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# SCIENCE AND TECHNOLOGY FACILITIES COUNCIL EXOPLANET SCIENCE REVIEW PANEL REPORT 2015

Exoplanets science review panel:

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# Executive summary

There are few questions more fundamental than that of whether 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 provide the answer directly answer the question 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 small Earth-sized objects. We now know that the Solar System is far from being the template 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, contributing to studies ranging from the discovery of planets and through determination of their planetary sizes and masses, through to detecting molecules in exoplanetary atmosphere, to theoretical models on how planetary systems form and evolve.

In 2007 STFC commissioned a report (McCraughrean 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 which 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 not 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 which 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 three 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. 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 characterizing their physical properties (e.g. bulk compositions and atmospheric chemistry), a major science goal is to understand planet formation and planetary system evolution.

To support these generic aims we make a series of 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 fund PDRAs through the grants line in support of the highest rated theoretical research.

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 continues to support access the exploitation of HST data for the characterisation of planetary atmospheres until JWST 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 optimized 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 E-ELT instruments specifically for exoplanet science (e.g. METIS, HIRES, PCS etc.).

R10 – Support the exploitation of HST, VLT, WHT, ALMA, JWST and E-ELT and associated modelling in studies of 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 and chemical models, data analysis and numerical simulations.

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 dataexoplanet science from the Gaia mission leading to the characterisation of exoplanets and their orbits

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 –Consider 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.

R17 – Support future ESA M-class missions that have a significant exoplanet science component.

This report presents the findings of the Science and Technology Facilities Council (STFC) Exoplanet Science Review Panel. 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 among the UK astronomical community, including observers, theorists and instrumentalists. 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:



## *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 realized. 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 AAO Planet Search that the UK became involved in observational searches for planets. Along with the HARPS surveys, AAO-PS has been one of the most prolific spectroscopic discovery projects. 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 composition tracks.

CoRoT was launched in December 2006 and was the first space-based transit experiment. This was later followed by the more ambitious Kepler mission in 2009. Together these missions have found the first terrestrial exoplanets, while Kepler data has also totally transformed our knowledge of multiple planet systems (already known from the HARPS surveys) and the size distribution of exoplanets. The UK community has not been well placed in these surveys as they originated before the community was well organized.

The field of view of CoRoT and Kepler and their observational strategies (especially for Kepler) have made follow-up observations challenging. None-the-less some individuals in the UK community have become involved in the Kepler follow-up campaign thanks to institutional involvement in HARPS-N. 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 atmospheres characterisation (5 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 ground-based instruments have proven it possible with transit 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 and line-lists calculations. 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.

In space the Gaia 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 neighbourhood. 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).

With the advent of SPHERE at the VLT and GPI at Gemini-S 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 (McCaughrean 2007) as an important area one, 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 – especially in the areas of discs and planet formation. This legacy has been built upon in recent years, as the UK theory community has increased in size and has broadened its research base while maintaining its international lead in key areas of exoplanet theory. Investments in HPC have played a key role in allowing UK theorists to maintain and increase their international competitiveness.

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. SKA) 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 is 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. The HARPS/N, SOPHIE and VLT-Espresso stabilized spectrographs 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, JWST, SPHERE, and GPI will all contribute to the atmospheric characterisation of transiting and imaged planets. ALMA and JWST will be critical for protoplanetary and debris disk studies. In the next decade the E-ELT is likely to contribute to many exoplanet areas through METIS (atmospheric studies, direct imaging, disks) and HIRES (radial velocity and atmospheric work) but selection of the final instrumentation for the telescope is still to occur.

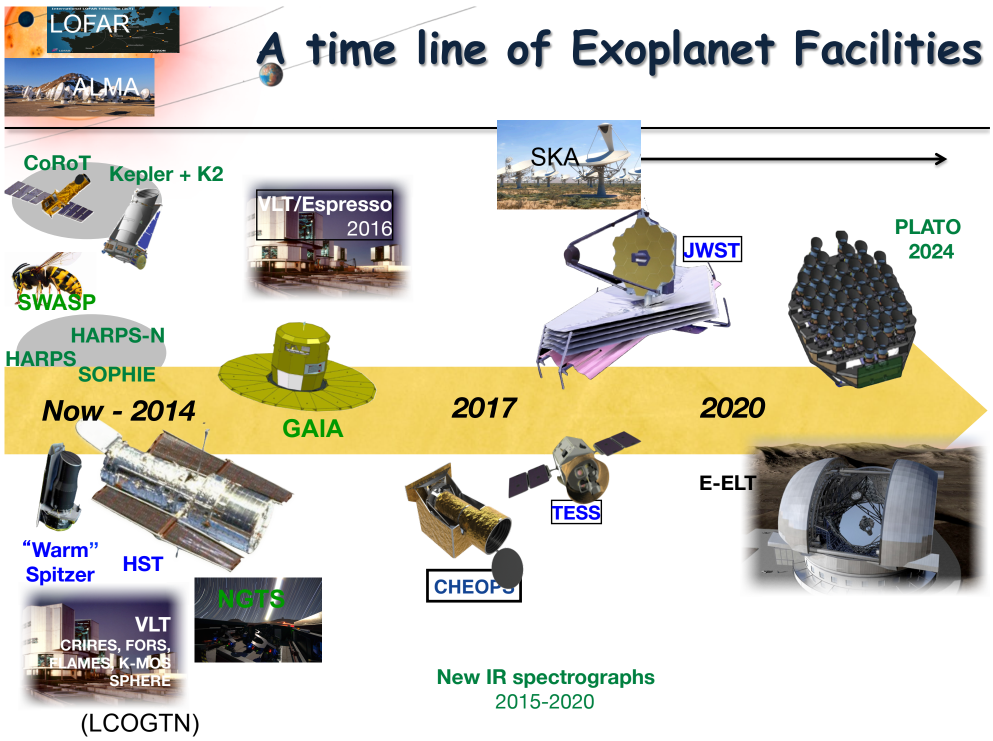



*Figure 1: A time line of funded exoplanet relevant facilities. Central to this are those specifically designed for transit discovery: SWASP, K2, NGTS, CHEOPS (ESA), TESS (NASA) and PLATO (ESA). Other ground-based facilities (e.g. HARPS and VLT-Espresso) will complement these discoveries by determining 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 characterisation. In the next decade the E-ELT will contribute to many exoplanet areas (in particular RV, atmospheric and disks characterization, direct imaging).*

## 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, particularly 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 Fig. 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

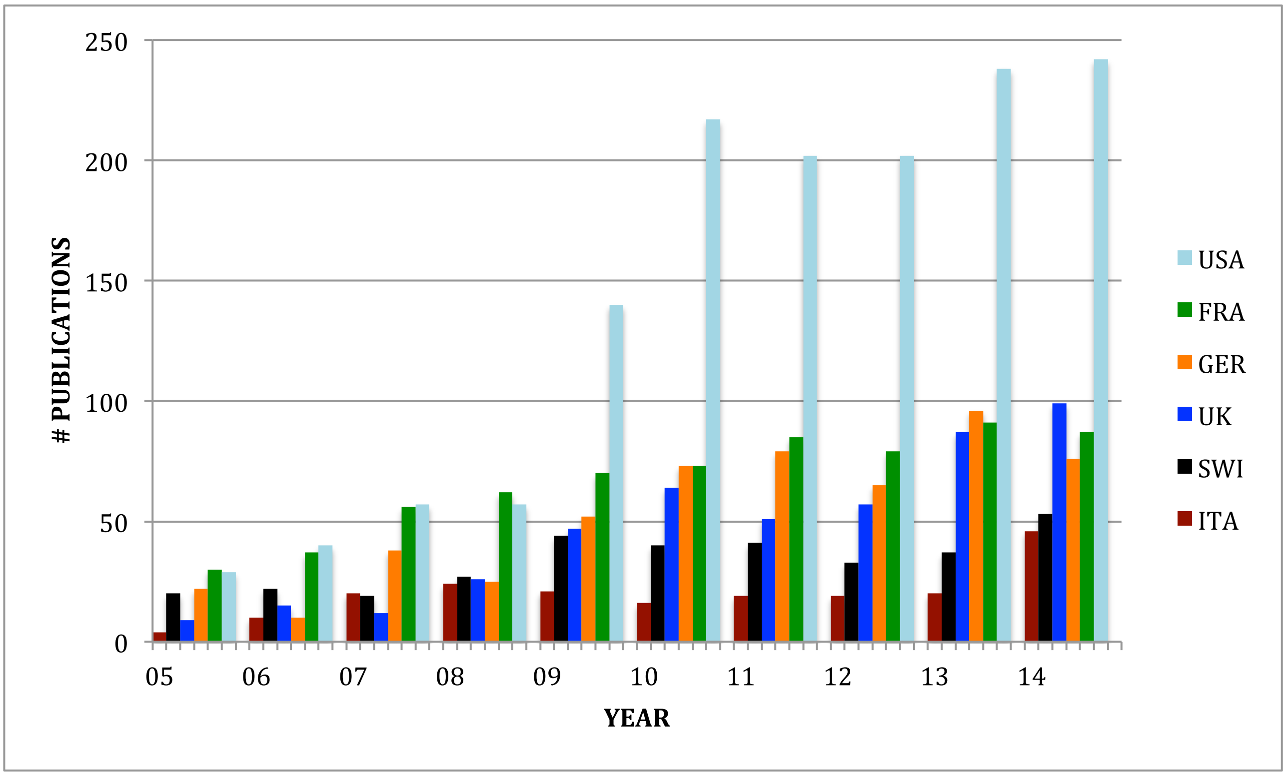



*Figure 2: Number of refereed publications with affiliated authors from the USA, France, Germany, UK, Switzerland and Italy over the period 2005-2014 that contain the words "exoplanet" and/or "extrasolar" in the abstract and/or title. Over the last ten years UK activity in the exoplanet area has caught up with and now exceeds that of several comparator countries.*

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 Fig. 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 McCraughrean (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.

**Radial velocities:**

The McCraughrean (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. PVRS), 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. 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.

**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 ~32% and 50% of planets targeted for detailed follow-up with these methods, respectively (Dawes 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. Simulations show an expected yield of ~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 ~24% of transmission spectroscopy papers at other wavelengths. 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 ever 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 micro-lensing 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 (Baulieu et al. 2006, Nature), the first 2-planet system discovered by microlensing (Gaudi et al. 2008, Science), and the determination of the power-law mass function of cool planets (Cassan et al. 2012, Nature).

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 Foundation (QNRF) grant, as well as support to individual researchers via Royal Society University Research and STFC Advanced Fellowships.

**Direct Detection:**
The McCraughrean (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) 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 led to UK involvement in the construction of the E-ELT HARMONI instrument, which will enable characterisation of known directly imaged planets. 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).

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 theoretically understanding the formation, evolution, and observed properties of exoplanets as well as modeling of their atmospheres. For example, UK researchers played a leading role in investigating planet formation in binary star systems, 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. Other areas of appreciable progress driven by UK scientists include disc-planet interactions and planet migration, as well as the theoretical understanding of tidal interactions between stars and short-period planets – 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 have provided considerable effort in the calculation of molecular line lists that are vital for interpreting spectroscopic observations of exoplanetary atmospheres.

**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.

## 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 characterized. 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 characterized by any other means.

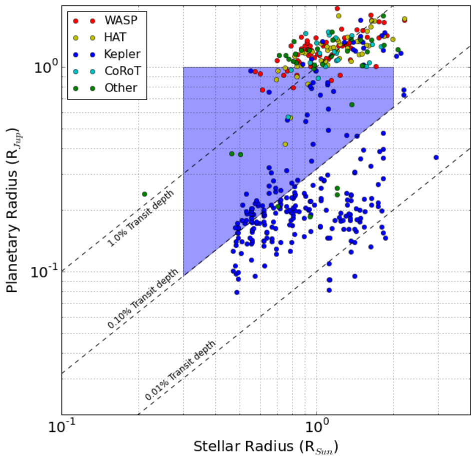



*Figure 3: Comparison of different transit surveys with the sensitivity space for NGTS (shaded area).*

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 supplier of 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. 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.

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 with the aim of detecting and characterizing ~50 planetary systems (planets down to super-Earthed 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~4-13$^{th}$ mag. 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 Asteroseismology Science Consortium.

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 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 characterize 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.

It is important to note that, in order to realize the full scientific potential of transit surveys, sufficient radial velocity instrumentation must be in place (see section 4.1).

### 3.2 Atmospheric characterisation

For planets transiting in front of their parent stars – of which some 1,100 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 density. While the planetary 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 and the other key observables for planets are the chemical compositions and states of their atmospheres (see Fig. 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, the atmospheric composition is the only direct observable to investigate planetary habitability (Lovelock, 1979).

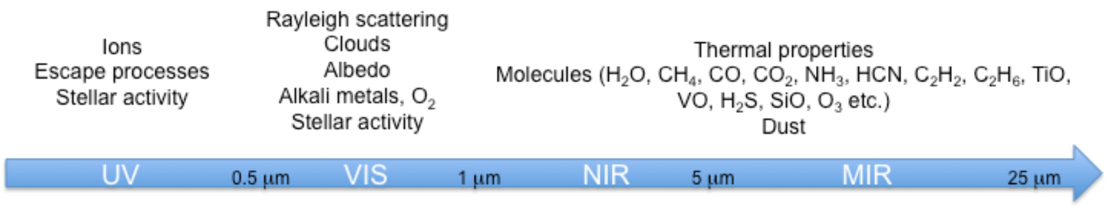



*Figure 4: summary of the atmospheric information that can be extracted from the spectra of a planet. The information that can be obtained from such studies strongly depends on the wavelength region that is observed.*

To date, two classes of methods can be used to sound 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 $\sim 10^{-4}$ 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 (e.g. Vidal-Madjar et al. 2003, Linsky et al. 2010; Fossati et al. 2010). 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 (e.g. Pont et al., 2008; Knutson et al., 2014; Sing et al., 2015). The IR range offers the possibility of probing the neutral atmospheres of exoplanets and their thermal properties (e.g. Knutson et al., 2007; Burrows et al. 2007, Majeau et al., 2012). On a large scale, the IR transit and eclipse spectra of hot-Jupiters seem to be dominated by the signature of water vapour (e.g. Barman 2007, Beaulieu et al. 2010; Birkby et al., 2013; Burrows et al. 2007, Charbonneau et al. 2008; Crouzet et al. 2012, 2014; Danielski et al. 2014; Deming et al. 2013; Grillmair et al. 2008; Kreidberg et al., 2014b, McCullough et al. 2014; Swain et al. 2008, 2009; Tinetti et al. 2007b, 2010, Todorov et al., 2014). 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. (e.g. Swain et al., 2008, 2010, Snellen, et al., 2010; Brogi et al., 2012). The analysis of the transit spectra for the 6.5 $M_{Earth}$ super-Earth GJ 1214b has oscillated between a metal-rich or a cloudy atmosphere.
(e.g. Bean et al. 2010; Berta et al., 2012; Kreidberg et al., 2014, Stevenson et al., 2014).

Despite these early successes, current data are rather sparse, i.e. there is not enough wavelength coverage and most of the time the observations were 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 (Swain et al., 2009; Madhusudhan and Seager, 2009; Lee et al., 2012; Line et al., 2013; Waldmann et al., 2014) 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 & 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.

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 hugely enhance this capability.

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 transit will be of great help to understand the role played by migration and by extreme irradiation on gaseous planets.

In the next decade, the James Webb Space Telescope will be launched (late 2018). JWST has an equivalent telescope diameter of 5.8 m; and is a true multipurpose observatory with multiple capabilities, instruments (NIRISS, NIRCAM, NIRSPEC, MIRI) and operating modes, optimised for background limited observations (http://www.stsci.edu/jwst/science/sodrm/jwst/science/sodrm/). JWST will allow the acquisition of better exoplanet spectra and with wider wavelength coverage (both through transit and direct imaging), compared to what is currently available (especially for fainter targets). However, both its extremely high sensitivity and general-purpose observatory nature mean there are significant restrictions on the type and number of targets that will be observable (e.g. NIRSPEC-PRISM saturates at J=11, http://www.cosmos.esa.int/web/jwst/exoplanets). The expectation is that a few tens of interesting planets will be observed, with the most challenging being temperate super-Earths around M-dwarfs.

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. 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 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.

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 widely vary. 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 echelon 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 help 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.

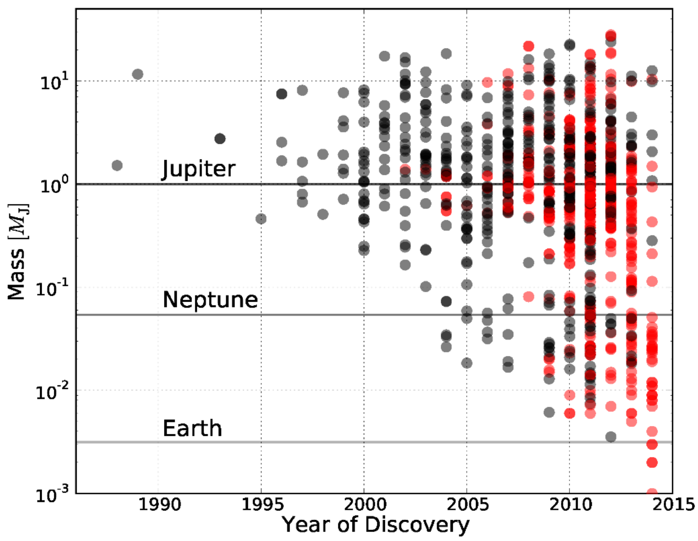



*Figure 5: Discovery date vs. mass for exoplanets from Laughlin & Lissaur et al. (2014) with the data taken from exoplanets.org. Plotted in red are transiting planets and in grey are planets detected by RV only. With a steadily increasing precision over the last 25 years, exoplanets in the Earth-mass regime can now be detected.*

| **Instrument** | **Telescope/Observatory** | **Start of Operations** | **Wavelength band (um)** | **Resolution** | Precision **(m/s)** |
|---|---|---|---|---|---|
| HIRES | Keck I/Mauna Kea | 1993 | 0.3–1.0 | 25,000–85,000 | 1-2 |
| **HARPS** | **3.6m/ESO La Silla** | **2003** | **0.38-0.69** | **115,000** | **<0.8** |
| SOPHIE | 1.93m/OHP | 2006 | 0.38-0.69 | 39,000-75,000 | 1-2 |
| PFS | Magellan II/Las Campanas | 2010 | 0.39–0.67 | 38,000–190,000 | 1 |
| CHIRON | 1.5m/CTIO | 2011 | 0.41-0.87 | 80,000 | <1 |
| HARPS-N | TNG/ORM | 2012 | 0.38-0.69 | 115,000 | <0.8 |
| LEVY | APF/Lick | 2013 | 0.37-0.97 | 114,00-150,000 | <1 |
| IRD | Subaru/Mauna Kea | 2014 | 0.98-1.75 | 70,000 | 1 |
| MINERVA | 4x1-m/Mt. Hopkins | 2015 | 0.39-0.86 | 53,000 | 1 |
| CARMENES | Zeiss 3.5-m/Calar Alto | 2015 | 0.55-1.7 | 82,000 | 1 |
| SPIROU | CFHT/Mauna Kea | 2017 | 0.98-2.35 | 70,000 | 1 |

| Instrument | Telescope/Observatory | Start of Operations | Wavelength band (um) | Resolution | Precision (m/s) |
|---|---|---|---|---|---|
| **ESPRESSO** | **VLT/ESO Paranal** | **2017** | **0.38-0.78** | **60,000-200,000** | **0.1** |
| G-CLEF | GMT/Las Campanas | 2019 | 0.35-0.95 | 120,000 | 0.1 |

*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 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 stuctures 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: 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 appointments mentioned above mean that the UK is well-placed to play a central role in the forthcoming surveys that will 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.

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 centre, 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 the above figure). 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 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.

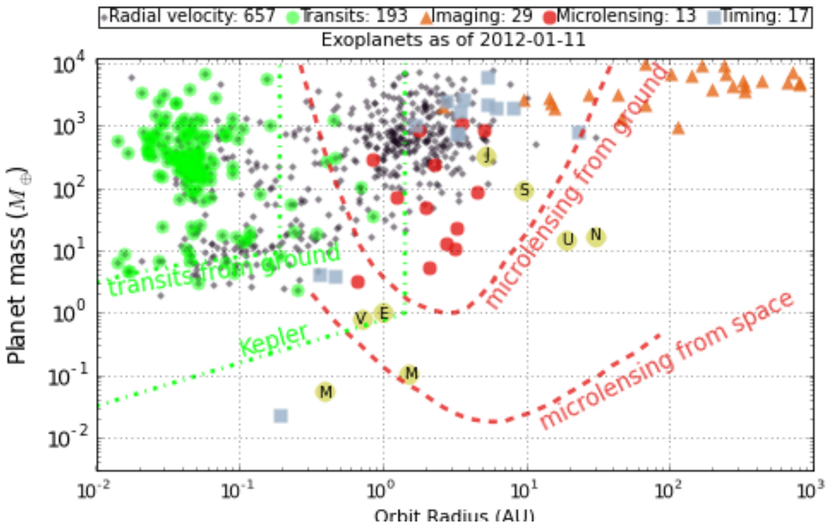



*Figure 6: Mass versus orbital distance diagram showing the unique discovery space of ground- and space-based microlensing surveys.*

### 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 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 and atmosphere dynamics; the theory of tidal dissipation 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; 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.

Evidence for the strength of U.K.-based theory is provided by the highly cited papers published by U.K. researchers (e.g. ~70 papers on exoplanet-related topics with > 100 citations), invitations to write major review articles and present review talks at large international conferences (e.g. three Annual Reviews articles published since 2008, five review talks at the 2013 conference Protostars and Planets VI and six leading authorships of the review articles appearing in the PPVI conference book). U.K. theorists contributing to exoplanet research have been successful in securing external grant support (e.g. 4 ERC advanced grants +1 starting grant), and have prominent roles in the PLATO mission work packages. Out of 8 work packages devoted to the study of planet formation and dynamical evolution, the U.K. leads in 2, will make major contributions to the other 6, and has an overall coordination role across all these work packages. More U.K.-based researchers have signed up to the PLATO theory working groups than from any other country. Reasons for the U.K. success in this area are manifold, but include the historical legacy in star and planet formation research which has been built upon, the openness of the U.K. academic jobs market which has enabled the hiring of high quality researchers from outside of the U.K., and strategic investment in HPC *via* DiRAC by STFC and by universities through SRIF and CIF initiatives. The increasing sophistication of theoretical models (e.g. multi-dimensional simulations of protoplanetary discs, *ab initio* calculations of molecular lines lists) means that the research is both computationally demanding and labor intensive.

We also refer the reader to the inputs from the Astronomy Advisory Panel and Solar System Advisory Panel to the STFC Computing Survey that are relevant for future capacity in this area.

### 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. There are also possible synergies with transit missions such as PLATO where the debris disc-planetary system connection can be explored in more depth.

## 4. Science roadmap and strategic goals (2015-2025)

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, and is vital to our ability to interpret our data and 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 – The UK provides long-term stable funding of HPC through DiRAC, and funds PDRAs through the grants line in support of the highest rated theoretical research.*

**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. 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 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 uncompetitive in their present form with the launch of TESS, NGTS will be quite capable of following up many of the single transit events that are likely to be long period planets.

*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 planetary 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 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.

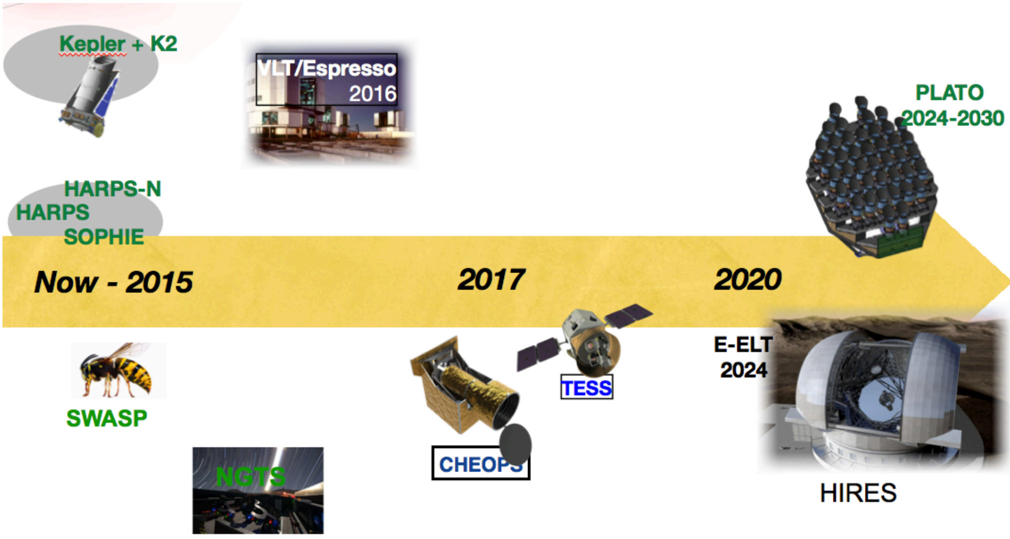



*Figure 7: The European Transit Roadmap (2015-2030+).*

◆ *Aim 2: Develop a better understanding of Planetary Atmospheres:*
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 continues 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, 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 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 and atmospheric 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.

*R10 – Support the exploitation of HST, VLT, WHT, ALMA, JWST and E-ELT and associated modelling in studies of 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 and chemical models, data analysis and numerical simulations.*

◆ *Aim 4: Statistics 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 number of habitable-zone planets for 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 have recently shown the likely existence of an enormous population of orphaned planets that cannot be detected through any other means.

*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.*

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 – which is also the propriety period for the data. To be useful to PLATO follow-up, significant time 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 but not 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 (1.2Re) 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 help prepare the community for the opportunities that are coming.

3) Given that mass determinations of habitable zone/long period terrestrial planets will need the capabilities and light gathering power of Espresso/VLT, there have been some suggestions (discussions?) of a new facility at the GTC with this aim. 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 UKIRT withdrawal). While CARMENES is already a funded project, opportunities may arise for further community involvement and exploitation. Note that PLATO and TESS (in particular) 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 a 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 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.

*Direct Imaging.* Direct imaging of exoplanets remains one of the most challenging areas of technology development and is driving many of the 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 advanced sufficiently.

## 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.

Space facilities will be selected by ESA and so it is difficult for us to influence the selection. 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 a 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 onboard 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 launch 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 these 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, paving the way for potential UK leadership roles in its science exploitation.

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 – Consider 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 the technical review stage, but are expected to be submitted to the forthcoming M5 mission call. Also, the SPICA mission concept is expected to be submitted to the M5 call, and a dedicated instrument for exoplanet atmospheric characterisation 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 – We recommend UK support for future M or L-class missions that have a significant exoplanet science component.*

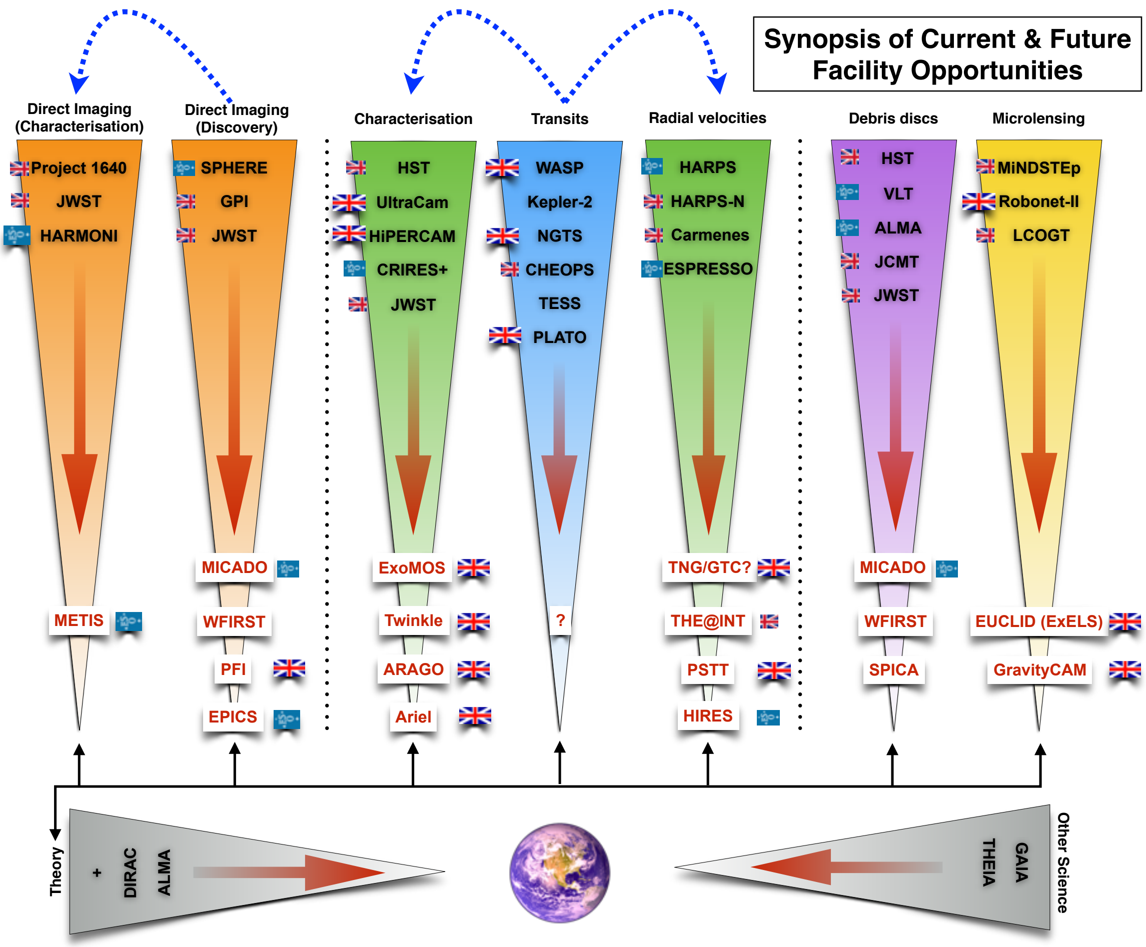
### 5.2 Long term (2035-2045)

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 (section5.1). 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

**TBD**




1) A UK-led project, with clearly defined benefits for the entire community, and/or
2) Substantial UK science and/or construction involvement. Data readily available to entire UK community.

1) A project with substantial UK involvement/leadership, with closed consortium structure primarily benefiting select private institutions only, and/or
2) Evidence of some UK science and/or construction involvement. Data may or may not be readily available to entire UK community.

1) A project with evidence of relatively limited UK involvement (but which may still benefit the entire UK community) and/or
2) A closed consortium structure primarily benefiting select private institutions only. Data may not be readily available to entire UK community.

1) An ESO-led project, with clearly defined benefits for the entire community and
2) Substantial UK science and/or construction involvement, either now or in the future.

1) Other ESO-led projects, with clearly defined benefits for the entire community.

| Science area | Funded missions/projects | Unfunded future mission/projects | Notes |
|---|---|---|---|
| Transit detection/Observation | SuperWASP*, Kepler-2, NGTS*, CHEOPS*, TESS, PLATO*, UltraCAM*, HiPERCAM* | | |
| Radial velocity detection | HARPS, VLT (ESPRESSO), HARPS-N*, CARMENES* | THE@INT*, PSTT*, E-ELT (HIRES) | |
| Transit atmosphere characterisation | JWST*, VLT (CRIRES+) | Twinkle*, ExoMOS*, Ariel* | |
| Direct imaging - discovery | SPHERE*, GPI*, JWST*, E-ELT (MICADO) | WFIRST, PFI*, E-ELT (EPICS)* | |
| Direct imaging - atmosphere characterisation | JWST*, E-ELT (HARMONI)*, E-ELT (METIS)* | | |
| Debris discs | VLT, ALMA, JCMT, JWST*, E-ELT (MICADO) | WFIRST, SPICA | |
| Microlensing | MiNDTEp, Robonet-II (LCOGT)* | EUCLID (ExELS), GravityCAM | |
| Theory (including planet formation) | DiRAC, ALMA | | |
| Post-main sequence planets | | | |

* Indicates significant UK involvement through instrument build or consortium membership.

**Appendix A** UK Exoplanet research groups

**Appendix B** References

**Appendix C Panel procedures**

The 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 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.
- An open call for community whitepapers to which 23 submissions were made to the 16 January 2015 deadline.
- A presentation of the draft report at the UK Community Exoplanet Conference: 30 March 01 April 2015.

**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 but included metadata such as academic status and institution.

Figure A1 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.

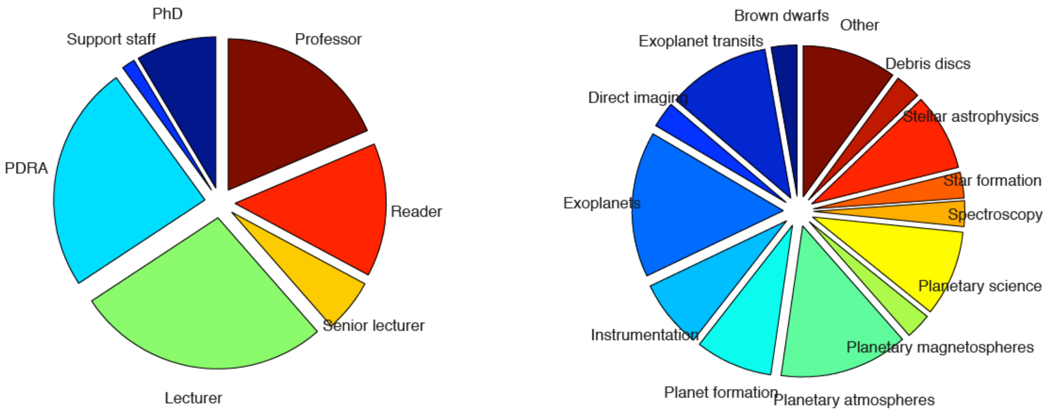



*Figure A1: Distribution of academic status and research areas.*

Table A1 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.

| **Institution** | **Respondents** |
|---|---|
| Birkbeck | 1 |
| Cardiff University | 1 |
| Durham | 1 |
| IAP | 1 |
| Imperial College London | 2 |
| JBCA, University of Manchester | 1 |
| Keele University | 4 |
| Queen Mary, University of London | 2 |
| Queen's University Belfast | 5 |
| The Open University | 2 |
| UCL | 13 |
| University of Cambridge | 9 |
| University of East Anglia | 1 |
| University of Edinburgh | 2 |
| University of Exeter | 6 |
| University of Leicester | 5 |
| University of Manchester | 1 |
| University of Oxford | 4 |
| University of St Andrews | 3 |
| University of Warwick | 5 |
| Unknown | 1 |

*Table A1: Responses by institution.*

Figure A2 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.

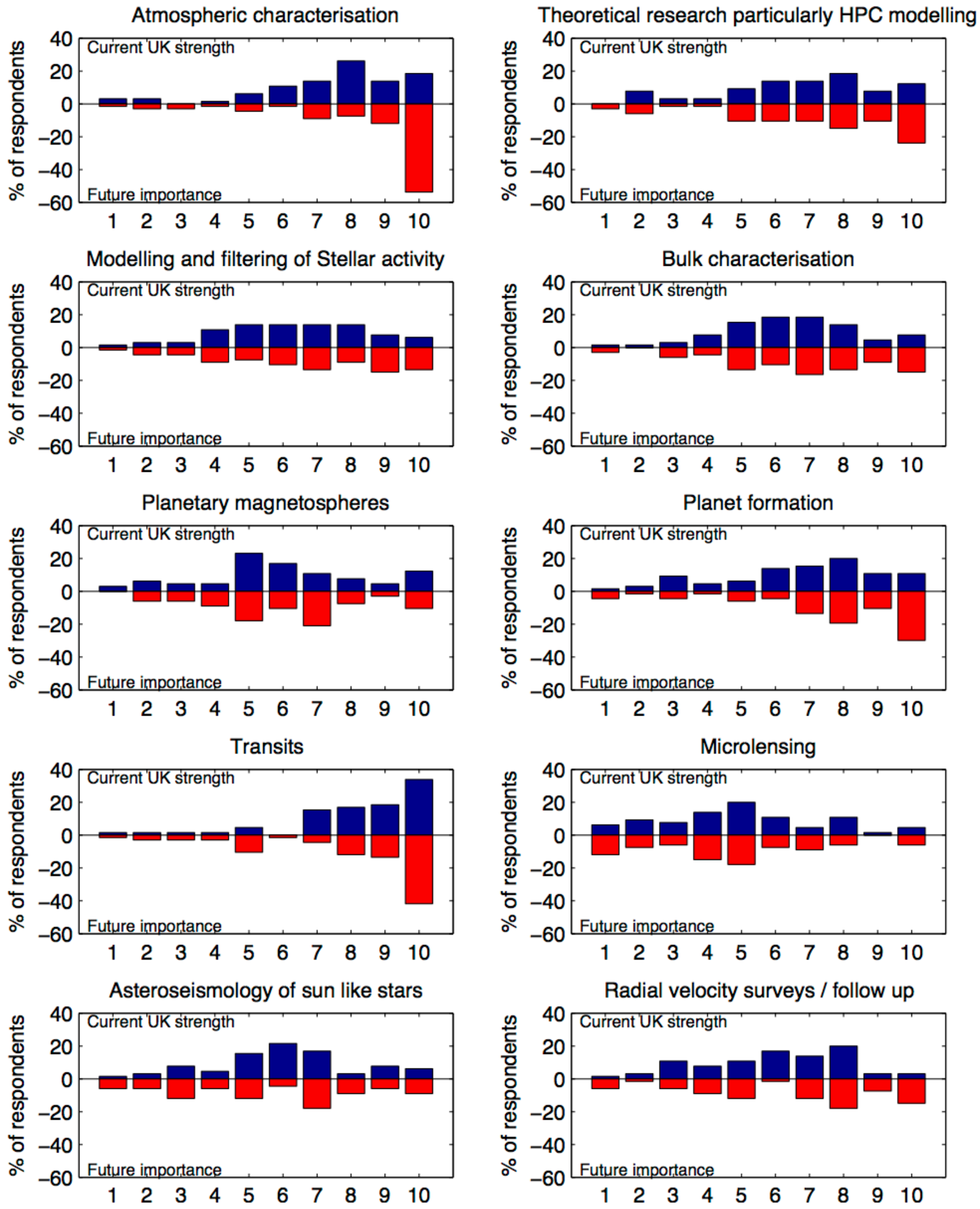



*Figure A2: Responses to questions 3a and 3b.*

**White paper submissions**

One-page white paper submissions were also requested and supplied by the community. Table A2 list the white-papers received by the panel.

| Author | Title |
|---|---|
| A. Cameron | HARPS-North and modeling of astrophysical noise – A short paper for the STFC ESP Review |
| O. Panić | Importance of CO snowline studies with ALMA |
| C. Haswell | Arago: White paper for STFC's UK Exoplanets Review |
| E. Pascale | ARIEL - Atmospheric Remote–sensing Infrared Exoplanet Large-survey |
| B. Biller | Probing Exoplanet Cloud Properties through Variability Monitoring |
| D. Pollacco | CHEOPS – A short paper for the STFC ESP Review |
| C.A. Haswell | Disintegrating Exoplanets: White paper for STFC's UK Exoplanets Review |
| E. Kerins | The Exoplanet Euclid Legacy Survey (ExELS): probing planet formation with a cool exoplanet microlensing survey |

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| J. Tennyson and S.N. Yurchenko | Molecular Line Lists for Exoplanet and other atmospheres |
| S. Hinkley and B. Biller | Strategic Importance of Exoplanet Imaging for the UK |
| J. Farihi | Exoplanetary science with debris polluted white dwarfs: a white paper for the STFC exoplanet panel |
| Beaulieu | GravityCam lucky-imaging microlensing survey: Population statistics of cool planets down to Lunar mass |
| V. Dhillon | HiPERCAM and exoplanet research |
| P. Wheatley | Next-Generation Transit Survey (NGTS) |
| S. Kraus | The Planet Formation Imager (PFI) project |
| D. Pollacco | PLATO – A short paper for the STFC ESP Review |
| I. Baraffe | Atmospheres models for exoplanets and brown dwarfs |
| H. Jones | Photonic Spectrograph for the ESO – NTT (PSTT) |
| C. Hellier and D. Pollacco | The Status of WASP: A Report to the STFC Exoplanets Review Panel |
| D. Pollacco | The Future of La Silla Observatory – A short paper for the STFC ESP Review |
| D. Queloz | A Terra Hunting Experiment for the Isaac Newton Telescope (THE@INT) |
| M. Tessenyi | Twinkle – Transiting worlds infrared explorer |
| D.K. Sing | ExoMOS - White paper for the STFC exoplanet review |

## Appendix D Panel membership and vested interests

Prof Paul O'Brien (Chair) (Leicester)
Dr Chris Arridge (Lancaster)
Dr Stephen Lowry (Kent)
Prof Richard Nelson (QMUL)
Prof Don Pollacco (Warwick): Co-Pi of WASP, NGTS, HARPS-N Official Collaborator and Science Coordinator for PLATO
Dr David Sing (Exeter)
Prof Giovanna Tinetti (UCL)
Dr Chris Watson (QUB).

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.

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

## Appendix E 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.