclusion of temperate planets in the sample, including the most favourable super-Earths around M-dwarfs (e.g. a dedicated instrument for exoplanet spectroscopy on-board SPICA).

Various imaging concepts are also being discussed within the European community but have yet to solidify into a technically feasible concept. With this in mind it is worth noting that WFIRST (NASA) to be launched around 2025 is considering a coronagraphic facility and opportunities may exist to join that mission.

R15 – Support technology development for future space projects. These could include wave front control systems, achromatic coronagraphs and IR detectors.
To support the medium-term goals, research and development studies are required into angularly resolved spectroscopy technologies, IR detectors, and coolers:

- For direct imaging, several technological concepts have to be developed to reach higher TRLs. Specifically, wave front control in space is crucial for achieving very high contrast close to $10^9 - 10^{10}$. The next step is the achievement of simple solutions for achromatic coronagraphs. Several prototypes are undergoing development in Europe and have to be further developed.

- Current IR detector technology for astrophysical missions is mostly imported from the US. Investment in IR detectors would allow the UK to produce such technology in-house, rather than having to import it.

By 2030 we will have a number of transiting Earth-like planets discovered by PLATO. Except for the very closest of these it is unlikely that we will have the technology to image these objects directly without a significant advance in engineering. Most of the proposed options are technologically exceptionally challenging and will have to be carried out as part of an international collaboration. Research and development is needed to understand the best approach and how to reach the required technology level. Options include:

- Very large space telescope using combined light (~ 10 m): While challenging and costly, this would have uses in several areas of astrophysics and lead to the detection of terrestrial planets in the habitable-zones of late-type stars.

- Coronographs or occulters + very large telescopes from space (~ 10 m): very challenging and extremely expensive. NASA is also studying this route.

- Interferometry from space: extremely challenging and expensive, there is currently no plan or study being carried on by NASA and ESA.

**Direct imaging:** The E-ELT instrument PCS/EPICS will provide the capability of imaging warm super-Earths on a 15-20 year time scale, representing a major leap forward in exoplanet science. We understand that there is likely to be an opportunity for significant UK involvement in the development of this instrument following on from the UK’s lead role in the development of the E-ELT first-light instrument HARMONI, paving the way for potential UK leadership roles in the science exploitation of PCS/EPICS.

The Planet Formation Imager (PFI) is a concept being developed to allow direct imaging of planets embedded in protoplanetary discs, with a resolution at the level of the planet Hill sphere. The possibility of being able to image planets in the process of forming represents something of a holy-grail for planet formation studies. Both the Project Scientist and Project Architect of PFI are UK-based, providing opportunities for UK leadership in all stages of this project.

**R16 – Examine the options for funding the development of E-ELT (PCS/EPICS) and PFI as a means of securing future UK leadership in the exploitation of these next-generation direct imaging facilities.**

**Future space missions:** We are aware of two mission concepts, driven strongly by exoplanet science goals that were submitted to the ESA M4 call for proposals: Arago and Theia. Both proposals were not selected for further study at this stage, but are likely to be submitted to the forthcoming M5 mission call. Also, the SPICA mission concept is likely to be submitted to the M5 call, and a dedicated instrument for exoplanet atmospheric characterization onboard SPICA is currently under discussion.

Arago consists of a 1.3 m Cassegrain telescope with a UV spectrometer, and is designed to study the interaction of planets with their host stars, with an emphasis on close orbiting systems. With the forthcoming decommissioning of HST, this would provide a valuable and unique spectral capability in the UV.

Theia is an ultra-high precision astrometry mission (astrometric precision of 0.3μas), whose primary exoplanet science aim would be to measure the 3D orbits and true masses of terrestrial and super-Earth planets around the nearest 50 planet-bearing stars to the Sun.

SPICA is a European-Japanese mission concept, multipurpose IR spectroscopic observatory, featuring a 2-3 m telescope in L2 actively cooled to allow spectroscopic observations from mid- to far-infrared.
R17 – Support future ESA missions that have a significant exoplanet science component and UK participation at an early stage sufficient to establish UK leadership.

5.2 Long term (2035-2045)
The long-term development of this young subject is extremely difficult to predict. In the last decade under-appreciation of instrumental effects plagued the development of both the atmosphere and internal characterisation fields. It is likely that as we push to the limits in other areas we will meet additional problems. However, there are aspects that seem reasonably clear cut, for example, post 2035 extensive biomarkers surveys of terrestrial will begin in earnest. Prior to that we are likely to be surveying the “best cases” only. The technological developments needed for this compose part of R15 (section 5.1). Leading up to this, understanding what “habitability” really means and what factors influence it will become increasingly important.

In the last decade we were hopelessly optimistic in our “Roadmap to Darwin” as many of the technologies for an interferometric imager and spectrograph mission were just too immature, post 2035 this will no longer be the case.

6. Summary and conclusions
The study of exoplanets – planets orbiting stars other than the Sun – has been transformed over the last twenty years from an esoteric field with few observational constraints into one of the most demanding and exciting fields of modern-day astronomy. The relationships between planet formation, growth and evolution established to occur in exoplanetary systems has had a dynamic effect on studies of our own Solar System and on the formation processes which govern stars. Just under a decade ago, the STFC McCaughrean (2007) report made a set of recommendations to strengthen the UK exoplanet community which was lacking “coherent ambition, strategy, planning and funding”. In this report we shown how the situation today is much improved, with the UK hosting one of the strongest, most successful and ambitious exoplanet communities in the world. Evidence to support these claims comes from publication (and citation) metrics, the numerous academic appointments at many UK universities, UK agency (Appendix B) and non-UK agency funding, mostly notably through ERC awards, and by the success of the UK community in getting access both to key observational and theoretical facilities (Figure 1).

In consultation with the UK exoplanet community (see Appendix C), we have identified several areas for future development, discussed below, primarily aimed at solving the perceived lack of community access to specific and specialised facilities. It is a fact that Universities have often filled the funding gap (often in collaboration with STFC) and supported new groups. In the future this will become more difficult as the instrumentation will become more specialised (and expensive). Nonetheless, over the next 10 year period we will see a number of relatively small projects, which are attracting private funding, come into existence and some larger ones funded by European or international consortia. Not all of these facilities are funded fully as yet. Figure 8 attempts to show the strands of our current and projected programme and the interconnections within and between them. Central to this programme is the European Transit roadmap (ground and space based) in which, thanks to previous successes, the UK is driving the agenda and in which the facilities are mostly funded.

To support the breadth of exoplanet research activities in the UK, the community make use of a wide-ranging, self-supporting set of facilities each of which plays a key role in the acquisition of observational data. The UK world-class theoretical work is supported mainly through access to powerful High Performance Computing facilities, notably DiRAC. These facilities support world-leading research on the determination of radial velocities, the discovery of transiting planets (supported by those found through direct imaging and microlensing), the characterisation of planetary atmospheres and studies of the formation and evolution of planetary systems. These research themes will continue to be enhanced as new facilities come on line, and in particular the UK is well placed, funding permitting, to exploit the availability of higher capability transit finding capability coupled with spectroscopic capability to exploit those exoplanets to characterise atmospheric properties.

As exoplanet research moves towards the detection of an Earth-like exoplanet, building on the past success of the UK exoplanet community will require some difficult decisions both for the community and the funding agencies. Some facilities are expensive to build and operate, some have restrictions on data rights, data archives and community involvement in target selection while others require long-term technology development. The UK astronomy community has access to fewer observational facilities by right, particularly on the ground than it did when the McCaughrean (2007) report was written. If the community is to thrive and grow, it is vital that the community
have access to common-user observational and HPC facilities alongside those which may be developed by and funded by consortia and that this be a factor when considering what facilities to support.

In this report we have identified four main aims for the UK exoplanet community:

Aim 1: Support of the Transit Roadmap. With the selection of the ESA M3 PLATO mission, Europe now has an exoplanet roadmap that stretches into the 2030’s. The backbone of this is transit detections and their applications (e.g. atmospheric studies). Throughout this period we see the science moving towards understanding the characteristics and evolution of terrestrial planet systems.

Aim 2: Develop a better understanding of Planetary Atmospheres through observations and theoretical research. Around the transit roadmap are common user facilities that have spectroscopic instruments capable of detecting planetary atmosphere signatures.

Aim 3: Understanding the structure of disks and the formation and evolution of planetary systems. Beyond detecting planets and understanding their physical properties (e.g. bulk compositions, atmospheric dynamics and chemistry), a major science goal is to understand planet formation and planetary system evolution.

Aim 4: Determine the frequency, mass distribution and origins of orphan and cool planets

To support these four aims we have made seventeen specific recommendations in the report (sections 4 and 5).

R1 - Support for exoplanet science should be awarded to projects of the highest academic excellence. This should occur over the entire breadth of the research area.

R2 – Provide long-term stable funding of HPC through DiRAC and smaller local facilities, and fund PDRAs through the grants line in support of the highest rated theoretical research. We recommend that support be maintained for both fundamental theory and for modeling aimed at interpreting observations.

R3 – The funded transit roadmap should be adequately resourced. Finding transiting planets is the bedrock of the UK programme due to existing leadership roles and the selection of PLATO.

R4 – Support transit experiments by ensuring adequate Radial Velocity facilities are available to the entire UK community. This is vital to exploit the transiting planet discoveries.

R5 - The UK should continue to support the exploitation of Hubble Space Telescope data for the characterisation of planetary atmospheres until the James Webb Space Telescope becomes available.

R6 - Encourage ESO to bring the CRIRES+ instrument online as soon as possible.

R7 - The UK should explore the possibilities in the near term of an optimised instrument(s) designed for atmospheric studies. If we are to better understand exoplanet atmospheres we require access to stable, well designed instruments.

R8 - Support the exploitation of the SPHERE and GPI instruments. Larger orbital radius planets beyond the range of the transiting planet facilities can be studied using imaging and spectroscopic techniques.

R9 - Support the development of European Extremely Large Telescope (E-ELT) instruments specifically for exoplanet science (e.g. METIS, HIRES, PCS/EPICS etc.).

R10 – Support the exploitation of Hubble Space Telescope, Very Large Telescope, Very Large Telescope Interferometer, William Herschel Telescope, Atacama Large Millimetre/sub-millimetre Array, James Webb Space Telescope and European Extremely Large Telescope and associated modelling in studies of planetary atmospheres, protoplanetary discs, debris discs and metal-polluted white dwarfs. This includes support for radiative transfer models and line-lists, accurate atmospheric and interior models, planet formation, chemical/cloud/dust models, data analysis, numerical simulations and other relevant fundamental physics.

R11 - Support the proposed Euclid microlensing survey to produce statistics on low mass planets at mostly long periods. While PLATO will well constrain the rate of habitable-zone planets for solar type stars, going beyond the habitable zone requires microlensing surveys. The Euclid survey provides an efficient way to achieve this goal.
R12 – Support the exploitation of data from the Gaia mission leading to the characterisation of exoplanets and their orbits, and to an improved understanding of the physics of planet host stars.

R13 – Continue support for PLATO during its full operational phase (2024-2030) including the 3-year wind-down period (2030-2033). This includes theoretical support for interpreting the main results from PLATO.

R14 – Increase support for Atmospheric Facilities in the post 2025 era. This includes support for any future ESA missions.

R15 – Support technology development for future space projects. These could include wave front control systems, achromatic coronagraphs and IR detectors.

R16 – Examine the options for funding the development of the European Extremely Large Telescope (PCS/EPICS) and Planet Formation Imager as a means of securing future UK leadership in the exploitation of these next-generation direct imaging facilities.

R17 – Support future ESA missions that have a significant exoplanet science component and UK participation at an early stage sufficient to establish UK leadership.

These recommendations are grouped into support for the four aims above. Recommendations 1-4 and 13 support aim 1 by providing long-term support for the transit roadmap. Recommendations 5-9 and 14 support our desire to see strong support for atmospheric characterisation. Recommendation 10 is to support aim 3, recommendations 11 and 12 support aim 4. Recommendations 15-17 are to support long-term technology and mission development. Most of the recommendations are targeted at the period 2015-25, to maintain research momentum, but we also wish to extend capability and growth into subsequent decades out to the 2040s.

Figure 8: Summary of current and future facility opportunities for exoplanet research and the interconnections between them. See below for details of the symbols used.
Appendix A  References

Bailey, J., 2014, PASA, 31, 43
Harrington, J. et al., 2006, Science, 314, 623
Lovelock, J., 1979, `GAIA, a new look at life on earth', Oxford University Press

Appendix B  STFC support for the UK exoplanet community

STFC support in the form of studentships, fellowships and PDRAs over the period 2011-2014 is shown in Figures B1 and B2. During this period STFC has supported ~75 people.
Appendix C  Review panel procedures

The Exoplanet Review Panel (EPRP) was convened in August/September of 2014 and had an initial meeting on 7 October 2014 during which the terms of reference for the review were confirmed.

EPRP solicited community input via several mechanisms:

- A community questionnaire survey, which closed on 10th November 2014 with 71 respondents.
- A community town hall meeting on 11th December 2014, during which provision was made for members of the community to give short 1-2 slide presentations.

Figure B1 Data derived from funded Astronomy Research Grants, Studentships and Ernest Rutherford Fellowships in the years 2011, 2012, 2013 & 2014 using a search for keywords taken from this report. (n.b. these data may include PDRA renewals)

Figure B2 Percentage of people supported on Exoplanet projects against the overall average number of PDRAs awarded in each annual Astronomy Grant Round; the overall allocation of studentships for each year and the overall allocation of Ernest Rutherford Fellowships for each year. NB, Ernest Rutherford Fellowships for 2014 are as yet un-announced and therefore do not feature in this data
• An open call for community whitepapers to which 23 submissions were made to the 16 January 2015 deadline (plus a few late submissions).
• A presentation of the draft report at the UK Community Exoplanet Conference: 30 March 01 April 2015 combined with an on-line comment form.

Community questionnaire
The community questionnaire consisted of the following items:
1. What is your primary research area?
2a. What do you believe are the top 5 goals in the exoplanets research field in an international context in the next 5, 10 & 20 years?
2b. What do you believe are the top 3 goals in the exoplanets research field in a UK context?
3a. What are the perceived current strengths of UK research in this field, in terms of the following areas? (On a scale of 1 - 10, with 10 the highest)
   • Atmospheric characterisation
   • Theoretical research particularly HPC modelling
   • Modelling and filtering of stellar activity
   • Bulk characterisation
   • Planetary magnetospheres
   • Planet formation
   • Transits
   • Direct imaging
   • Microlensing
   • Asteroseismology of sun-like stars
3b. How important are these strengths for the UK now and in the future? (On a scale of 1 - 10, with 10 the highest)
   • Atmospheric characterisation
   • Theoretical research particularly HPC modelling
   • Modelling and filtering of stellar activity
   • Bulk characterisation
   • Planetary magnetospheres
   • Planet formation
   • Transits
   • Direct imaging
   • Microlensing
   • Asteroseismology of sun-like stars
3c. Are there any areas in the UK exoplanets research field missing from this list?
4. Which UK-funded observational or computing facilities are the most important to you for exoplanet research (please indicate the specific instrument and telescope for a multi-instrument telescope)?
5. Which other (international) facilities are the most important to you for exoplanet research?
6. What facilities, technologies or capabilities should be provided in this field in the next 5, 10 & 20 years?
7. Where does your work fit into the current STFC Science roadmap?
8. Do you have any other comments concerning exoplanet research in the UK to feed into this review?

The questionnaire responses were collected by a third party company (SurveyMonkey) and responses were anonymised to the panel but included metadata such as academic status and institution.

Figure C1 shows the distribution of academic status and research areas of the respondents and shows approximately equal representation across the main levels of academic seniority. In terms of research area the respondents represented a broad range of areas of scientific and technical interest. The other category includes topics such as aurorae, microlensing, protoplanetary discs, white dwarfs, and time-domain astrophysics.
Figure C1: Distribution of academic status and research areas

Table C1 below shows the distribution of respondents amongst various institutions and demonstrates a roughly even split between submissions from institutions in London and the South East (33) and those outside (36), including 1 in Eastern England, 18 in Northern England, 6 in the South West, 5 in Northern Ireland, 1 in Wales, and 5 in Scotland. Most submissions came from UCL and Cambridge, with a roughly even distribution across other institutions.

<table>
<thead>
<tr>
<th>Institution</th>
<th>Respondents</th>
</tr>
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<tbody>
<tr>
<td>Birkbeck</td>
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<td>Cardiff University</td>
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<td>Durham</td>
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<td>IAP</td>
<td>1</td>
</tr>
<tr>
<td>Imperial College London</td>
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<td>JBCA, University of Manchester</td>
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<tr>
<td>Keele University</td>
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<tr>
<td>Queen Mary, University of London</td>
<td>2</td>
</tr>
<tr>
<td>Queen’s University Belfast</td>
<td>5</td>
</tr>
<tr>
<td>The Open University</td>
<td>2</td>
</tr>
<tr>
<td>UCL</td>
<td>13</td>
</tr>
<tr>
<td>University of Cambridge</td>
<td>9</td>
</tr>
<tr>
<td>University of East Anglia</td>
<td>1</td>
</tr>
<tr>
<td>University of Edinburgh</td>
<td>2</td>
</tr>
<tr>
<td>University of Exeter</td>
<td>6</td>
</tr>
<tr>
<td>University of Leicester</td>
<td>5</td>
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<tr>
<td>University of Manchester</td>
<td>1</td>
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<tr>
<td>University of Oxford</td>
<td>4</td>
</tr>
<tr>
<td>University of St Andrews</td>
<td>3</td>
</tr>
<tr>
<td>University of Warwick</td>
<td>5</td>
</tr>
<tr>
<td>Unknown</td>
<td>1</td>
</tr>
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</table>

Table C1: Responses by institution

Figure C2 shows the responses to questions 3a and 3b which show the communities’ estimate of the current strengths and future importance in various areas of exoplanet science. These were broadly in-line with expectations of the panel and generally show that UK strengths match future requirements, except in areas of atmospheric characterisation, theoretical work and HPC, and planet formation.
White paper submissions

White paper submissions were also requested and supplied by the community. Table C2 list the whitepapers received by the panel.

<table>
<thead>
<tr>
<th>Author</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Cameron</td>
<td>HARPS-North and modeling of astrophysical noise – A short paper for the STFC ESP Review</td>
</tr>
<tr>
<td>O. Panić</td>
<td>Importance of CO snowline studies with ALMA</td>
</tr>
<tr>
<td>C. Haswell</td>
<td>Arago: White paper for STFC’s UK Exoplanets Review</td>
</tr>
<tr>
<td>E. Pascale</td>
<td>ARIEL - Atmospheric Remote-sensing Infrared Exoplanet Large-survey</td>
</tr>
<tr>
<td>E. Pascale</td>
<td>Exoplanet studies from stratospheric platforms</td>
</tr>
<tr>
<td>B. Biller</td>
<td>Probing Exoplanet Cloud Properties through Variability Monitoring</td>
</tr>
<tr>
<td>D. Pollacco</td>
<td>CHEOPS – A short paper for the STFC ESP Review</td>
</tr>
<tr>
<td>C.A. Haswell</td>
<td>Disintegrating Exoplanets: White paper for STFC’s UK Exoplanets Review</td>
</tr>
</tbody>
</table>
Appendix D  Review panel membership and vested interests

The panel comprised representatives from STFC's Astronomy Advisory Panel (AAP) (O'Brien and Pollacco) and Solar System Advisory Panel (SSAP) (Arridge and Lowry) as well as additional exoplanet science experts.

Prof Paul O'Brien (Chair) (Leicester): institutional membership of WASP, NGTS, PLATO and JWST.
Dr Chris Arridge (Lancaster): Chair of SSAP, co-I on magnetometer team for Jupiter Icy Moon Explorer ESA L1 mission, PI of M3 and M4 Uranus Pathfinder proposals.
Dr Stephen Lowry (Kent): Member of SSAP.
Prof Richard Nelson (QMUL): PI on DiRAC project dp035, coordinator of PLATO work package WP 116 300, likely member of CARMENES consortium (negotiations on-going).
Prof Don Pollacco (Warwick): Member of AAP, Co-PI of WASP, NGTS, Official Collaborator for HARPS-N, Science Coordinator and Board Member for PLATO, and Board Member for CHEOPS.
Dr David Sing (Exeter): PI of ExoMOS and co-I of THE HARPS III.
Prof Giovanna Tinetti (UCL): PI of ARIEL M4 proposal and science lead Twinkle.
Dr Chris Watson (QUB): co-PI of NGTS, co-PI of HARPS-N, member of the Ultracam consortium, member of the ExoMOS team.

The panel was supported by Sharon Bonfield and Michelle Cooper from STFC.

Appendix E  Review Panel Terms of Reference

Introduction

The UK has a strong and sizable community interested in extra-solar planets which has significantly grown in recent years. We are involved in a number of ground and space based projects, including modelling, simulations and data analysis challenges. Some of the currently planned projects related to exoplanet research with UK involvement are: E-ELT, NGTS, Gaia, JWST/MIRI, SPICA, CHEOPS, ESPRESSO, PLATO and other planned space missions.

Up to now, exoplanet research has been dominated by the detection methods, but the characterisation of exoplanets is becoming increasingly important. The technology required to advance the field is challenging and will involve both new space missions and ground-based instruments over the next 20-30 years. A key long-term goal is
to detect and characterise Earth-like planets in the habitable zones of solar type stars. UK involvement in the development and exploitation of such future missions and instruments and associated theory and modelling is dependent on an overall financial settlement for STFC and UKSA that will allow involvement in the booming field of exoplanet research, and on satisfactory peer review. A Review Panel has been convened in order to prepare and provide advice to STFC’s Science Board on a strategy for STFC supported exoplanet research.

Terms of Reference
The remit of the Review Panel is to develop a coordinated strategy for UK involvement in exoplanet research that could enhance UK leadership in this area, taking into account the outcomes from previous reviews. The Review Panel will work with all elements of the UK exoplanet community to develop the strategy. The Review Panel is responsible for drafting the strategy; the Review Panel will meet in person or via teleconference as appropriate to develop the strategy. Support for meeting arrangements will be provided by the STFC’s Astronomy Group.

The Chair of the Review Panel will present the Review Panel recommended strategy to Science Board.

Appendix F  List of acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAO</td>
<td>Anglo Australian Observatory</td>
</tr>
<tr>
<td>AAO-PS</td>
<td>Anglo Australian Observatory Planet Search</td>
</tr>
<tr>
<td>AAT</td>
<td>Anglo Australian Telescope</td>
</tr>
<tr>
<td>ALMA</td>
<td>Atacama Large Millimeter/submillimeter Array</td>
</tr>
<tr>
<td>ARIEL</td>
<td>Atmospheric Remote–sensing Infrared Exoplanet Large-survey</td>
</tr>
<tr>
<td>CARMENES</td>
<td>Calar Alto high-Resolution search for M dwarfs with Exo-earths with Near-infrared and optical Echelle Spectrographs</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>CHEOPS</td>
<td>CHaracterising ExOPlanet Satellite ESA S Mission</td>
</tr>
<tr>
<td>CHIRON</td>
<td>Cross-dispersed echelle spectrometer for the SMARTS 1.5m Telescope.</td>
</tr>
<tr>
<td>CIF</td>
<td>Capital Investment Framework</td>
</tr>
<tr>
<td>CoRoT</td>
<td>Convection, Rotations and planetary Transits</td>
</tr>
<tr>
<td>CRIRES</td>
<td>Cryogenic InfraRed Echelle Spectrograph</td>
</tr>
<tr>
<td>CRIRES+</td>
<td>Cryogenic InfraRed Echelle Spectrograph +</td>
</tr>
<tr>
<td>DEBRIS</td>
<td>Disc Emission via a Bias-free Reconnaissance in the Infrared/Submillimetre</td>
</tr>
<tr>
<td>DIRAC</td>
<td>Distributed Research utilizing Advanced Computing</td>
</tr>
<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Centre)</td>
</tr>
<tr>
<td>E-ELT</td>
<td>European Extremely Large Telescope</td>
</tr>
<tr>
<td>ECHO</td>
<td>Exoplanet Characterisation Observatory</td>
</tr>
<tr>
<td>EMCCD</td>
<td>Electron Multiplied CCD</td>
</tr>
<tr>
<td>EPICS</td>
<td>ELT Planetary Camera and Spectrograph</td>
</tr>
<tr>
<td>EPRP</td>
<td>Exoplanets Review Panel</td>
</tr>
<tr>
<td>ERC</td>
<td>European Research Council</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ESA SPC</td>
<td>European Space Agency Space Programme Committee</td>
</tr>
<tr>
<td>ESPRESSO</td>
<td>Echelle Spectrograph for Rocky Exoplanet and Stable Spectroscopic Observations</td>
</tr>
<tr>
<td>ESO</td>
<td>European Southern Observatory</td>
</tr>
<tr>
<td>ESO-NTT</td>
<td>Photonic Spectrograph for the ESO-NTT</td>
</tr>
<tr>
<td>ExoMOS</td>
<td>Exoplanet Multi-Object Spectrograph</td>
</tr>
<tr>
<td>FIES</td>
<td>Fibre-fed Echelle Spectrograph (Nordic Optical Telescope)</td>
</tr>
<tr>
<td>G-CLEF</td>
<td>A General Purpose Optical Echelle Spectrograph for the GMT with Precision Radial Velocity Capability</td>
</tr>
<tr>
<td>GPI</td>
<td>Gemini Planet Imager</td>
</tr>
<tr>
<td>GTC</td>
<td>Gran Telescope Canarias</td>
</tr>
<tr>
<td>HARMONI</td>
<td>The first light integral field spectrograph for the E-ELT</td>
</tr>
<tr>
<td>HARPS</td>
<td>High Accuracy Radial velocity Planet Searcher (ESO 3.6m Telescope)</td>
</tr>
<tr>
<td>HARPS-N</td>
<td>High Accuracy Radial velocity Planet Searcher – North (TNG 3.6m Telescope, La Palma)</td>
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<td>HAT-NET</td>
<td>The Hungarian Automatic Telescope Network</td>
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<td>HIRES</td>
<td>High RESolution Spectrograph for the E-ELT</td>
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<td>HPC</td>
<td>High Performance Computing</td>
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<td>Acronym</td>
<td>Description</td>
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<tr>
<td>HST</td>
<td>Hubble Space Telescope</td>
</tr>
<tr>
<td>HST STIS-COS</td>
<td>Hubble Space Telescope Space Telescope Imaging Spectrograph-Cosmic Origins Spectrograph</td>
</tr>
<tr>
<td>IR</td>
<td>Infra-Red</td>
</tr>
<tr>
<td>IRD</td>
<td>Infrared Doppler instrument for the Subaru Telescope</td>
</tr>
<tr>
<td>JCMT</td>
<td>James Clark Maxwell Telescope</td>
</tr>
<tr>
<td>JWST</td>
<td>James Webb Space Telescope</td>
</tr>
<tr>
<td>LBTI survey HOSTS</td>
<td>Large Binocular Telescope Interferometer Hunt for Observable Signatures of Terrestrial Systems</td>
</tr>
<tr>
<td>LCOGT</td>
<td>Las Cumbres Observatory Global Telescope network</td>
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<tr>
<td>LEVY</td>
<td>Ken and Gloria Levy Spectrometer at the Automatic Planet Finder Telescope (Lick)</td>
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<tr>
<td>MAST</td>
<td>Barbara A. Mikulski Archive for Space Telescope</td>
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<td>METIS</td>
<td>The Mid-infrared E-ELT Imager and Spectrograph</td>
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<tr>
<td>MICADO</td>
<td>Multi-AO Imaging Camera for Deep Observations for E-ELT</td>
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<td>μFUN</td>
<td>Microlens Follow Up Network</td>
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<tr>
<td>MiNDSTEp</td>
<td>Microlensing Network for the Detection of Small Terrestrial ExoPlanets</td>
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<tr>
<td>MINERVA</td>
<td>An array of small-aperture robotic telescopes outfitted for both photometry and high-resolution spectroscopy (Caltech)</td>
</tr>
<tr>
<td>MIRI</td>
<td>Mid-IR Instrument for JWST</td>
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<td>NGTS</td>
<td>Next Generation Transit Survey</td>
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<td>NIR</td>
<td>Near Infra-Red</td>
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<td>Near InfraRed CAMera for JWST</td>
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<td>NOT</td>
<td>Nordic Optical Telescope</td>
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<td>OGLE</td>
<td>Optical Gravitational Lensing Experiment</td>
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<td>OHP</td>
<td>Observatoire Haute Provence</td>
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<td>OPTICON</td>
<td>Optical Infrared Coordination Network for Astronomy</td>
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<td>PCS</td>
<td>Planetary Camera and Spectrograph</td>
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<td>Rayleigh Atmosphere Machine</td>
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<td>Radial Velocity</td>
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<td>SAAO</td>
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<td>SCExAO</td>
<td>Subaru Coronographic Extreme Adaptive Optics</td>
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<td>SKA</td>
<td>Square Kilometer Array</td>
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<td>SPICA</td>
<td>SPace Infrared telescope for Cosmology and Astrophysics</td>
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<td>Science Research Infrastructure Fund</td>
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<td>TNG</td>
<td>Telescope Nazionale Galileo</td>
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<td>UKATC</td>
<td>U.K. Astronomy Technology Centre</td>
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<td>UKIRT</td>
<td>UK Infrared Telescope</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>VLT</td>
<td>Very Large Telescope</td>
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<td>VLTI</td>
<td>Very Large Telescope Interferometer</td>
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<td>WASP</td>
<td>Wide Angle Search for Planets</td>
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<tr>
<td>WFIRST</td>
<td>Wide-Field Infra-Red Survey Telescope</td>
</tr>
<tr>
<td>WHT</td>
<td>William Herschel Telescope</td>
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<tr>
<td>WISE</td>
<td>Wide-field Infrared Survey Explorer</td>
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