A European Roadmap for Exoplanets

Prepared by the ESA-appointed

Exoplanet Roadmap Advisory Team (EPR-AT)

11 October 2010

Exoplanet Roadmap

The Exoplanet Roadmap Advisory Team (EPR-AT) was appointed by ESA with the purpose of advising the Agency on the best scientific and technological roadmap to pursue in order to address one of the most exciting goals in modern astrophysics: the characterization of terrestrial exoplanets.

The main scientific areas covered by this roadmap are:

- The detection of exoplanets
- The characterization of their internal structure
- The characterization of their atmospheres including biosignatures

The procedure followed by the Advisory Team was as follows:

- ESA issued a Call for White Papers from the scientific community in May 2008; a total of 25 White Papers were received. These were evaluated and used by the EPR-AT.
- The Advisory Team met in a series of meetings between September 2009 and January 2010.
- The roadmap effort was presented at several international conferences September to October 2009.
- An open workshop to the community was held 7-8 April 2010 at University College, London, U.K attended by approximately 60 members of the community. The draft of the roadmap was discussed in parallel discussion groups.
- A final meeting of the advisory team after the workshop took into account the input of the workshop.

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Executive Summary

The study of exoplanets is arguably one of the most exciting and vibrant fields in astronomy and planetary science that has developed in the past decade. It is a field that attracts some of the brightest young minds. Understanding the process of planet formation and why life developed on our Earth provides answers to scientific questions of fundamental importance. Exoplanets also enchant the general public because as a concept they are easy to grasp. Anyone who has stared up at the night sky and wondered how many worlds like ours are out there understands the basic reasons of why we search for exoplanets. As astronomers we seek answers to the questions posed by humanity.

The progress in the field of exoplanets has been phenomenal. Twenty years ago only a handful of researchers were actively searching for exoplanets. The topic would barely merit a session at a modest-sized meeting. Now there are several well-attended (mostly by young people!) international conferences per year devoted entirely to exoplanets. Since the early efforts in this field we have discovered over 450 planets in orbit around other stars including the first terrestrial mass objects. We have characterised exoplanets in terms of their mass, radius, and mean density and thus have been able to construct the first simple models of their internal structure. We have also measured the albedo, effective temperature, and atmospheric features of a few short period giant planets. Twenty years ago these discoveries could not have even been imagined possible by those of us who were working in this largely unnoticed field.

The EPR-AT was created to advise ESA on the best roadmap for the characterization of exoplanets up to and including terrestrial planets. This is no easy task as the field is technologically challenging. The detection and characterization of exoplanets requires a diverse range of astronomical measurements that are pushed to the extreme limits: radial velocity precisions of 0.1 – 1 m s^{-1}, astrometric measurements of a few micro-arcseconds, angular resolutions of a few milli-arcseconds, and the measurement of contrast ratios of $\sim 10^{-10}$. The needs of the exoplanet community are drivers of new technologies and many of these “extreme” measurements often require expensive space missions.

The community is also diverse that embraces a wide range of detection methods and research areas, the later including planet formation, planetary structures and atmospheres, dynamical evolution, the formation and evolution of life, etc. It is this diversity that makes for a vibrant and exciting field, but challenges any task force to “keep up with developments”. The field is producing discoveries at such a rapid pace that we risk having roadmaps that are outdated before they are even published. For example, when the EPR-AT was formed it was thought that exoplanets should have orbits aligned with the spin axis of the star. Now we know that a significant fraction of planetary orbits are misaligned and planets can even have retrograde orbits. These discoveries may present challenges to current formation theories. Likewise, less than a decade ago relatively few chemical species (H, Na) were detected in the atmospheres of giant exoplanets. Since then the chemical species of CH_4, H_2O, CO and CO_2 have also been observed.

The field of exoplanets is rapidly moving from one that was dominated by detections, to one where the characterization of exoplanets are producing the most exciting results. The explosion in transiting planet discoveries that have enabled us to measure the mass, radius, mean density, and dominant atmospheric spectral features of exoplanets has driven this shift to characterization. The field is quickly moving to one where we can do true comparative exo-planetology: comparing exoplanets not only to each other, but also to the planets of our own solar system. Drawing from solar system planetary studies, exo-planetary science covers three broad themes: 1) Detections: understanding the census and architecture of planetary systems. 2) Characterization of the internal structure: measuring the fundamental exoplanetary parameters of mass and radius and comparing these to structure models. 3) Characterization of the exoplanetary atmospheres: understanding the effective temperature, composition, and presence of possible biosignatures in the atmospheres of exoplanets.

For these reasons an exoplanet roadmap is not a simple path carrying us from point “A” (the present) to point “B” (the detection of an exo-earth). Rather it is more like a 3-lane road whose lanes are defined by our themes of detection, the characterization of the internal structure, and the characterization of the atmospheres. Each lane moves at its own pace and with developments, both scientific and technological, providing a “burst of speed” that is often unpredictable. This 3-lane roadmap is schematized in Fig. 1.

The EPR-AT acknowledges that the community must accelerate the pace of characterization of exoplanets. Discoveries of all types of exoplanets should continue, but the most important ones are the “added value discoveries” on which we can perform detailed characterization. In this respect PLATO has a key role in this roadmap, as it will constrain the internal structure of exoplanets down to the terrestrial mass regime. Since this mission is targeting bright stars, it will provide good targets for additional atmospheric characterization.

The EPR-AT also recognizes that more progress is needed in the characterization of exoplanetary atmospheres. We cannot hope to detect and characterise biosignatures in the atmospheres of Earth-like planets without first characterizing the conditions and composition of exoplanets having a wide range of masses, orbital distances, and host stars. An M class mission that can study the atmospheres of exoplanets which orbit close to the parent star (using the combined light) and/or at large orbital distances (utilizing direct imaging), would provide a major push in the characterization studies of exoplanets.

The EPR-AT emphasizes that extensive ground-based observations should continue parallel to space-based efforts. In particular, for transit missions (CoRoT, Kepler, and PLATO) ground-based radial velocity measurements are an important component for the complete characterization of the transiting exoplanet.

In devising the current roadmap the EPR-AT acknowledges that the detection and characterization of Earth-like planets is an important milestone. However, our main goal is to perform comparative planetology on exoplanets spanning the full parameter space of mass, orbital distance, and host star. Terrestrial planets in the habitable zone occupy only one small region of the parameter space, albeit an important one since this is where we may find planets analogous to our Earth. Because this region of the parameter space poses the most technological challenges it thus serves as the logical “destination” for this roadmap.

The detection and characterization of Earth-like planets in the habitable zone of Solar-type stars most likely will require a large class, flagship mission in the next 20-30 years. Such a mission must be one of characterization and *not* discovery and that is aimed at stars that we by then know host terrestrial planets. An important part of this roadmap is to undertake the efforts from ground (e.g. radial velocity measurements), and/or space (e.g. transit observations with PLATO or astrometric measurements with SIM-Lite) to produce the best possible target list of known terrestrial planets in the habitable zone of nearby stars. Furthermore, the technology to perform such characterization should be in place, tested, and reliable. All efforts must be made to ensure that we *successfully* fill this "last piece of the puzzle."

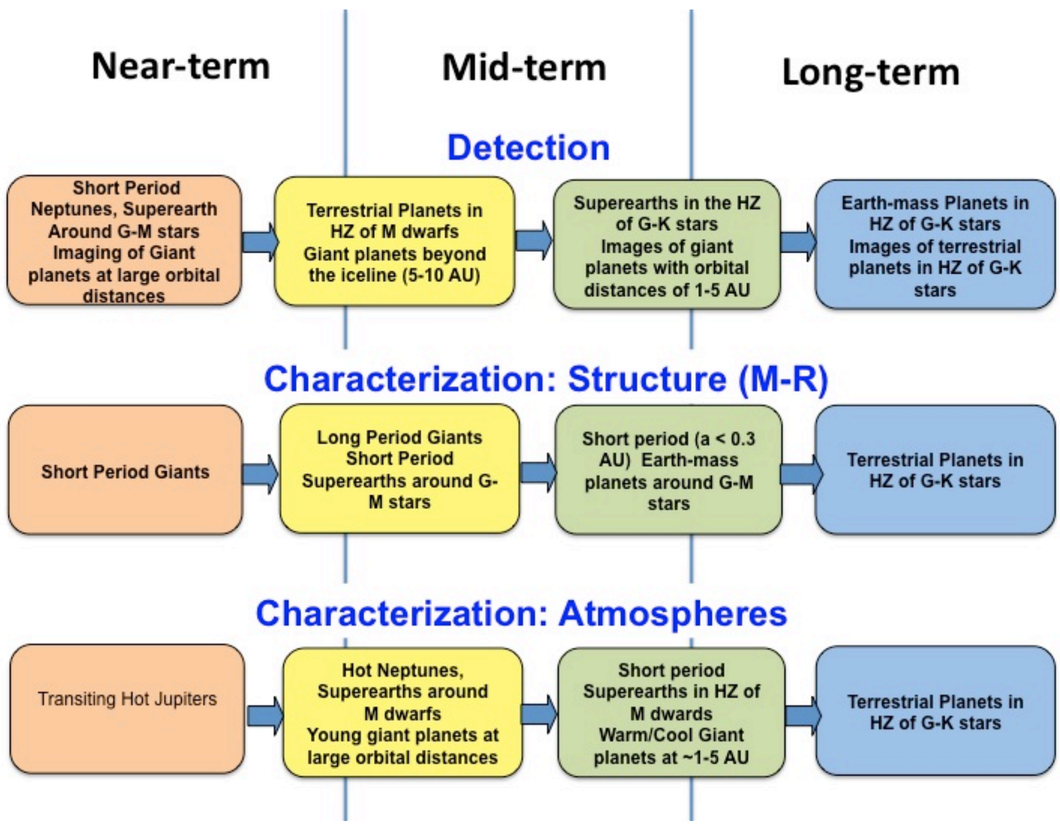

Fig. 1 Schematic showing the rough timeline for milestones for our "3-lanes" of detection, characterization of internal structure (mass, radius, mean density) and the characterization of spectral atmospheres. Near term is approximately 2011-2017, Mid-term 2015-2022, and Long-term beyond 2010. Technological difficulty and time proceeds left to right, and top to bottom.

1 Table of Content

2 Introduction

The objective of this ESA-appointed advisory team was to devise the best roadmap for the characterization of exoplanets including terrestrial planets. As stated earlier, this is not an easy task. The exoplanet community is diverse. It uses a wide range of detection methods (at least 5). The field has researchers that work on planet formation, planetary atmospheres, dynamical evolution, etc, areas nominally in the realm of planetary science. Its umbrella also covers stellar astronomers who study how the properties of the star can influence planet formation and evolution. Exoplanets is also a highly competitive field. This is surely the underlying reason for the rapid progress it has shown in the past decade. Researchers in each sub-field are passionate about what they do, and are rightfully convinced of the importance of their efforts. This is what continues to make the field so vibrant. But this is also what makes our task so difficult. As an advisory team our role is not to tell colleagues what aspect of exoplanet research is more important than others – we are no greater experts than many of our colleagues that work in this exciting field.

Although the EPR-AT is making a recommendation to the community of a space agency, we recognize that a complete roadmap involves surveying the landscape of not only on-going and planned space missions, but ground-based efforts as well. Ground-based efforts still dominate the field and play a key role in the two current exoplanet space missions CoRoT and Kepler. An effective roadmap must take into account all aspects of the field. The knowledge gleaned from ground-based studies and previous space missions is essential for the effective planning of future space missions

Our roadmap is organized as follows. In Section 3 we present the *Exoplanet Landscape*, a brief summary of the current status of the various sub-fields of exoplanet research. This is not meant to be an extensive review of the field, but serves as a starting point for our journey. In the *Facility Landscape* of Section 4 we summarize the "vehicles" available for exoplanet roadmap. A more detailed listing is found in the appendix. In Section 5 our Roadmap is presented.

Before proceeding a few caveats are in order. The EPR-AT does not replace the peer review process. Space missions are solicited through an ESA call for proposals, and evaluated by the ESA advisory structure, which is supplemented by outside experts whenever required. Our roadmap only recommends the different areas the advisory team feels is important for the further development of exoplanet research. The roadmap is also the opinion of the advisory team. We bring our expertise, but also our own biases to the roadmap. It is our hope, however, that in a broad sense our roadmap has elements that are important for making the study of exoplanets truly "exoplanetary science".

3 The Exoplanet Landscape

3.1 Detections

The various methods that have been employed for the detection of exoplanets are: 1) the Radial Velocity, or Doppler method, 2) Transits, 3) Astrometry, 4) Direct imaging, 5) Microlensing, and 6) Timing variations. To date, all of these techniques have been successful at detecting extrasolar planets. (There has been no confirmed exoplanet discovered with astrometric measurements, but there have been several detections of known exoplanets with this method.) The exoplanet discoveries/detections (see e.g. www.exoplanets.eu or exoplanet.eu) are shown in Fig. 2. Blue dots represent the detections using the radial velocity (RV) method; red triangles represent exoplanets found with the transit method; inverted yellow triangles represent astrometric detections; the pale blue pentagons are imaging detections; the deep red diamonds are discoveries made with timing variations; and the green squares are microlensing detections. For comparison the large letters mark the location of planets in our solar system.

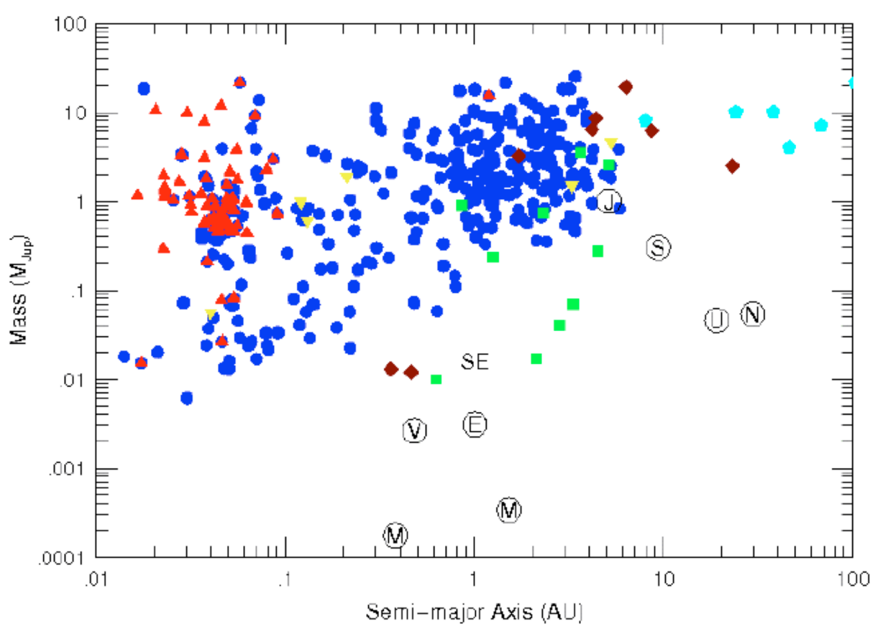

Fig. 2. Exoplanet discoveries from the various search methods in the Mass-Semi-major axis plane. Blue dots: Radial velocity detections; Red triangles: Transit detections; Inverted yellow triangles: astrometric detections; Green squares: Microlensing detections; Blue Pentagons: Imaging detections; Red diamonds: Timing detections. The letters mark the location of the planets in the solar system. "SE" denotes a Super earth with 5 M_{Earth}.

The symbol "SE" in Fig. 2 represents a Super-Earth (5 M_{earth}) at 1 AU. The other letters mark the location of planets of the solar system. Note that current discoveries dominate the upper left of the diagram. To date we have found relatively few extrasolar planets that have direct analogs in our own Solar System. A major milestone for detections in this roadmap is to fill the lower right of the mass-distance parameter space and to determine just how unique the properties of our solar system are. Because "characterization" is a critical next step in exoplanet science, it is important that these detections are of the kind that are conducive for characterization studies of both the planet and host star from the ground or from space.

3.1.1 Radial Velocity Method

To date over 450 extrasolar planets have been discovered and more than 40 stars are known to host multiple planet systems. The vast majority of these have been discovered with the radial velocity (RV) technique (see Fig. 2). Not only is the RV method the most successful at detecting exoplanets, but also it has played a pivotal role in the confirmation of planet candidates found by the transit method. The derivation of the planet mass provided by RV measurements together with the planet radius measurements from photometry have provided the first characterization studies of exoplanets. It is expected that the RV method will continue to play a significant role in exoplanet research for the next decade and beyond. RV searches will continue to provide a significant number of exoplanet discoveries needed for statistical studies and understanding exoplanet architectures, to provide the confirmation of transit candidates from ground-based surveys, CoRoT, Kepler, and PLATO, and most importantly to provide targets for future characterization studies.

The RV reflex motion of a star due to a planetary companion is proportional to m_p x $P^{-1/3}$ where m_p is the planet mass and P is the orbital period. Thus the method is most sensitive to planets in orbit at relatively short orbital distances (semi-major axis < 5 AU) to the star. The radial velocity method has detected a planet as light as 1.94 M_{earth} around the M dwarf GL 581e (Mayor et al. 2009) but at a distance of 0.02 AU. Recently, a paper has been accepted (Vogt et al., 2010: arXiv:1009.5733v1) reporting a 3.1 M_{earth} planet orbiting in the habitable zone of GL 581. To date the least massive planet near the habitable zone around a G-type star is 55 Cnc f with a mass of 0.14 M_{Jup} located at a distance of 0.78 AU from its G8 V host star (Fischer et al. 2008).

High precision RV measurements are currently made using two techniques: simultaneous 1) Th-Ar calibration, or, 2) Gas absorption cells (predominantly using molecular iodine).
Both methods produce comparable precision. The iodine absorption cell has a demonstrated RV precision of 1-2 m s^{-1} and the Th-Ar technique exemplified by the High Accuracy Radial Velocity Planet Searcher (HARPS) spectrograph has a precision of better than 1 m s^{-1} (Mayor et al. 2003). The Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO) is an instrument proposed for the Very Large Telescope (VLT) of ESO (Pasquini et

al. 2009) with a key science goal of detecting terrestrial planets in the habitable zone of stars with RV measurements.

A major goal of exoplanet searches is to fill the parameter space of known habitable planets including the detection of Earth-mass planets in the habitable zone of G-type stars. This goal is clearly driven by the solar system paradigm. We want to understand the planetary conditions for life to form and the only known example of a habitable planet is that of an Earth-mass object at 1 AU distance away from a G2 main sequence star. When searching the possible parameter space for habitable planets this is thus an obvious region to explore. To detect such a planet with the RV method requires a precision of about 10 cm s^{-1} over a period of several years. In Fig. 2, the "E" marks the location of an earth-mass planet at 1 AU; the "SE" is for a 5 M_{Earth} planet at 1 AU, which we shall refer to as a "Super-Earth". Currently, the RV method is within a factor of 3 of being able to detect a Super-Earth of 5 M_{Earth} at 1 AU distance from a G-type star, but more than an order of magnitude away from having the precision to detect an Earth analog. Providing that the amount of photons collected from the star is sufficient, there are three limiting factors hindering the method from detecting such planets: 1) Improved wavelength calibration that is needed to achieve an RV error of better than 10 cm s^{-1}, 2) improved instrument stability, and 3) overcoming the intrinsic variability of the star (stellar activity noise). Efforts are currently underway to overcome these problems. Spectrometers based on laser frequency combs have shown promise as an excellent wavelength calibration that may achieve an RV precision of a few tens of cm s^{-1} (Steinmetz et al. 2008). Repeated measurements of stars over a long time span may be able to beat down the intrinsic stellar noise.

Radial velocity measurements of transiting planets taken during a planetary transit (see below) enables astronomers to measure the angle between the spin axis of the star and the orbital axis of the planet through the well known Rossiter-McLaughlin effect (e.g. Winn et al 2005). One of the more unexpected results in the past few years is the discovery that a significant fraction (~40%) of the transiting planets for which the R-M effect has been measured have significantly misaligned orbital spin axes and a large fraction (~20%) are found in retrograde orbits (see Triaud et al. 2010).

3.1.2 Transit Detections

The photometric transit method detects planets by the dimming of stellar light during transit of an orbiting planet through the line-of-sight. The transit signal is proportional to the occulted area of the stellar disc by the planet, and thus depends on the radii of the planet and its host star ($\Delta F \alpha R_p^2/R_s^2$). Transits are the only observations that give us a direct measure of the size of extrasolar planets. The transit geometry also determines the inclination of the planet orbital plane. In combination with radial velocity measurements it allows us to determine the planet mass and to derive the mean planet density. Transiting planets, furthermore, provide targets for detailed planet characterization through spectroscopic observations of their atmospheres during primary and secondary eclipse.

Currently, more than 70 confirmed transiting planets are known. From these, 7 were first detected by radial velocity measurements. So far, transiting planets have been detected by wide-angle transit surveys from the ground (e.g. Super-WASP, HATNet, MEarth, STARE, OGLE) and from space (CoRoT (Europe) and Kepler (U.S.)). A key for a successful transit search is to have high photometric precision since the signal is small (~1% for a Jupiter-size planet and ~0.01% for an Earth-sized planet orbiting a star similar to the Sun). The transit geometry imposes additional constraints on a search. One requires a high number of surveyed target stars to overcome the low geometrical probability of detection due to the transit viewing geometry (the probability of a transit scales as ~1/*a*, with *a* being the semi-major axis), and long-term, continuous observations so as not to miss the short (hours) transit event. Most modern ground-based transit surveys therefore use wide-angle multi-telescope facilities to observe a large number of stars. Networks of such facilities around the globe have been established to overcome data gaps due to the day/night cycle. Recently, the MEarth project (Charbonneau et al. 2008), which targets M dwarf stars, chose another search strategy. Since M dwarfs are sparsely distributed in the sky, a wide-field survey would be very inefficient. Thus the project observes the M star targets sequentially in a one-by-one approach, using multiple robotic telescopes at each site in order to improve efficiency.

Space-based, wide-angle telescopes have significant advantages over the ground-based transit searches. They overcome the limitations posed by the atmosphere and can obtain an excellent photometric measurement precision ($\sigma \sim 10^{-5}$). Just as important they can provide a long string of nearly uninterrupted observations, which is difficult, if not impossible, from the ground even with network facilities. Both of these advantages make space-based telescopes the only effective facilities for the photometric detections of terrestrial-sized exoplanets.

The first space mission searching for planets via transits is CoRoT (CNES), which was launched in Dec. 2006 (Baglin et al. 2009). It was followed by the Kepler mission (NASA), operating since March 2009 (Borucki et al. 2009). CoRoT so far has reported ~ 20 extrasolar planets and several orbiting brown dwarfs. Among these are the first transiting terrestrial planet, CoRoT-7b, and the CoRoT team has succeeded in measureing its basic parameters, (Léger, Rouan, Schneider et al. 2009, Queloz et al. 2009, Hatzes et al., 2010). The second space mission, NASA's Kepler has announced its first 5 planet detections, including a hot Neptune (Borucki et al. 2010). The exquisite photometric precision of these space-based facilities have enabled the first detections of the secondary transit and phase curve at optical wavelengths (Snellen et al. 2009, Alonso et al. 2009, Borucki et al. 2009). Kepler has also managed to measure the asteroseismological signature of the first planet-hosting star (HAT-P7-b, Christensen-Dalsgaard et al., 2010). Both missions are still operating and a steady stream of exciting exoplanet discoveries is expected.

The low geometrical transit probability leads to a detection bias of the transit method towards low orbital distances (Fig. 2). The most distant planet yet detected by transits has been found by CoRoT (CoRoT-9b with 95 day period, Deeg et al. 2010). Space missions clearly allow for the detection of the transiting planets at modestly large orbital distances due to their continuous observations. Kepler, for instance has the goal of detecting transiting planets in the habitable zone (≈ 1 AU) of G stars. It should be able to detect transiting giant planets with periods comparable to the mission length (~3 years).

Current transit searches, both ground- and space-based target relatively faint stars. The median brightness of the host-stars of RV discovered planets is about V = 8 whereas the median V-magnitude of those of exoplanets discovered via the transit method is about V = 11.5. The fainter magnitude range of transit candidates makes spectroscopic follow-up observations challenging.

This problem is more severe with the CoRoT and Kepler missions that produce transit candidates in the V-magnitude range 11–16. Although it is possible to characterise transiting giant planets around stars of this magnitude range, confirming terrestrial-mass planets is considerably more difficult. The PLATO mission under definition study at ESA plans to expand the future search domain by targeting brighter stars that are more conducive for ground-based spectroscopic observations. Its goal is to significantly increase the statistics of confirmed small, terrestrial planets in different stellar environments. Because these stars will be brighter than most transit survey targets the characterization of the planets in terms of their mean density and atmospheric composition will be considerably easier.

Transit planet candidates in stellar light curves always require an extensive follow-up program, since other phenomena like eclipsing binary stars or starspots can also produce a periodic dimming of stellar light. Follow-up observations using high-resolution imaging and photometric observations are needed to confirm the signal on the target star. Medium to large telescopes are finally required to derive the planet mass as well as important fundamental parameters of the host stars. Depending on the size of the potential planet and the brightness of its host star, such follow-up observations can require a significant amount of time at the available telescopes. For example, the confirmation of the first transiting super earth, CoRoT-7b required over 100 radial velocity measurements taken with the HARPS spectrograph (Queloz et al. 2009). In the future, ground-based radial-velocity follow-up could be a bottleneck for terrestrial planet detections via transits, unless sufficient telescope resources to support the ongoing and planned transit space missions can be provided. It became evident in the past successful years of transit searches that every transit survey has to be seen as a project with two, equally important parts: photometric detection of the transit signal and confirmation of a planetary nature of the detected object through determination of the objects mass.

3.1.3 Astrometric Detections

The existence of extrasolar planets can be inferred from observations of their parent stars orbiting the common center of mass. This is the foundation of both the radial-velocity and the astrometric methods. Whereas the radial-velocity technique detects the radial component of the orbital motion, astrometry measures the two coordinates in the plane of the sky. From these two-dimensional data, the planet's mass can be determined without sin i ambiguity.

The Earth's atmosphere imposes serious limitations on the precision that can be achieved with astrometric measurements from the ground. These can be overcome if pairs of stars that are close to each other on the sky are observed simultaneously. The development of such narrow-angle astrometric techniques, in particular with long-baseline interferometers, will soon enable measurements with a precision of a few tens of microarcseconds (Shao & Colavita 1992, Quirrenbach et al. 1998, 2004). The PRIMA instrument at the VLTI will begin a large planet survey in the course of 2011.

A number of successful exoplanet observations have been conducted with the fine guidance sensors (FGS) of the Hubble Space Telescope (e.g. GJ876 b, Benedict et al. 2002; ε Eri b, Benedict et al. 2006). The astrometric orbits of the two outer planets in the υ And system have also been determined with the FGS (McArthur et al. 2010). The mutual inclination i_{mut}=30° between these planets has been determined from a combined fit to the astrometry and an extensive set of radial-velocity measurements. This provides an important input for dynamical models of the system, and shows that modeling based on the assumption of co-planarity can miss crucial aspects of the dynamical behavior.

As the field of extrasolar planets is progressing towards a physical characterization of the discovered planets, astrometry is coming into focus as the only technique that can yield the most fundamental parameter of a planet, namely its mass. (Except for the small fraction of all planets that transit their parent stars, in which case the mass can also be determined from the transit geometry and radial velocities.) Without knowing the mass, one cannot get a handle on the bulk composition or surface gravity, which introduces enormous uncertainties into the analysis of spectroscopic data. Astrometry must therefore be an important component of any comprehensive strategy for the characterization of nearby Earth-like planets. As an added benefit, an astrometric survey of the solar neighborhood could provide the targets for a spectroscopic mission.

The astrometric detection of Earth analogs requires a precision of better than 1μas, which can be achieved with a space-based interferometer. In fact, a survey with such an instrument is the only proven method at this time with which a census of Earth-like planets in the close solar neighbourhood could be conducted. This was one of the main scientific drivers for NASA's Space Interferometry Mission (SIM Lite), which was under development at JPL (Goullioud et al. 2008). It would have employed a demonstrated astrometric precision of 1 μas and a noise floor under 0.1 μas to take time series of astrometric measurements of the nearest about 60 F-, G-, and K-type stars during a five-year mission to detect the ~0.3 μas amplitude induced by a benchmark Earth-mass planet orbiting in the habitable zone (1 AU) about a solar-mass star at 10 pc. SIM Lite could have detected rocky planets in a broad range of masses and orbital distances, and measure their masses and three-dimensional orbital parameters, including eccentricity and inclination, to provide the properties of terrestrial planets in general. However, SIM-Lite was not chosen as a high priority mission by the U.S. Decadal review. An astrometric mission with a targeted approach to astrometric searches may be able to achieve the exoplanet science goals of SIM-Lite but at lower cost.

3.1.4 Imaging Detections

The attempt to image directly an extrasolar planet was undertaken as soon as their existence was proven in 1995. Facing large contrasts and small separations was at the time considered a showstopper for current instruments motivating the development of new technologies. In reflected light, the terrestrial planets of our Solar System can be 10^9 to 10^{10} times fainter than the Sun, while angular separation would be a fraction of an arc-second for a star in the solar neighborhood. However, theoretical work on evolutionary models has demonstrated that these characteristics are much more relaxed for young systems since such planets will be self-luminous (e.g. Burrows et al. 1998). Since the intrinsic light from the planet is independent of the orbital distance these systems can be searched farther from the star than exoplanets that shine predominantly from reflected light. The first successful direct images of extrasolar planets were obtained in 2005 at VLT for GQ Lupi

(Neuhäuser et al. 2005) and 2M1207 (Chauvin et al. 2005). Both host stars are young, very low mass stars. Since then, several detections of low mass objects have been made in young (1-700 Myr) systems with 8-10m class telescopes on the ground and using the HST. Most objects detected this way have masses of 5 to 10 times that of Jupiter and could be planets (some are yet unconfirmed). As shown in Fig. 3, error bars on the mass can be large due to uncertainty in the age of the systems. The mass itself is derived from evolutionary models, which are lacking calibrations at low masses and young ages. This may place some detected objects either in or out of the planetary regime. A single image is only able to measure the projected separation, but additional measurements can eventually lead to a full characterization of the orbital parameters. Recently, orbital motion has been detected for the planetary companions to Fomalhaut (Kalas et al. 2008), HR 8799 (Marois et al. 2008), and β Pic (Lagrange et al. 2010). Orbital distances that can be probed are quite large so far (tens of AUs) due to the bias of the detection method (see Fig. 3) while at the same time young systems are relatively distant except for a few cases (β Pic for instance).

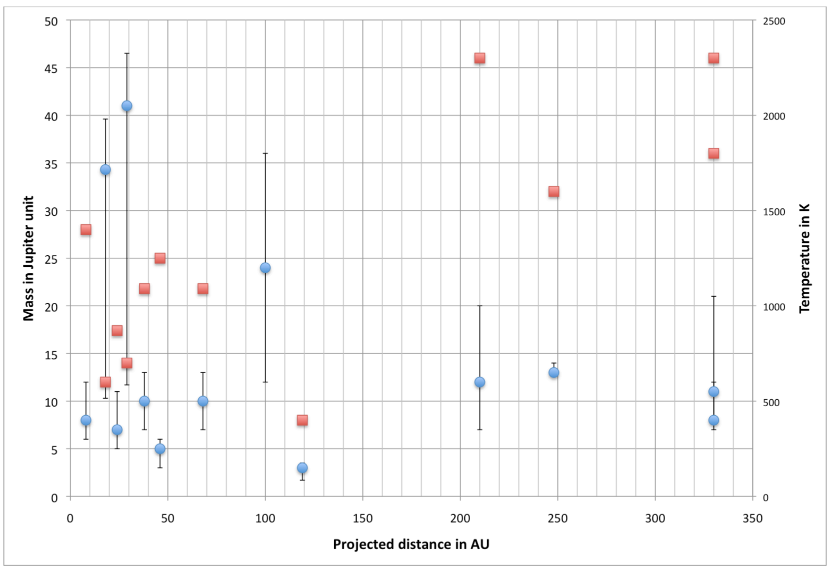

Figure 3. Estimated mass (blue dots) and temperature (red squares) vs. separation diagram of young planet candidates found by direct imaging. Objects significantly more massive than planets have been included because unconstrained parameters (like age) can still place them in the planetary regime. Error bars are shown for the mass estimates.

As what concerns spectral characterization, some of these planets have been observed in several broadband filters (mostly in the near IR), which allow us to measure colors and derive effective temperatures. For the brightest and farthest from their star (2M1207 b, AB Pic b, RSX 1609 b) some spectra in the H and/or K bands show mostly H_2O absorptions. These objects are sharing the same properties with L and T type (Brown dwarf) stars.

Another interesting point is that the latest imaging detections (of HR 8799 b, c, d, Fomalhaut b, β Pic b) were made of objects orbiting massive A-type stars with circumstellar disks suggesting, as suspected, that more massive stars tend to form more massive planets. This result is consistent with those of RV surveys of intermediate mass evolved stars (Setiawan et al. 2005: Döllinger et al. 2009: Niedzielski et al. 2009; Johnson et al. 2010: Bowler et al. 2010). Direct imaging allows us to study exoplanets at very large orbital distances that may have formed in a different way either by "core-accretion", or gravitational disk instabilities. For instance, it is very likely that most planets in the Fig. 3 and 4 have been formed like stars (gravitational disk instabilities), while β Pic b could be the first detected object formed as "a planet" since it is located at a distance that is compatible with the core-accretion model.

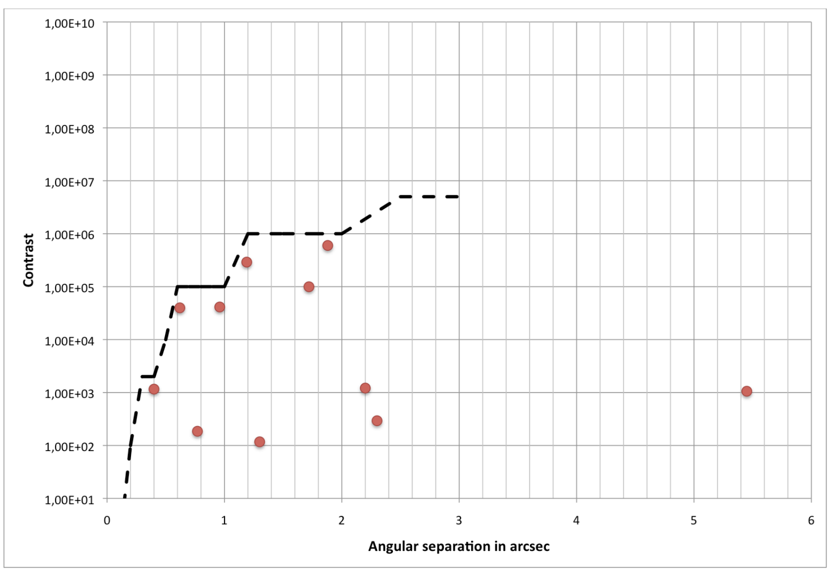

Figure 4: Measured contrasts of young planet candidates found by direct imaging. The dotted line is illustrative of the detection limit with current instruments

3.1.5 Microlensing

Exoplanet detection via gravitational microlensing is a relatively new method (Mao and Paczynski 1991, Gould and Loeb 1992). If a foreground object (star, free floating planet, black hole) passes very close to the line of sight to a background star, the 'source', then the gravity of the foreground object acts as a lens. The result, as the projected separation on the sky between source and lens changes, is a characteristically shaped brightening and fading of the source star on a time-scale of a month. If a planet orbits the (not necessarily seen) foreground 'lens' object, its gravity can affect the light rays as well, causing a short deviation from the otherwise symmetric light curve. The duration of these deviations depends upon the mass of the planet - days for a Jupiter mass and hours for an Earth mass.

The outstanding feature is that the microlensing effect does not rely on detecting photons from the host star let alone the planet. This leads to it being able to find and measure the mass and separation (occasionally even orbits) of a wide mass range of planets, at separations ranging from the habitable zone outward (including free floating planets), around any type of host star. The sensitivity to different types of host stars depends upon their relative abundance, with M stars being most common and objects like black holes being very rare. Generally distant (> 1 kpc) and hence very faint host stars are probed. Even planets in other galaxies can be detected (Covone et al. 2000).

So far 10 exoplanets have been published by this method (with at least 7 more detections being in preparation). While this number is relatively modest compared with that discovered by the radial velocity method, microlensing probes a part of the parameter space (host separation vs. planet mass) not accessible in the medium term to other methods. The mass distribution of microlensing exoplanets has already revealed that cold super-Earths (at or beyond the snow line and with a mass of around 5 to 15 Earth mass appear to be common (Beaulieu et al. 2006, Gould et al. 2006, Sumi et al. 2010). A half-scale model of our solar system has been detected (Gaudi et al. 2008, Bennett et al. 2010), several hot Neptune's/super earths, showing that the detection efficiencies extends to 1 Earth mass planets (Batista et al. 2009). Microlensing has made the first measurement of the frequency of ice and gas giants beyond the snow line, and has shown that this is about 7 times higher than closer-in systems probed by the Doppler method. This comparison provides strong evidence that most giant planets do not migrate very far (Gould et al. 2010).

Microlensing is currently capable of detecting cool planets of super-Earth mass from the ground (and under favourable circumstances down to 1 Earth mass). In order to improve the discovery rate and the overall efficiency, the microlensing networks are currently going through a transition to utilizing wide-field imagers (Gaudi et al. 2009). The advantage is that the survey telescopes can provide the high cadence observations needed to detect and follow anomalies. These new networks will eventually reach the limits of what is possible from the ground. The sensitivity of ground-based microlensing campaigns is governed by angular resolution. To probe to lower masses, and into the habitable zone, will require a space mission. A space-based survey (Bennett et al. 2008, Beaulieu et al. 2010), could provide a complete census of planets down to Earth mass with separations exceeding 1 AU and complementary coverage to that of Kepler in terms of the planet discovery space, as well as sensitivity to planets down to 0.1 M_{earth}, including all Solar System analogs except for Mercury. A space-based mission would also provide complete lens solutions for most planet events, allowing direct measurements of the planet and host masses, as well as the distance from the observer. There is a great potential opportunity for such a survey to be carried out as a secondary science objective on a dark energy mission such as Euclid (Refregier et al. 2009, 2010). If Euclid is selected, a 3-month microlensing program (Beaulieu et al. 2010) will already efficiently probe planets down to the mass of Mars at the snow line, as well as free-floating terrestrial or gaseous planets and habitable Super-Earths. A 12+ months survey, towards the end of the mission, once the cosmological objectives would have been reached, would give a census on habitable Earth planets around solar-like stars.

3.1.6 Timing detections

It is also possible to detect planetary companions to stars by searching for timing variations of periodic phenomena associated with the star that can act as a stable "clock". If the star hosts a planetary companion, there will be slight variations in the observed maximum of the periodic phenomenon caused by differences in the light travel time as the star orbits the barycenter of the star-planet system. In fact, the first exoplanets discovered, the planets around neutron stars, used the timing variations provided by the clock of a milli-second pulsar (Wolszczan & Frail, 1992).

Timing variations of stellar oscillations can also be used to detect the presence of planetary companions. Silvotti et al. (2007) used timing variations in the pulsations of the extreme horizontal branch star V391 Peg to infer the presence of a 3.2 M_{Jup} planet at 1.7 AU from the star. Because V391 Per is on the horizontal branch the planet must have survived the red giant expansion phase of the star. Mullally et al. (2008) used timing variations of oscillating white dwarfs to search for planetary companions, but with no confirmed detections although one white dwarf, GD 66 looks promising for hosting a giant planet.

Eclipsing binary stars can also be used to search for timing variations in the eclipses caused by planets either around on companion, or circumbinary planets. Planetary companions found by timing variations have been claimed for the eclipsing binaries HW Vir (Lee et al. 2008) and DP Leo (Qian et al. 2010). Timing variations due to additional bodies can also be searched for in the light curves of transiting planets. This has been done for some CoRoT transiting planets with no detections (Bean 2009, Csizmadia et al. 2010). Timing variations of transits can also be used to search for additional planets to known transiting planets. Recently, Maciejewski et al. (2010) claimed the discovery of a 15 earth-mass planet in a 2:1 resonance around WASP-3 detected via transit timing variations.

3.2 Characterization

3.2.1 Fundamental Planetary Parameters (Mass, radius, density, internal structure, orbital parameters)

For a basic characterization of extrasolar planets it is essential to derive their fundamental parameters: radius (R), mass (M), density (ρ) and orbit. The former three determine the overall nature of a planet (e.g. gas giant, Neptune-like, terrestrial) and give us the first insights into their interior structure (Figure 5). The planetary orbit determines the dynamical evolution of the planet and the energy it receives from its host star. Examples of the understanding of planetary nature that we already have gained from the fundamental planet parameters mentioned above include, for example, the study of hot gas giants with expanded atmospheres and the mean composition and internal structure of terrestrial super-Earth planets.

In particular for terrestrial planets studying their interior is challenging. Numerical models of planetary interiors using laboratory data for material properties are aimed at improving the general understanding of the origins, evolutions, and current states of planets. In the case of the terrestrial planets and satellites within the solar system the resultant radial profiles of density and related material properties are required to be consistent with geophysical observations and cosmochemical evidence for the likely compositions of crust, mantle and core as obtained from measurements by interplanetary space probes. For terrestrial exoplanets, the numerical models have to be consistent with the observed planetary masses and radii measured. Models can be used to derive mass-radius relationships for exoplanets assuming a range of different mineralogical compositions in order to gain insight in the interior structure and possible bulk compositions of these planets. Furthermore, obtaining scaling laws for key physical and chemical properties will be essential for a better understanding of global planetary processes controlling the general evolution of a planetary body and its astrobiological potential to be life sustaining.

The fundamental parameters radius, mass and density can be determined by combining a detection method determining their mass (e.g. radial velocity which is the most successful today) with the transit method providing the size of the object. The detection of a significant number of transiting planets, therefore, has been a major step forward to the field of comparative planetology. For the majority of planets, which do not transit their parent stars, astrometry is the only technique that can determine their mass. In the future, comparative planetology will enable us not only to compare different types of planets to those in our solar system, but also to compare similar type planets that are in different environments and in different evolutionary stages. We have taken the first tentative steps towards opening this exciting new research area. Looking back at the enormous surprises we already had when detecting exoplanets in all kinds of unexpected configurations (hot giant planets, large eccentricities, large inclinations, etc.) we should not underestimate the scientific impact of increasing the sample of planets with known prime parameters.

An important near future goal is therefore to expand, within current technological and financial constraints, the range of planets with known fundamental parameters towards smaller planet sizes. The fundamental planet parameters must be known with a sufficient accuracy before statistics and comparative planetology on a larger scale can be made. It is therefore crucial to develop and maintain photometric facilities that allow us to determine planet radii, especially for small, terrestrial planets discovered in the future. This goal requires wide-field transit detection surveys providing high detection statistics for bright stars, but also photometric facilities with sufficient observing time allowing for a one-by-one transit search approach. Spectroscopic facilities should also be maintained that can provide us with the planetary mass. These facilities are also important for an accurate determination of stellar parameters that form the basis for determination of the planet parameters.

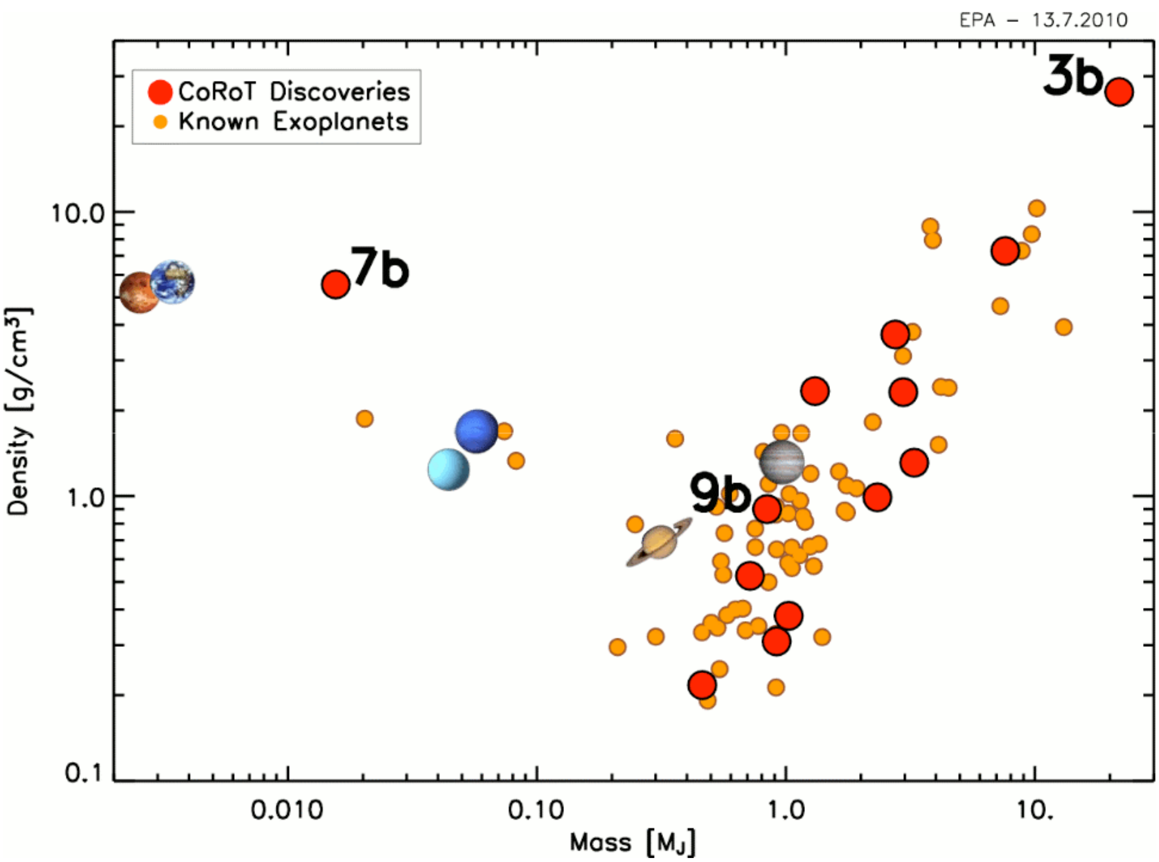

Figure 5: Density versus mass of known transiting planets.

3.2.2 Atmospheric Characterization (composition, albedo, thermal structure, biomarkers)

Spectroscopic measurements of the atmospheres of extrasolar planets are a key tool towards understanding the planetary composition, formation and evolution, and will eventually lead to identification of chemical biosignatures. For a growing sample of giant/Neptune-size exoplanets orbiting very close to their parent star, we can already probe their main atmospheric constituents using transit techniques. With the primary transit method, we can indirectly observe the thin atmospheric annulus surrounding the optically thick disk of the planet -the limb- while the planet is transiting in front of its parent star. The use of transmission spectroscopy to probe the outer layers of transiting hot exoplanets has started in the visible spectral range from space with the Hubble Space Telescope and the ground (Charbonneau et al. 2002; Redfield et al. 2007, Snellen et al. 2008) and only more recently the technique was applied in the Near and Middle Infrared spectral window, producing novel and interesting results (Tinetti et al. 2007, 2010; Swain et al. 2008). Transmission spectra are sensitive to atomic and molecular abundances and less to temperature variation. Temperature influences the transmission spectrum by way of its impact on the atmospheric scale height (Brown 2001) and the absorption coefficients of the molecules present.

In the secondary transit technique, we observe first the combined spectrum of the star and the planet. Then, we take a second measurement of the star alone when the planet disappears behind it: the difference between the two measurements consists of the planet's contribution. Two different teams pioneered this technique in 2005, using the Spitzer Space Telescope (Deming et al. 2005; Charbonneau et al. 2005) and then used successfully from space and the ground. In the infrared spectral range, with this technique we can not only detect the molecular species showing a noticeable rotational/vibrational signature (Grillmair et al. 2008; Swain et al. 2009a,b; Swain et al. 2010), but also constrain the bulk temperature and the thermal gradients (Knutson et al. 2007, 2008; Burrows et al. 2007; Swain et al. 2009b). Compared to transmission spectroscopy, emission spectroscopy may scan different regions of the atmosphere for molecular signatures and cloud/hazes contributions. The same considerations are valid in the UV-visible spectral range, except that the photons reflected by the planet do not bring any information about the planetary temperature and the thermal structure, but instead about the planetary albedo (Rowe et al. 2006) and the presence of atomic/ionic/molecular species having electronic transitions.

Monitoring the light-curve of the combined star-planet spectrum can be a useful approach both for transiting (Knutson et al. 2007, Snellen et al. 2009; Borucki et al. 2009) and non-transiting planets (Harrington et al. 2006). In the latter case the planetary radius cannot be measured, but we can detect temperature or albedo variations with time (depending if the observation is performed in the visible or infrared).

The problems that we can tackle with current instrumentation are:

- Detection of the main molecular species in the hot transiting planets atmosphere (water vapor, methane, CO2, CO, ammonia etc.).
- Constrain the horizontal and vertical thermal gradients in the hot exoplanet

atmospheres.
- Detect the presence of clouds or hazes in the atmospheres.

Today we can use two approaches to reach these objectives: (a) Broadband or low resolution spectroscopy from a space based observatory. This can be accomplished by SPITZER, HST, MOST, CoRoT, Kepler. (b) High resolution spectroscopy from ground based observatories in the optical and NIR down to 5 microns. The next steps with these indirect techniques will be:

- Detection of minor atmospheric species and constraint of their abundance.
- More accurate spectral retrieval to map thermal and chemistry gradients in the atmospheres.
- Cloud microphysics: understanding the composition, location and optical parameters of cloud/haze particles.
- Cooler and smaller planets. With current telescopes we can already approach the case of hot super earths transiting bright, later type stars, e.g. Gliese 1412b (Charbonneau et al., 2009).

However, there are many more exoplanets known, although they do not transit or they orbit at large separation from their parent star. It is thus impossible to study these with the transit technique. Most recently the first spectrum of a hot giant planet at a projected separation of 38 AU from its host star was observed from the ground with VLT/NACO (Janson et al. 2010). Spectroscopy in the shorter wavelength range of YJHK-band will likely start soon with dedicated integral field units on VLT (SPHERE) and Gemini (GPI). The young exoplanets that these instruments are expected to find and characterise are likely to feature several molecular species, mostly methane, ammonia, and water. Near IR observations will also be sensitive to dust and possibly clouds in their atmosphere.

3.3 The solar neighborhood: Understanding our Sample

The characterization of exoplanets, including terrestrial ones will be restricted to nearby stars, so it is important to know what the solar neighborhood offers us in terms of stellar samples. The choice of the stellar samples to be observed depends on the specific questions to be addressed. For example, statistical studies, which require unbiased samples, will be based on a large number of stars, randomly selected, regardless of their magnitude or distance. On the contrary a program with the goal of determining planetary structure will be based on bright stars for which it is possible to measure masses through radial velocity measurements and for which stellar parameters may be well determined. Orbital parameters may be derived for nearby systems, whereas imaging of the planetary system will be possible. Finally, planetary atmospheric measurements will be focused on nearby and bright objects, in order to maximize the planetary signal and the signal to noise simultaneously. In light of the above considerations it is clear that a good knowledge of stellar populations in the solar neighborhood is necessary. The stellar composition of a given sample depends on the stellar luminosity function, on the mass-luminosity relation and on the limiting factors of the specific survey.

In a volume-limited survey the number of dwarf M stars (dM) stars overwhelms the number of larger mass stars. However dM stars are intrinsically faint, making them difficult to be observed. On the contrary, in a magnitude-limited sample the volume accessible is larger for bright stars, making such samples dominated by stars intrinsically bright, and detectable at large distance. The solar neighborhood (here defined as the volume in a radius of 300 pc) is mainly populated by main sequence stars, thus in the following we will consider only dwarfs. Using the luminosity function of main sequence stars in the solar neighborhood derived from Hipparcos (Kroupa 2001), we may derive the apparent magnitude distribution of dwarfs within 300 pc in different ranges of mass as represented in Fig. 6 (left panel). Intrinsically, the bright star distributions flatten because we have imposed a maximum distance of 300 pc, while the faint stars number increases with a power of 1.5. Analogously, for comparison, the right panel shows the apparent magnitude distribution of stars within 30 pc, that give the number of stars accessible for characterization studies. Given the smallest distance we are using the distributions flatten at brightest apparent magnitudes.

The magnitude distributions derived above are based on the average luminosity function in the solar neighborhood. The true stellar distribution includes local fluctuations. This is especially true in the 300 pc volume samples. For example, within this volume a number of star forming regions and young stars (e.g. the Gould Belt population) are present. These young nearby stars are of considerable interest for the study of the planetary systems formation mechanisms.

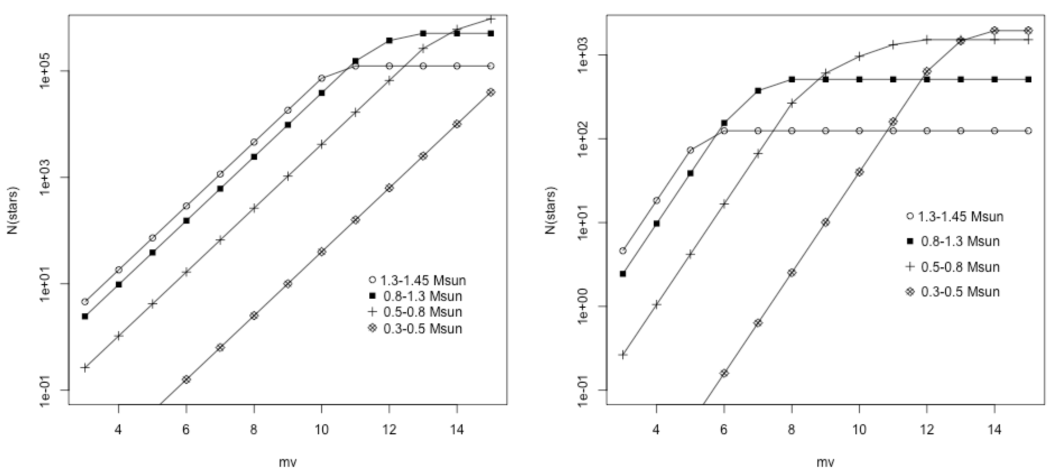

Figure 6: Number of solar-like stars in four mass bins as function of apparent magnitude expected in the solar neighborhood in a volume of radius of 300 pc (left) and of 30 pc (right).

3.4 Theory: News on the Evolving State of the Art

The long-lasting scientific debate on whether extra-solar giant planets form by gravitational instability or by core-accretion is finally settling down. Gravitational instability seems to be effective only in the distant regions of the disk, say beyond 50-100 AU (Boley 2009), where the disk cools rapidly. It is still unclear, though, whether the end product of gravitational instability can be a giant planet or must be a more massive brown-dwarf-mass object (Stamatellos and Whitworth 2008). The planets found at large distances from their parent stars (HR 8799 - Marois et al., 2009; Fomalhaut - Kalas et al., 2009) are not necessarily the result of the gravitational instability process: they might also be giant planets formed closer to the star by core-accretion, which subsequently achieved large orbital distances through planet-planet scattering (Veras et al. 2009) or outwards migration (Crida et al. 2009).

Although now largely favored by the community, the core-accretion model has its own unsolved problems. It is generally expected that the giant planets cores formed by runaway/oligarchic growth. Levison et al. (2010), however, have showed that this expectation is naive: When the cores reach ~1 Earth mass, they start to open gaps in the planetesimal distribution and their growth slows down substantially. Migration of the proto-cores relative to the planetesimal disk does not help in most of the cases, because planetesimals are trapped in resonances with the cores, which prevents their accretion. Thus, the rapid formation of ~10 Earth mass cores, as invoked in the standard model of giant planets formation, is not trivial. It probably requires processes not accounted for in most simulations. An interesting idea has been proposed by Lyra et al. (2008, 2009), according to which the cores of the giant planets could form by the gravitational instability of a population of meter-sized boulders, concentrated into very large density clumps inside long-lasting vortices.

On the other hand, what was considered to be the main problem of the core-accretion model seems now to be alleviated. In fact, several mechanism preventing type-I migration of the cores into the star have now been found. After the role of turbulence (Nelson 2005) and that of planet traps (Masset et al. 2006), the last proposed mechanism, and probably the most relevant one, is that of migration reversal in the inner part of disks with inefficient cooling (Paardekooper and Mellema 2006; Paardekooper and Papaloizou 2008; Baruteau and Masset 2008; Kley and Crida 2008). This mechanism has the advantage of concentrating planetary embryos in the central part of the disk, which might favor their mutual accretion and the formation of a few giant planet cores.

Some progress has been made on the evolution of giant planets in gas disks, but important problems remain open. Giant planets (defined here as planets massive enough to open gaps in the gas distribution of the disk) migrate towards the central star by Type-II migration. This process explains the existence of the hot Jupiter's in a natural way, but poses the problem of why in our solar system and in many extra-solar systems there are giant planets at several AUs from the central star. So far, the only mechanism that has been found to prevent Type II migration is the interaction of two giant planets in resonance with a specific mass hierarchy: the outer planet needs to be from about one quarter to one half of the mass of the inner planet (Masset and Snellgrove 2001; Morbidelli and Crida 2007). In all other cases, the presence of giant planets at several AUs from their parent star is explained by invoking the timely disappearance of the proto-planetary disk. The disappearance of the disk is also invoked to explain the large range of masses of exoplanets, because, in theory, the self-limitation of the accretion process due to gap opening should become operational only around 5-10 Jupiter masses.

As both Type II migration and the runaway accretion of massive atmospheres are very rapid processes, it seems surprising that disks may disappear at the right time to explain the wide range of orbital radii and masses observed. However, the so-called "planet population synthesis models" (Ida and Lin 2005, 2008; Mordasini et al. 2009), which simulate the competition between planet migration, planet growth and disk evolution/evaporation, do reproduce fairly well the observed distribution of extra-solar planets in terms of mass and orbital radius. It is true, though, that this result is achieved by tuning the synthetic recipes for planet growth, migration, disk evolution etc. and it is unclear whether these tuned recipes have any pertinence with reality. For instance, the growth process of the planetary cores implemented in the planet population synthesis models is refuted by the N-body simulations by Levison et al. (2010). It may be possible that the need to invoke the timely disappearance of the disk to explain observations just hides our ignorance of basic processes. For instance, for years it was believed that the migration of a pair of planets in resonance forces the indefinite growth of the eccentricity of the inner planet, eventually leading to an orbital instability (Kley et al. 2005). So, the existence of stable pairs of resonant planets on orbits with moderate eccentricities, like in the system of GJ 876, was explained by invoking the disappearance of the disk soon after the capture of the two planets in their mutual resonance. However, Crida et al. (2008) later showed that the inner part of the disk, artificially removed in the previous simulations because of numerical limitations, has a strong damping effect on the eccentricity of the inner planet. If its action is taken into account, an equilibrium eccentricity can be achieved, consistent with the observations of the GJ 876 system.

There is a dominant consensus that the large orbital eccentricities of the extra-solar planets have been achieved by planet-planet scattering and not by planet-disk interactions. The latter may excite eccentricities of massive planets (larger than 3-5 Jupiter masses), but not enough to explain at least some of the observed values (D'Angelo et al. 2006; Kley and Dirksen 2006). Conversely, planet-planet scattering seems to be able to generate, in a natural way, the observed eccentricity distribution of extra-solar planets (Juric and Tremaine 2008; Chatterjee et al. 2008). It is clear, though, that scattering alone cannot explain the semi-major axis distribution. Thus, a combination of migration and scattering is necessary to explain the orbital distribution in both semi major axis and eccentricity (Moorhead and Adams 2005). Whether planets first acquire large eccentricities, and then migrate or the opposite, is still unknown.

Concerning the physical structure and evolution of giant planets, thanks to the more than 70 objects detected in transit, constraints on the global composition have been derived and point towards masses of heavy elements (possibly core masses) that vary between ~0 and 100 Earth masses and are positively correlated with the metallicity of the parent star (e.g. Guillot 2008). However, the thermal evolution of these planets is still incompletely understood, with evidence of a missing physical mechanism responsible for an abnormal inflation of most of the close-in planets (the most anomalously large being presently CoRoT-2b, WASP-12b, TrES-4b). At the same time, the discovery of Uranus-type planets (GJ 436b, Kepler-4b, HAT-P-11b) and super-Earths (CoRoT-7b, GJ 1214b) has brought the field into the study of planets that are not dominated by hydrogen and helium. The question of the composition and structure of these objects is even more complex than for the giants, as the degeneracy in possible compositions (hydrogen and helium, volatiles, rocks, iron) is larger (e.g. Valencia et al. 2007; Miller-Ricci et al. 2009). On the front of terrestrial planets, several studies have focused on the dependence of their accretion process on the architecture of the pre-existing giant planets system. If the giant planets are on distant, quasi-circular orbits, a system of several terrestrial planets with moderate masses forms in the inner region, like in our solar system; if a giant planet is very eccentric, then typically only one terrestrial planet forms, also on a very eccentric orbit (Levison and Agnor 2003; Raymond 2006; Raymond et al. 2006a). The migration of a giant planet towards the central star favors the formation of a "hot" terrestrial planet in one of its interior resonances; moreover, one or more terrestrial planets can form in the temperate region of the disk, after the migration of the giant planet (Fogg and Nelson 2005, 2007; Raymond et al. 2006b). It is still unclear whether "super-Earths" formed rapidly, like giant planets cores, and moved close to the star by Type I migration, or they formed in situ like terrestrial planets, by the collision of planetary embryos on a 10-100My timescale. An attempt to combine accretion and migration in a N-body simulation failed to produce super-Earth more massive than 8 Earth masses (McNeil and Nelson 2010).

4 The Facility Landscape

Figure 7 shows the current and planned major facilities that can be used for exoplanetary studies. Not shown are ground-based 8-10m class telescopes. These facilities as well as their instrumentation are listed in the Appendix.

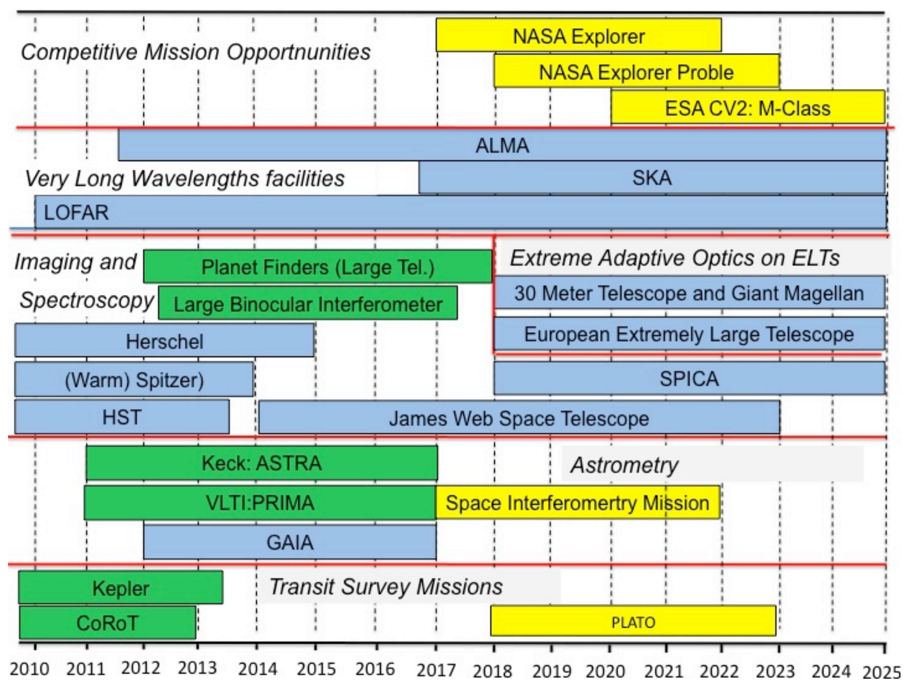

Figure 7. Timeline of current and planned large facilities. Green indicates facilities that are primarily used for exoplanet studies (based on a figure by Peter Lawson). Note: In August 2010 the U.S. Decadal Report did not support SIM(-Lite). Currently there is no proposed astrometric space mission for the time frame > 2017.

5 The Exoplanet Roadmap

5.1 Goals and Key Questions

The goal of this roadmap is to perform comparative planetology of a wide range of planetary systems including planets down to the terrestrial mass regime in the habitable zone of F-M dwarf stars. Although detections are an important step, in order to perform comparative planetology these detections should also lead to the characterization of the systems. We should note that "planetary systems" are not merely stars with multiple planets. Drawing from the solar analogy a planetary system includes terrestrial planets, giant planets, asteroids and minor bodies, trans-Neptunian-like objects, comets, debris disks, zodiacal dust, etc. Clearly for exoplanetary systems some components are easier to study than others
The major components of this roadmap are:

1. Detections: Completing the mass to semi-major axis parameter space and understanding the architecture of extrasolar planetary systems.
2. Characterization of internal structure: mass, radius, and mean density.
3. Characterization of atmospheres: temperature, albedo, composition and including biosignatures.

The key questions to be answered by this roadmap (in order of difficulty) are

KQ1: What is the diversity and architecture of exoplanetary systems as a function of stellar parameters and birth environment?
KQ2: What is the diversity of the internal structure of exoplanets?
KQ3: What is the diversity of exoplanetary atmospheres?
KQ4: What is the origin of the diversity and how do planets form?
KQ5: What are the conditions for planet habitability, how common is exo-life and can we detect the biosignatures.

Rather than dividing our roadmaps into discrete time intervals with fixed boundaries we chose to define the roadmap chronology broadly in terms by short-, mid-, and long-term goals. The reader should keep in mind that there could be significant overlap between the three intervals:

Near term: ~2011-2017
Mid-term : ~2015-2022
Long-term: ~2020 and beyond

As with weather forecasting, our near term assessment of the roadmap is good and extensive – we know the current status of the field and the direction it is currently taking. Our mid-term assessment is less clear and not as extensive – we have a general idea where we would like the field to be in the next 10 years. Our long-term assessment is the least clear – the status of the field will depend on discoveries not yet made and technologies not yet developed. As with most roadmaps this one should be outdated in 5 years. If not, the field would have lost its vibrancy. The progress and rate of discoveries for the field of exoplanets is so fast that a future task force, in say 5 years should meet and access if any "mid-course corrections" are needed in our roadmap. One should keep in mind when reading this roadmap, that the members of the EPRAT not only bring their expertise, but also their respective biases. To the best of our abilities the EPRAT tried to make dispassionate and unbiased recommendations as far as possible.

For each time interval we divide our recommendations into three categories:

1. Ground: Recommendations directed to ground-based efforts.
2. Space: These are recommendations directed primarily to the community.
3. Technology: Recommendations directed to ESA, the community, and industry.

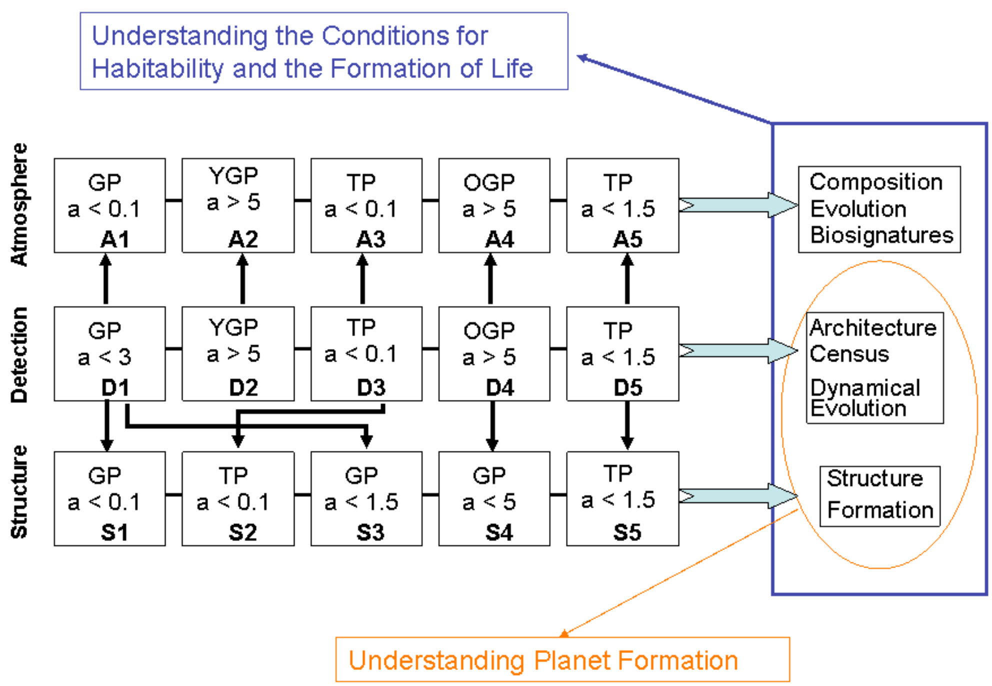

Figure 8. Schematic of how the key recommendations fit into the basic themes of the Roadmap: Detection, Structure, and Atmospheres of exoplanets. Key: GP = giant planets, YGP = young giant planet (age less than 100 million years), OGP = old giant planets (age > few Gyears), TP = terrestrial planets (mass = 1–5 M_{Earth}). Orbital semi-major axis, *a*, is in AUs. Although chronologically "Detections" are first, we show these in the middle of the diagram because they "feed" characterization studies.

Figure 8 schematically shows the inter-relationship between the respective milestones of Detections, Structure, and Atmospheres. Table 1 indicates how our specific recommendations fit into the overall roadmap of "Detections, Structure, and Atmospheres". Note that an important goal of detections is to provide targets for further characterization studies. The last region of the "parameter space" that will be filled is the detection and characterization of terrestrial planets out to 1.5 AU (last column), the nominal outer limit of the habitable zone for a G-type star. At the end of our Roadmap "Detections" will have given us a better understanding of the census and architecture of exoplanets as well as their dynamical evolution. "Structure" studies will have given us knowledge of the internal structure of the planet. Together with detections the internal structure of exoplanets are important for understanding the process of planet formation. "Atmospheric" studies tell us the atmospheric composition and by studying exoplanets in different stages of evolution, the time variation of the exoplanet atmosphere. These studies may also provide us with evidence of biosignatures. All studies are needed for understanding the conditions for a planet to be habitable and to form life.

	Detections (**D**)	Structure (**S**)	Atmosphere (**A**)
1	OG1, OG4, NG5, NS2, NS6, NT3, MT1, LG1, LS1	OG3, OG1, OG5, NG1, NG6, NS1, NS2, MS4	OG3, OG5, NG4, NS1 NS2, NS3, NS4, NT2, NT3, MS1, MS2, MS5
2	NG8, NG9, NS5, NT3, MG3, MS3, MS6, MT1, LG1, LS1	NG6, NG9, NS1, NS2, MG1, MS2, MS4	NG8, NG9. NS4, NS5, NT2, NT3, MG2, MG3, MS1, MS5, MT1
3	NG2, NG3, NG5, NS2, MG2, MS3	NG2, NG3, NG6, NS1, NS2, MG1	NG2, NG3, NG4. NG11, NS1, NS2, NS3, NS4, NT1, NT3, MS1, MS2, MS5
4	NG7, NG8, NG9, NS5, NS6, NT3, NG3, MS2, MS3, MS6, MT1, LG1, LS1	NG9, MS4	NG8, NG9, NS4, NS5, NT2, NT3, MG3, MS1, MS5, MT3
5	NG3, NG5, NG7, NG10, NS2, NS6, NT1, NT2, NT3, MG4, MS2, MS6, MT1, LS2, LS3, NG6	NG3, NG6, NS2, MG1, MS2, MS4	NT3, NG11, NS2, NS4, NS5, NT2, NT3, MG4, MS2, MS5, MS6, MT1, LS2, LS3

Table 1. Relationship of our roadmap recommendations with the roadmap milestones shown in Fig. 8.

The major goals of "Detections" are:

- Census.
- Architecture.
- Targets for characterization studies.

The major goals of "Structure" are:

- Mass-Radius relationship for exoplanets down to terrestrial mass.
- Internal structure models of exoplanets (requires good precision in mass and radius determination).
- Input for formation and evolution models.

The major goals of "Atmospheres" are:

- Composition of young and old giant planet atmospheres.
- Composition of terrestrial planet atmospheres.
- Evolution of exoplanet atmospheres.
- Bio-signatures and habitability.

5.2 On-Going recommendations

There are a few recommendations for work that should be on-going throughout the roadmap and with no specific time boundaries. These include radial velocity surveys, ground-based transit studies, and theoretical work.

OG-1 *Continue and expand radial velocity searches among several thousand nearby F-K main sequence stars and evolved, intermediate mass stars using optical spectrographs.*

Over 15 years since RV surveys provided the first extrasolar planet discoveries it continues to play a dominant role in the field and will continue to do so in the foreseeable future. These RV surveys should continue throughout the course of this roadmap. A continuing survey of several thousand stars will ensure that we can correlate statistical properties with a wide range of stellar properties *(e.g. abundance, mass, age, etc.).* These radial velocity surveys should put particular emphasis on:

a) *Extending searches to cover a wide range of stellar masses*. About 60% of the known planet hosting stars have masses in the narrow range of 0.8-1.2 $M_{\odot}$. We thus have a very limited knowledge of the process of planet formation as a function of stellar mass. Several programs are searching for planets around low mass stars (Kürster et al. 2009, Irwin et al. 2009, Bonfils et al. 2010) as well as for planets around intermediate mass evolved stars (Setiawan et al. 2005, Döllinger et al. 2009, Niedzielski et al. 2009, Johnson et al. 2010). Preliminary indications are that planet formation is a sensitive function of stellar mass. Search programs for planets around low mass and high mass stars should be continued and expanded. (**KQ1**)

b) *Continue long-term monitoring (> 20 years) of the large sample of F-M stars (already being monitored) to extend the exoplanet discovery space to long period orbits. (***KQ1)**

c) *Continue RV monitoring of all known exoplanet-hosting stars in order to investigate the architecture of exoplanetary systems and to derive accurate orbital parameters.* (**KQ1**).

Planets most likely always occur in systems and it is essential to investigate this architecture. It is relatively easy to find that first giant planet around a star, but extracting the additional signals from less massive planets require additional monitoring of known planets and systems.

It is also important to get accurate orbital parameters of known planets, especially multiple systems that are key input to dynamical studies. These studies can point to stable zones where additional planets may reside and provide a more targeted approach for RV measurements as well as to find regions of dynamical stability in the habitable zone of multiple systems. In some favorable configurations (e.g. HAT-P-13 b), a promising link between the inner structure (density profile) of a close-in planet in a multi-planet system and the dynamical evolution of the system towards a measurable fixed value of the planet non-zero eccentricity has also been pointed out (Mardling 2010).

Accurate orbital parameters are also needed for photometric searches for transits of long period systems. For example, a giant planet in a 100 days orbit has a 1% chance of transiting the star. As the number of exoplanet discoveries increases there should be a sufficient number of exoplanets in each period bin so that the probability of finding a transiting planet, even for a long period one, is relatively high. However, photometric searches require an accurate ephemeris and thus good orbital parameters. For known transiting planets, RV monitoring should be done to search for additional companions.

We should extend our searches around other types of stars where we have good characterization of the astrophysical parameters of the host star. The transit searches combined with the RV measurements could provide us with the necessary data for a wide variety of planetary systems. Although each search strategy will have its own biases, only by exploring the full parameter space of exoplanets is it possible to make a classification of planetary systems in terms of the architecture of planetary systems. The question is whether there exist well-distinguished and different types of extrasolar planetary systems. Then it will be possible to use these data to place constraints on current theories for the formation of planetary systems.

d) *A Search for Planets Among Stars in Diverse Environments.* (**KQ1**)

To date most exoplanet discoveries have been made for isolated field stars, or stars that are in very wide binary systems. It is not known how important the birth environment is for the formation of planetary systems. RV searches show a clear correlation of planet hosting stars tending to have higher metallicity that is currently not seen in the transit discoveries and this may indicate an effect of the sample choice. This metallicity relationship is also not seen in planet-hosting giant stars (Pasquini et al. 2007). There is evidence that the stellar birth environment plays a role. For example a search for planets around a sample of 100 Hyades cluster stars yielded no planets suggesting a planet frequency significantly less than for field stars (Paulson et al. 2004). Why are Hyades stars different? Planets around binary stars also can provide important clues to planet formation. The wide binary system16 Cyg A and B has identical stars that are solar twins. Component B has a giant planet while 16 Cyg A does not (Cochran et al. 1997). What accounts for the differences?

Searching for planets in as diverse environments as possible may uncover the "Rosetta Stone" which can hold the key to understanding planet formation.

e) *Find targets for future characterization studies.* (**KQ2, KQ3**)

Because radial velocity surveys require high-resolution spectral measurements their exoplanet discoveries are almost always around nearby, bright stars, which are better, suited for follow-up measurements.

OG-2: *Securing the necessary telescope resources*

The telescope resources needed to carry out the proposed recommendations OG-1 are large. A survey of a large sample of F-K stars alone requires several telescope facilities. Pushing these discoveries to the low planet mass regime requires more measurements in order to extract the weak planetary signal from the stellar noise. Furthermore, detecting multiple systems also require significantly more measurements than detecting single exoplanets. The follow-up of transit candidates, particularly of CoRoT and Kepler targets, which are essential for determining the mass-radius relationship of exoplanets are already over-taxing the current telescope resources. *Currently, there are insufficient telescope resources to continue the much needed survey work and to perform follow up from transit programs.* For RV planet searches having access to sufficient telescope resources is a major problem.

Possible solutions:

1. *Dedicated facilities (4-8m class telescopes) for RV measurements*. ESO has already taken a step in this direction by making the 3.6m a HARPS-only telescope. 200 nights could be dedicated to exoplanet work on the 3.6m telescope as well as a significant fraction of one VLT.
2. *Inclusion of small telescopes in the effort*. RV searches among bright stars provide an ideal niche for small 2-4 m class telescopes, which are often underutilized (in fact most planet discoveries were made on such facilities). Several are already equipped with spectrographs capable of RV precision of ~3 m s^{-1}, sufficient for a large portion of the survey work (see Table 1 in appendix). Others can join the effort by equipping existing spectrographs with absorption cells at modest cost, or Th-Ar simultaneous calibration, but without the additional mechanical and thermal stabilization, which drives up the cost.
3. *Coordinated search activities*. Currently, there are a handful of programs searching for planets with the RV method and each has its own target list and each pursues its own observing strategy. A coordinated search should result in a more effective and efficient survey/follow-up strategy. Workshops and working groups could be established to organize such activities.
4. *Increased funding at a National and European level*. It is fine to recommend investing telescope time for RV work, but the reality is that these also require human and monetary resources. Who will pay? National and European funding agencies should be encouraged to support this work at the national level and to keep national facilities, which typically have 2-4m class telescopes, relevant in the era of large telescopes. Observatories that operate 2-4 m telescopes could be suggested to devote a fraction of their telescope time to RV planet work if there is monetary compensation similar to what is done in the OPTICON program.

OG-3: *Optimizing ground-based transit searches.* (**KQ2, KQ3**)

Although the CoRoT and Kepler missions are producing forefront exoplanet discoveries these missions have not completely rendered ground-based transit searches superfluous. There are still a number of areas where ground-based transit searches can still make a significant contribution:

1. Focusing on bright stars. Transiting planets around bright stars are “gems” to the exoplanet community. These objects are easy for radial velocity confirmation and are conducive for further follow-up observations. They will also provide the best targets for JWST and future spectral characterization missions. We note that ground-based transit searches among bright stars will only be able to achieve a photometric precision of 0.1%. Space-based missions such as PLATO will be required to find terrestrial-size planets around bright stars.
2. A search for transiting low-mass planets around M dwarfs (e.g. MEarth project). Transiting hot Neptune’s and hot Super-Earths around M dwarfs in the habitable zone are especially important. Current radial velocity techniques can measure the mass of the planet and these objects will provide targets for characterizing the atmospheres of the planets with Herschel, JWST, or future spectral characterization missions.
3. A search for transits of planets already found by the RV method, including long period systems.
4. A search for transit timing variations (TTVs) and transit duration variations (TDVs). Both of these give indications of additional bodies in the system like Trojan planets and possibly moons around a known giant planet.

OG-4 *Theoretical Studies* (**KQ1, KQ2, KQ4, KQ5**)

Theoretical work on exoplanets is an important standing recommendation that should continue throughout the course of this roadmap. A comprehensive understanding of planet formation and evolution is not possible without the theoretical framework to interpret the observations in a physical context. This theoretical work includes planet formation, planetary structure, planetary atmospheres, dynamical studies etc.

Observations should not be de-coupled from theory. Theorist should propose observations to confirm/refute theories, and observers should strive to make those observations needed by theoretical models. Which observations would be the most influential to improve our theoretical understanding of planet formation and evolution? So far, we have a good knowledge of extra-solar planets within a few AUs from their central stars, but we have little knowledge of bodies in the distance range 5-50 AU. Finding planets in this region and measuring masses and orbital properties would be essential to complete our census of the possible outcomes of the planet formation/evolution process. Are planets in this region on orbits systematically more circular than those of the warm/hot planets? Can we deduce that orbital excitation is correlated with evidence for migration? Are distant planets in a systematic mass hierarchy, similar to that characterizing the giant planets in our own solar system? What is the frequency of solar system analogs in the broad planet-systems census?

Characterizing planetary systems, rather than individual planets, will also be essential to constrain models of planet formation and orbital evolution. We urge the observers to pursue the searches for new planets around stars with at least one known planet companion, using all possible techniques in order to push further and further the detection limit in both mass and distance.

However, as long as we find planets only around main sequence stars, the constraints on the planet formation processes will be indirect. A real observational breakthrough would be the detection of planets in their birthplaces: the disks. In the case of both β Pictoris b and Fomalhaut b, this has already been achieved, but we are here dealing with massive debris disks and not the actual star- and planet-forming disks. At which stage of T-Tauri evolutions do giant planets appear? At what orbital radius? Are they still on circular orbits when they are embedded in the disk? Do super-Earths appear early, like giant planets cores, or late, like our terrestrial planets? The prospect of observing planet formation in action is by far the most exciting one.

OG-5: *Laboratory measurements to produce line lists, atomic and molecular transition probabilities, opacities, and equation of states.* (**KQ2, KQ3, KQ5**).

Roadmaps and recommendations to space agencies largely focus on observational efforts from the ground, and space-based observations. These tend to forget the need for basic experimental work such as laboratory studies determining basic physical parameters. Our models of exoplanet interiors are only as good as our equation of state and the theoretical models of exoplanet atmospheres can be no better than the atomic and molecular data (transition probabilities, collisional cross sections, etc.) and opacities that are used as input to these models. Laboratory measurements of such parameters are absolutely essential for realistic models of the internal structure and atmospheres of exoplanets. Furthermore, laboratory measurements of the collisional and coagulation properties of solid materials are essential input data for theoretical models of planet formation. It is imperative that such studies are supported during the course of this roadmap.

5.3 Near-term Road Markers (~2011-2017)

In the near term the community will continue with detections that are important for understanding the diversity and architecture, and most importantly for defining targets for future characterization studies. These detections should push the parameter space to the lower planetary mass regime as well as to larger orbital distances. During this time the characterization of the internal structure (mass, radius and mean density) will play a more important role as results from ground-based and space-based transit searches increase. The PLATO space missionhas the potential to extend these characterization studies to terrestrial mass planets. The understanding of exoplanetary atmospheres has taken its first steps and these efforts should be accelerated.

5.3.1 Ground Recommendations

NG-1: *Observations of all stars out to 50 pc: understanding the host stars of exoplanet systems, statistics as a function of stellar properties* (**KQ4, KQ5**).

Any characterization mission (imaging, spectroscopy, etc) will have target stars at distances no greater than about 50 pc. In spite of the relative brightness of objects within this volume of space there is much that is not known about these stars. Intensive ground based observations (coupled with future GAIA results) should be used to establish basic stellar properties (mass, radius, abundance, effective temperature), age, level of activity, environment, binarity, number of planetary companions, etc. An important product of such a study will be a target list of stars that are quiet in terms of activity that would be suitable for RV searches for terrestrial mass planets in the habitable zone. Since most of the stars are relatively bright, this is ideal work that can be carried out using 2-4m class telescopes. The radial velocity community has already obtained high resolution, high signal-to-noise spectra for many of the nearby stars as part of their planet surveys. These and other data can be used by the community for obtaining a better understanding of these stars. The community is encouraged to put such data in a central archive easily accessible by stellar researchers.

NG-2: *Radial Velocity Planet Searches in the Infrared with emphasis on short-period, low mass planets around M dwarfs* (**KQ1,** targets **for KQ2, KQ3, KQ5**).

The RV amplitude of an M dwarf star due to a planet in the habitable zone of the star is ~ 1 m s^{-1}, a precision achieved by current methods. The reflected/irradiated light signal from such planets will be studied with current or near-future technology. *Terrestrial planets in the habitable zone of M dwarf stars will provide us with the first spectral characterizations of habitable planets and as such they represent an important milestone.* A search for such planets will provide suitable targets for characterization studies in the mid-term part of this roadmap. Furthermore, RV measurements made during the appropriate phases of the transit can detect the Rossiter-McLaughlin effect, and thus measure the spin orbit alignment of exoplanets. For F-G type stars there is a significant fraction of misaligned systems. It is important to see if this phenomenon extends to planetary companions of low mass stars.

Radial velocity measurements in the infrared are also important for confirming planets, particularly around young active stars for which the activity signal can mimic that of a planet (Queloz et al. 2001; Setiawan et al. 2008). The RV variations due to a planet should have the same amplitude in the optical and infrared. Any difference means that the RV signal is most likely caused by spots (e.g. Figueira et al. 2010).

M dwarf stars are faint, and most of their flux is in the Infrared (IR) regions of the spectra. High-resolution spectrographs in the IR will be required to search for small planets around M dwarfs. Recent studies using IR spectrographs have already achieved an RV precision of 5 m s^{-1} (Bean et al. 2010, Figueira et al. 2010). An ultimate precision of 1 m s^{-1} or better may be achieved in the near future. Currently there are only two high-resolution infrared spectrographs: Phoenix on Gemini South (Hinkle et al. 2003) and CRIRES on the VLT (Käufl et a. 2003), but both have limited wavelength coverage. Precise radial velocity measurements require spectrographs with large wavelength coverage. The EPR-AT recommends the construction of several high-resolution IR spectrographs for precise RV measurements. Exoplanet searches require considerable telescope resources and it is unlikely that a single instrument will satisfy these needs.

NG-3: *Terrestrial planets in the habitable zone of G-type stars: High cadence monitoring of a sample of 50-100 G-type stars with low levels of activity* (**KQ1**, targets for **KQ3, KQ5**).

The detection of terrestrial planes around M dwarf stars is an important step in this roadmap since these will most likely provide the first information on the atmospheres of habitable planets. However, for comparative planetology we must also characterise habitable terrestrial planets around other types of stars, most notable those like our sun. The RV amplitude of terrestrial planets in the HZ of G-type stars is small due to the higher stellar mass and the larger orbital distance. For late-type stars this amplitude will most likely be considerably less than the intrinsic RV scatter of the star. Furthermore, because of the longer orbital periods of HZ planets around G-stars compared to M dwarfs, observations have to be carried out over a longer time span.

Before one can begin characterizing terrestrial planets in the habitable zone of G-type stars one must first have a target list. Due to the large number of RV measurements required over a relatively long time span the effort to detect such exoplanets should begin in the near-term. In spite of the difficulties RV measurements using current technology may be able to detect Super-Earths in the habitable zone of solar type stars.

Ground-based RV surveys are a cost-effective means of searching for terrestrial planets in the habitable zone of solar-types stars. A search among a reasonable sample size (50-100 stars) may well find such planets, which can be targets for future characterization missions. Spectrographs at smaller telescopes could help in this effort by searching for the most intrinsically RV quiet stars for scrutiny by the premier RV facilities (e.g. HARPS, ESPRESSO).

NG-4: *Characterization of Transiting Planets in the visible and IR with ground-based and on-going space based facilities* (**KQ3, KQ5**).

The science problems that we can tackle with current telescopes are:

- Detection of the main molecular species in the hot transiting planets atmospheres (water vapor, methane, CO2, CO, ammonia, etc.).
- Constraint on the horizontal and vertical thermal gradients in the hot exoplanet atmospheres.
- Presence of clouds or hazes in the atmospheres.

Today we can use two approaches to reach these objectives: (a) Broadband or low resolution spectroscopy from space or from a ground-based observatory. This can be accomplished by e.g. SPITZER, HST, MOST, CoRot, Kepler, Keck, IRTF, VLT etc. (b) High resolution spectroscopy from ground based observatories in the optical and NIR down to 5 micron (e.g. VLT-CRIRES).
The next steps with these indirect techniques will be:

- Cooler and smaller planets. With current telescopes we can already approach the case of warm super earths and Neptune's that transit bright, late-type stars, e.g. Gliese 1412b, GJ 436b, etc.
- Detection of minor atmospheric species and constraints of their abundance.
- More accurate spectral retrieval to map thermal and chemistry gradients in the atmospheres, distribution/characteristics of clouds/hazes.

Broad- and narrow-band imagers operating in the Near IR such as HAWK-I at the VLT should be used to search for secondary transits of giant planets. Low-resolution IR spectrographs can also be used to search for spectroscopic signatures. Such ground-based measurements can provide early data for planning future space missions.

NG 5: *Radio studies of Exoplanets* (**KQ3, KQ5**).

The study of radio emission from exoplanets is important for understanding the formation and evolution of magnetospheres. The detection of exo-magnetospheres around giant exoplanets may be accomplished by the LOFAR Array. Whether this emission can be detected is model dependent. Work by Griessmeier et al. (2007) indicate that a few of the known giant exoplanets may have radio emission that can be detected by LOFAR.

Although the first extrasolar planets were discovered around pulsars, the number of such planets is still very small due to the small number of known milli-second pulsars. It is not known whether the pulsar planets survived the supernova explosion that created the pulsar, or were formed from a circum-neutron star disk after the supernova (first generation versus second generation). In either case, pulsar planets give us information about the formation of planetary objects in extreme environments, which ultimately will aid in our understanding of planet formation in general. Currently progress in understanding pulsar planets is severely limited by the small sample size. This must be increased.

NG-6: *Ground-based support of CoRoT, Kepler, and preparation for ground-based support for GAIA* (**KQ1, KQ2).**

The lessons we have learned from CoRoT and Kepler is that RV spectroscopic follow-up for confirmation of transit candidates are an essential part of achieving the science goals of the mission. Furthermore, without the planetary mass measurement provided by ground-based spectroscopy we will not be able to determine the mass-radius relationship or the mean planet density needed to study the planetary structure. Having sufficient ground-based support for CoRoT and Kepler is essential.

Prepare for follow-up of Gaia detections. 1) High-resolution, high-precision spectroscopy of Gaia-discovered systems, with the three-fold aim of improving the phase sampling of the astrometric orbits found by Gaia, extending the time baseline of the observations to better characterise long-period companions, and to search for additional, low-mass, short-period components which might have been missed by Gaia due to lack of sensitivity. RV campaigns should be carried out at both visual and IR wavelengths, depending on target properties. 2) Direct imaging campaigns (SPHERE/VLT,EPICS/E-ELT) will complementary astrometric detections by probing the wide-separation regime for faint stellar/substellar companions, with the aim of better understanding the connection between the possible architecture of planetary systems and their occurrence and the binarity/multiplicity properties of the primaries. Although the full GAIA results will not be available before 2017, planning for resources and instruments to perform such support missions should be done in the short term.

NG-7: *Continue ground-based microlensing searches* (**KQ1, KQ4**).

Microlensing is a search technique that probes an important parameter space of exoplanets – the low mass end. It has the capability of detecting terrestrial mass planets and giving us a statistical estimate of η_{earth}. It also can discover planets around more distant stars and thus sample different regions of our galaxy. Do the type of planetary systems we find depend on where in the galaxy we look?

Ground-based microlensing networks should continue their work on exoplanet searches. Since microlensing searches require a network of telescopes the community should strive to ensure that there is an adequate infrastructure. Microlensing events from planets have duration of hours, so large networks of telescopes is essential for capturing these events.

NG-8: *Make Effective use of Planet finders for Exoplanets Studies* (**KQ1, KQ3, KQ4**).

The progress of imaging observational techniques now allows for the detection of certain classes of planets directly. Currently, exoplanets with a few Jupiter masses down to separations (from the host star) of 10 AU and with an age of up to about 10-50 Myr can be and have in some cases been detected. Ground-based telescopes (VLT, Gemini and Subaru) will soon (2011) be equipped with new imaging "planet-finders" (SPHERE, GPI and HiCIAO) making use of extreme adaptive optics, achromatic coronagraphs and differential imaging systems. These instruments will achieve contrast ratios of 10^6 to 10^8 in the near IR and will be able to probe the region within 5-10 AU in search for giant planets. Prime targets will be young stars (hundreds are available within 200 pc) and nearby stars (<25pc).

Operated in large surveys, these facilities should allow the identification of tens of giant planets. Spectral characterization will be feasible at low resolution (R=50) between 0.95 and 2.3 μm and medium resolution for the brightest objects (R=800). SPHERE at VLT has an additional particularity since it can detect polarimetric signals of planets at very high contrasts and hence achieves the detection of mature giants around a few close bright stars on relative short orbits (0.5-1 AU).

In addition to new detections and characterization of warm giant planets (either young or massive) the number of stars surveyed by the planet finders will allow producing statistical analyses. The discoveries will provide inputs for the next step. Planet finders will also provide an accessible test-bench to demonstrate new concepts for high contrast imaging. They could be milestones for the achievement of ELTs and space missions.

NG-9: *Calibration of giant planet evolutionary tracks* (**KQ1, KQ3).**

The masses of giant planets at large orbital radii as well as free-floating planets found by imaging surveys (see Quanz et al, 2010 and references therein) rely on theoretical models to estimate the planet mass. This mass determination, and thus the nature of the object will be uncertain. These theoretical tracks must be calibrated against giant planets with well-known dynamical masses. Ground-based direct imaging techniques may have a long enough time base to detect orbital motion of a long-period giant planet and thus to measure its mass. Also, the ELT may provide the first direct images of giant planets in outer orbits found by RV surveys. The calibration of these giant planet evolutionary tracks are essential for establishing whether the population of “free-floating planets” found in star clusters are indeed planetary in nature and to understand the evolution of giant planets. This work can begin with the “Planet Finders” on the 8-m class telescopes and continue with the extremely large telescopes (TMT, E-ELT, GMT). The recent detection of orbital motion around several imaging planets (Kalas et al. 2009, Marois et al. 2009, Lagrange et al. 2010) suggests that we may soon be able to derive dynamical masses for direct imaging detections.

NG-10: *A study of exo-zodi systems and their influence on direct imaging of terrestrial planets* **(KQ1).**

A study of exo-zodiacal light around nearby stars should establish whether this exo-zodi light would hinder future efforts to image directly terrestrial planets in the habitable zone of other stars. The exo-zodi systems are also interesting in their own right as they are one component of exoplanetary systems. The LBT, Keck nuller, and planet finder can make a contribution to this in the near term; however, space-based missions are probably best suited for such studies (e.g. JWST and the proposed Fourier Kelvin Stellar Interferometer which has the primary science case to detect exo-zodis down to the 1 zodi level).

NG-11: *An investigation of the influence of stellar activity on habitability and anticipated atmospheric signatures* (**KQ4**, **KQ5).**

Stellar activity will definitely have an influence on the habitability of a planet, but in ways that are not well understood. In particular, current efforts are focusing on finding planets in the habitable zone of M dwarfs because these will be the easiest to detect. However, these objects may provide an extreme case of habitability. M dwarfs tend to be very active with large UV and X-ray fluxes, and frequent coronal mass ejections. This will clearly influence both the evolution of the planetary atmosphere and any life forms that can develop on the surface.

Theoretical work investigating such influences should be undertaken and to assess whether bio-signatures of planets in the habitable zone of M dwarfs can even exist. Such studies would benefit from an interaction of the stellar activity community and those modeling the planetary atmosphere. This work not only has implication for planets around M dwarfs. The early sun was itself quite active, and an understanding of how this activity influenced the evolution of life on earth will help to interpret possible biosignatures around planets of young, active stars.

5.3.2 Space Recommendations

NS-1: *Continuation of the CoRoT and Kepler past the nominal mission life* (**KQ1, KQ2**).

Both CoRoT and Kepler are producing exciting new results on the characterization of exoplanets. CoRoT has found the first hot Super-Earth (CoRoT-7b). Kepler has demonstrated a performance that can find an one-earth radius planet in the habitable zone of a G-type star (and it will surely shortly find the first "hot earths", an earth radius planet in a short period orbit). Both missions will give us our first estimate of η_{earth}, the frequency of terrestrial planets around relatively nearby stars. Kepler could give a first estimate of this frequency for terrestrial planets in the habitable zone. These space missions, along with the proper ground-based support, will also calibrate the Mass-Radius relationship for planets, particularly Super-Earths. This is important because for the very low-mass (i.e. small radius) objects one will have to rely on this relationship for inferring the planetary mass.

Currently, CoRoT and Kepler are the only functioning space platforms devoted to extrasolar planet searches (until the possible launch of PLATO) and these should be continued as long as possible. CoRoT has been extended for an additional 3 years, and it is hoped that if there is no serious degradation of performance that it be extended beyond this time. Kepler has a nominal life of 3.5 years, but this should be extended to the maximum value possible. Significant scientific return can result with modest resources needed for continued operations**.** *ESA has already provided modest support for the CoRoT mission and we recommend that ESA continues this support if it insures that CoRoT will continue to operate.*

It is expected that both space missions will produce a treasure of archival data that should be exploited to its maximum extent with support from national and European funding agencies.

NS-2: *Characterization of exoplanets with PLATO* (**KQ2, KQ4, KQ5**, targets for **KQ3**).

The science goals of the PLATO (PLAnetary Transits and Oscillations) are to "discover and characterise a large number of close-by exoplanetary systems, with a precision in the determination of mass and radius of 1%" using the transit method. The only way to measure stellar parameters to this accuracy is via asteroseismology – the key tool of the PLATO mission. The asteroseismic studies of PLATO targets will also yield accurate stellar ages needed for the understanding of planet evolution. The EPR-AT fully supports this mission, as it will accomplish two major milestones of this roadmap:

1) The characterization of the internal structure (mass, radius, and mean density) of exoplanets planets down to the terrestrial mass regime.

2) To provide targets for future characterization studies of the planetary atmospheres and the spin orbit alignment using ground-based and future space-based missions.

PLATO will focus on stars considerably brighter than the targets for CoRoT and Kepler. As such it will be

1) Possible to carry out a determination of the asteroseismological frequencies and thus determine the stellar parameters to approximately 1% accuracy, as well as main sequence ages to around 250 million years
2) The stars will be well suited for ground-based follow up measurements to determine the planet mass.

Accurate planetary parameters are needed in order to characterise the internal structure of a terrestrial planet. For example to distinguish whether an earth-mass planet is Earth-like (33% core, 63% mantle), or 100% silicate mantle requires knowing the planet radius to better than 3% and its mass better to 10% (Valencia et al. 2010). Both of these hinge on accurate determination of the stellar parameters as the transit depth gives only the ratio of planet-to-star radii stellar and the mass function used to derive the planetary mass depends on the two-thirds power of the stellar mass. Thus stellar radii and masses must be determined to better than 3% and 10%, respectively.

In terms of the characterization of exoplanets down to the terrestrial mass regime PLATO represents a key component of this roadmap.

NS-3: *Make effective use of JWST for Exoplanets Studies (spectral characterization, imaging, photometry, phase curves, colors)* (**KQ3, KQ4, KQ5**).

The James Webb Space Telescope (JWST) is also very promising for the exoplanet spectral characterization as the Near Infrared Camera (NIRCAM), Mid Infrared Instrument (MIRI) and Tunable Filter Imager (TFI) include high contrast imaging devices offering a large spectral coverage from about 2 to 15 μm thus complementing the planet finders by 1) extending the surveys to very late type stars (contrast is more favorable) and cooler objects and 2) extending the characterization to mid IR (2.5-25 μm) thus allowing the identification of ammonia, methane, CO_2.

The same instruments will enable us to perform transit spectroscopy, which has the potential of detecting small planets. The designs of a number of the JWST instruments have been driven by this very science case. *JWST can be the first facility to achieve spectral characterization of Super-Earth atmospheres and thus achieve a key milestone in this roadmap.*

Although JWST will be a valuable facility for performing characterization studies of exoplanets, it *is* a general-purpose facility, so it is expected that relatively few targets will be observed. The amount of JWST time available to European scientists will be limited (NIRSPEC is a European contribution and MIRI is a 50-50 US-Europe collaboration). *The European community must move fast and organize itself so as to effectively use its share of the time effectively on exoplanet studies. Open Time Key Programs for Exoplanets on JWST, is a concept that worked well with Herschel and should be considered by European scientists in this context. Open time on JWST is regulated through the ESA – NASA MoU.*

NS-4: *Theoretical studies on the spectroscopic and possible bio-signatures expected from exoplanets covering a wide range of masses (terrestrial to giant planets) and a wide range of temperatures* (**KQ3, KQ5**).

In the mid-term part of this roadmap we expect that space missions will be proposed to perform spectral characterization of exoplanets. Spectroscopic instruments on extremely large telescopes will also start to become available. To plan effectively observations on these expensive facilities it is important to understand what spectral features can be detected and the required signal-to-noise ratios. Such studies should not only focus on short period systems that are best suited for studies using in-transit spectroscopy and secondary transits, but also longer period and thus cooler planets that are best suited for studies using angularly resolved detections.

Before one can plan space missions or instrumentation for extremely large telescopes it is essential that theoretical studies be performed to establish:

1. Spectral Coverage
2. Spectral Resolution
3. Minimum Signal-to-Noise ratio requirements
4. Exposure times
5. Required Instrumental Stability

These studies should cover the full range of parameter space of planetary temperatures and masses. It is expected that the observational data acquired on exoplanet atmospheres will follow a rough chronological order from relatively easy observations to the more challenging:

Young giant planets at large orbital radii → Hot Transiting Jupiter's → Hot transiting Neptune's → Terrestrial Planets in HZ of M dwarfs → Hot Terrestrial Planets around G dwarfs → Old giant planets in the HZ of G-dwarf stars → Terrestrial planets in the HZ of G-dwarfs.

Note: Although this recommendation is not strictly a "Space Recommendation" this work is important for the planning of future space missions for characterization of atmospheres. ESA can provide support via internal studies to establish if technical requirements can be achieved.

NS-5 *External Occulters* **(KQ1, KQ3).**

The use of an external occulter is a method recently proposed for the angularly resolved detection of extrasolar planets. The reduction of the central light of the host star is accomplished by a free-floating starshade flying some distance from an existing telescope facility (e.g. JWST). The promise of external occulters is "an affordable, technically ready approach to finding and characterizing planets from the habitable zone to the cold outer edges" (Cash et al. 2008, EPR-AT white paper). If external occulters can deliver as promised they may provide a fast track to the direct imaging of giant exoplanets, and possibly terrestrial planets. Because of this promise, and because this is a relatively new technology the EPR-AT recommends that ESA investigates in more detail, in collaboration with U.S. colleagues, whether an external occulter can be used with JWST. However, in carrying out this recommendation ESA should take into account the following:

1. To exploit fully the resources offered by JWST it is essential that external occulters be in place for a significant fraction of the lifetime of JWST.
2. A number of technical issues have to be resolved in a relatively short time span: construction and deployment of the starshade, the effects of space environment on the performance of the starshade, the orbital mechanics involved in positioning the shade, etc. It is not clear to the EPR-AT that these technical hurdles can be overcome just from ground-based studies and without flying a prototype. These issues should be clarified.
3. Only finite resources of JWST can be devoted to observations with the external occulter and there are long time requirements for positioning the shade after each observation. It is not clear if an external occulter can be used in "discovery mode", i.e. to survey a large number of stars. A suitable target list *must* be in place prior to the use of an external occulter.
4. A realistic cost assessment should be made so that a peer review process can judge whether an occulter, or another mission fully devoted to direct detections of exoplanets gives the best scientific return to the community.

NS-6: *Space-based Microlensing Surveys* (**KQ1, KQ4**).

The microlensing technique is a method that explores an important regime in the mass – semi-major axis plane: terrestrial planets at ~1-2 AU from the host star. Although important for detections, microlensing does not provide targets for future characterization studies. The characterization exoplanets is a major emphasis of this roadmap and because of limited available resources we do not recommend a dedicated space-based mission for microlensing studies. However, we encourage ESA to find ways to incorporate microlensing studies on space missions dedicated for other science.

The community has suggested (at the EPR-AT workshop) that the dark energy experiment Euclid can also be used for microlensing survey of exoplanets. We should emphasize that Euclid is *not* an exoplanet mission, nor are exoplanets part of its stated science goals. PLATO can provide key milestones of this roadmap in the characterization of exoplanets, something that microlensing studies with Euclid cannot accomplish. Should Euclid be funded, however, we encourage ESA to investigate whether a microlensing component can be included (via set-aside time or an extended mission) on Euclid without compromising the major science goals of the mission or impacting future higher priority exoplanet missions.

5.3.3 Technology Recommendations

NT-1 *Improved wavelength calibration for radial velocity measurements* (**KQ1**).

The two most common techniques for wavelength calibration of radial velocity measurements are the simultaneous Thorium-Argon (Th-Ar) calibration and the iodine gas absorption cell. Both have a demonstrated precision of 1-3 m s^{-1}. However, to achieve a wavelength calibration sufficient to detect the reflex motion of a terrestrial planet at 1 AU requires a much improved wavelength calibration. A promising approach laser frequency comb techniques, a technology currently pursued by ESO.

In conjunction with improved wavelength calibration it is essential to have the highest possible instrument stability to ensure a stable Instrumental Profile (IP). Even the slightest asymmetry in the IP will mimic a Doppler shift regardless of the accuracy of your wavelength calibration. There are many contributors to the IP: guide errors, the individual optical elements, and the CCD detector. The IP must be sufficiently stable to ensure that an RV precision of a few 10 cm s^{-1} can be achieved. CCD detectors with low, and invariant noise characteristics that are stable over a long time period are also essential (see NT-2).

NT-2: *Detector Development* (**KQ1, KQ3**).

The key component to any instrument is the detector. Unstable or noisy detectors will seriously compromise the quality of the data needed for exoplanet studies. The greatest need is for improved noise level and stability of mid IR detectors for the range 5–20 μm. These are needed for spectroscopic studies of exoplanet atmospheres, as well as for radial velocity measurements in the IR. In fact, it is detector stability that may ultimately prevent us from achieving an RV precision better than 1 m s^{-1} at mid-IR wavelengths. Such detectors are currently built in the U.S. but have yet to be developed in Europe. Clearly, several future ESA missions will benefit from such technological acquisitions.

Although the quality of optical CCD detectors has dramatically improved over the past 20 years, industry should not neglect developing even more stable and lower noise optical detectors and detectors with a large dynamic range. These will be needed for ultra-precise photometric measurements ($\sigma \sim 10^{-6}$) and ultra-precise RV measurements ($\sigma \sim 10$ cm s^{-1}). For these measurement precisions to be possible the current stability and noise characteristics of optical detectors may be inadequate.

NT-3: *Technological studies for the direct imaging and spectroscopy of exoplanets* (**KQ1, KQ3, KQ5**).

The key techniques for the direct imaging and spectroscopy of exoplanets are:

1. High precision photometry or spectroscopy of transiting planets (primary and secondary transit).

White papers provided to the EPR-AT are based on using small telescopes equipped with stable instruments. The small collecting area is compensated with a large spectral coverage (ideally 0.5-20 μm). In particular, it is expected that exoplanets in the habitable zone of their parent stars can be characterised if the instrument band can extend to the mid IR (>10 μm).

Therefore, the key technology here is the development of mid IR detectors typically for the range 5-20 microns with a noise level and a stability that is compliant to spectroscopy of transiting planets.

2. High contrast imaging of planets in reflected light.

As a starting point, small telescopes (1.5-2m) are proposed to undertake the spectral characterization of Giant planets and super earths (at visible wavelengths). This concept will evolve into larger versions that will be optimized for detecting Earth-like planets, similar to the former TPF-C. Several projects are developed around the world and they share two main key technologies.

- *Deformable mirrors*: Together with wave front sensors, they will be needed to achieve very small wave front errors. The important parameters are actuator density (the more actuators, the larger the corrected field of view), and actuator precision at the nanometer level (the higher precision, the better contrast).

Two solutions are being pursued: one based on a warm sub-system and the other is cryogenic. The first one was the baseline for TPF-C and the other is the concept of the SPICA coronagraph. So far, JPL has demonstrated large contrasts of 10^{-9} to 10^{-10} in the lab under vacuum, and the systems are going to be tested in the space environment. Several other working groups are involved in such development (e.g. NASA Ames, Subaru, JAXA, Observatoire de Paris, etc.)

- *Coronagraphy*: Modern coronagraphy has been evolving during the last 15 years and has led to many concepts, which are in development worldwide. In addition to the standard occulting spot of Lyot, more advanced systems are already installed on ground-based telescopes such as VLT/NACO and the Palomar 5m telescope. Newer systems are being built for VLT/SPHERE and GEMINI/GPI. Several of the latest concepts like band-limited masks, phase masks and apodized masks will also be implemented on JWST (NIRCAM, MIRI, TFI). Chromaticity is an important limitation for coronagraphs. This can be mitigated using several wavelength bands in the same instrument, but achromatic versions are desirable. Among the (nearly) achromatic concepts we mention here the Phase Induced Amplitude Apodization and the Optical Vortex that are promising techniques for application on space missions. Developments are ongoing both in the US and in Europe. Most of the concepts described above have been demonstrated in the lab, and EPR-AT anticipates that a demonstration in a space environment is not critical.

3. Free Flying and deployable structures.

Projects to study Earth twins involve large structures either in the form of interferometers with diluted apertures or with single apertures but two separate spacecrafts (Occulters or Fresnel lenses). *The formation flight is therefore a key technology to be developed in that respect. The precision depends on the concept but is in any case very small compared to the size of these structures.* Europe has already invested in this activity in the former Darwin concept, and the currently flying technology demonstrator PRISMA (Swedish National Space Board mission), which uses European technology (partly developed in the context of the Darwin study). These technologies are probably directly applicable to other concepts (e.g. External Occulters).

The occulter is significantly larger in size than the other technologies mentioned, with a typical size of 50 meters or larger and thus requires an *ability to deploy such large structures. Some technical assessments are ongoing, in the US and in Europe. One critical aspect is the ability to* *test such structures in a representative environment (See NS-5).*

An overall common point of these different observational techniques is the stability or reproducibility as exoplanets imply long observations of several hours or days.

The Technological Readiness Level (TRL) of these key points is now ranging between 3 and 4 and has to mature to TRL 5 in order for the mission concepts to be considered for an assessment phase at ESA. Therefore, a clear *technological* roadmap should be established for the three aforementioned families of techniques. Currently, such a technological roadmap is outside the main expertise of the EPR-AT.

There is considerable work done in laboratories at the national level where the first demonstration prototypes are usually built. These facilities also have the ability to undertake ground based implementations on actual telescopes or instruments but are lacking experience when it comes to proposing a whole space mission. This is especially true because new technologies are considered risky for space and thus a more careful analysis is needed. The expertise of space agencies and industrial partners is required to implement such technical solutions into mission concepts. Small but exhaustive studies should be carried out to define properly the main characteristics of a space mission (launchers, orbits, mission strategy, operation, ground segment, risk analysis, cost estimates, etc.). A closer connection between national labs, space agencies and industrials is strongly recommended.

Several technological activities where triggered by ESA in the context of the Darwin study but not actually started (IR optics and detectors). A significant amount of funding (~ 4Meuros) was therefore provisioned at that time. One of the EPR-AT tasks is precisely to advise ESA on the technological requirements for the future exoplanets missions. The items described above gives a clear view of the main critical aspects of where to invest in technological studies as soon as possible. This will be definitely important for the mid and long term missions.

5.3.4 Anticipated milestones at end of term:

1. Detections
    a. ~1000 exoplanets around host stars with stellar masses 0.1 – 2 $M_{\odot}$
    b. ~100 multiple systems
    c. A few super earths (5-10 M_{Earth}) at 1 AU from G-type stars
    d. Tens of Terrestrial planets (1-5 M_{Earth}) in the habitable zone of M dwarfs
    e. The first estimate of η_{Earth}, the estimated fraction of stars with terrestrial planets in the habitable zone of stars
    f. Direct detections (imaging) of up to tens of Giant planets at semi-major axis a > 10 AU
2. Characterization of the Internal Structure
    a. Mass-Radius relationship of giant planets with a < 0.5 AU
    b. Mass-Radius relationship of super earths (5-10 M_{Earth}) with a < 0.1 AU
3. Characterization of Atmospheres

    a. Spectra of tens of giant planets with a < 0.05 AU
    b. Spectra of a few giant planets and super planets (mass = 5-20 M_{Jup}) at a > 10 AU
4. Technological
    a. Low noise Infrared Detectors
    b. Doppler precision ~ 10 cm s^{-1}
    c. Assessment of various direct detection (angular resolved) methods: coronagraphs, nulling interferometer, occulters

5.4 Mid-term Road Markers (~2015-2022)

During the midterm portion of this roadmap exoplanet studies should have moved from an era dominated by detections to one dominated by the characterization (mass, radius, density, and atmospheric composition) of a significant sample of exoplanets. CoRoT and Kepler will have defined the mass-radius relationship of hot giant planets and a sample of hot Super-Earths. This should lead to the first studies of the internal structure of terrestrial exoplanets. JWST may offer the spectral characterizations of select hot Jupiter's, hot Neptune's and hot-Super-Earths. For late-type stars within 25 pc the Gaia mission will be sensitive to planets with M ~ 15-20 Earth masses, or smaller (depending on spectral type).

5.4.1 Ground Recommendations

MG-1: *Secure the ground-based support necessary for follow-up of PLATO transit candidates* (**KQ1, KQ2**, targets for **KQ3**).

If PLATO is approved it will be launched in the mid-term part of this roadmap. The ground-based spectroscopic follow-up of PLATO transit candidates is a critical component of this mission. Without radial velocity and ancillary measurements the nature of the transiting objects cannot be confirmed, and the companion masses determined. *Both* the mass and radius are crucial for models of the internal structure of the planets. The ground-based program should be in place prior to the launch of PLATO. ESA does not provide ground-based observations for mission support. Such efforts will have to come from the exoplanet community that is primarily funded on a national level, and possibly through ESO. *ESA can aid in this effort by stressing the need for this ground-based follow-up and supporting these efforts in the appropriate forums.*

MG-2: *Use of Atacama Large Millimeter Array (ALMA) to study exoplanets in their birth environments* (**KQ1**)

As long as we find planets only around main sequence stars or evolved giant stars, the constraints on the planet formation processes will be indirect. A real observational breakthrough would be the detection of planets in their birthplaces: the disks. Ideally, we would like to answer questions like: At which stage of T-Tauri evolutions do giant planets appear? At which orbital radius? Are they still on circular orbits when they are embedded in the disk? Although definitive answers will require a lot of time, some information can already be achieved in the near term. RV detections in the infrared may provide these discoveries. Direct imaging of the disk may reveal clear signatures of the presence of planets. The new instruments of VLTI (PIONEER, Gravity, Matisse) and ALMA should be used for a search for planets in disks starting from ~ 2012. ALMA will also provide information on the turbulence in proto-planetary disks by measuring the velocity dispersion in the gas from the width of some spectral lines

MG-3: *Continue direct imaging studies from the ground (AO, coronagraphy) to find large planets at large orbital distances* (**KQ1, KQ3, KQ4**).

The next generations of planet finding instruments (e.g. EPICS in Europe or PFI in the US) are already planned for implementation on the class of Extremely Large Telescopes (30-40m aperture). The goal of these instruments will be to extend the parameter space to lower masses, older planets and to access fainter stars. Exploring the 10^9 contrast ratio level with angular resolution of a few milli-arcseconds will definitely open a new exploration field in exoplanet science. As of today it is difficult to predict when these projects will happen (mid or long term). A lot of technical issues have to be solved: 1) The manufacture and operation of 30-40 meters telescopes, 2) Atmospheric compensation with adaptive optics, and 3) The optimization of high contrast instruments. However ELTs will nicely complement a large space mission dedicated to spectral characterization of exoplanets. Therefore, space and ground projects should be harmonized and could lead to a potential ESA/ESO collaboration.

However, the over-subscription rate on these telescopes will be enormous. The time spent on exoplanet observations will likely be small, so careful thought has to be given as to what observations are the most important. *The exoplanet community should organize and be an effective lobby to ensure that exoplanet studies are part of the key science programs of ELTs.*

MG-4 *Obtain a sample of Terrestrial planets in the Habitable Zone of G-K type stars* (**KQ1, KQ4, KQ5**).

The detection and characterization (structure and atmospheres) of terrestrial planets in the habitable zone of M-dwarfs is an important first step, but in order to do comparative planetology in the real sense these studies have to be extended to the habitable zone of earlier type stars. Furthermore, “habitability” of M-dwarfs may be an extreme case due to the high activity levels of M-dwarfs. A major focus of the mid-term roadmap will be to have a sample of known or candidate terrestrial planets orbiting G-K main sequence stars that can serve as targets for spectral characterization in the long term. PLATO can also contribute to this.

The near-term RV searches for extrasolar planets should define a small sample of suitable stars i.e. bright and quiet in terms of stellar activity. A “Golden Sample” of these should be defined and scrutinized with intensive RV measurements in order to beat down any remaining activity noise. The major goal of this effort is to have a sample of a least a few terrestrial planets (Earths or Super-Earths) in the habitable zone of G-K type stars.

5.4.2 Space Recommendations

MS-1. *Preparation for an M-class and/or smaller mission for characterization of exoplanet atmospheres from gas giants to Super-Earths* (**KQ2, KQ4**)

Efforts to characterise the atmospheres of exoplanets should span the entire parameter space from hot, close in planets, to the cooler ones at large distances that are analogous to what is found in our solar system. In the mid-term roadmap preparations for a mission to perform this characterization should be undertaken. We can identify two classes of exoplanet for which spectral characterization can be realistically done in the near term:

1. Combined light mission: This is aimed at the atmospheric characterisation of hot and warm (including the habitable-zone of M-type stars) Giants, Neptune's, and Super-Earths using transit or combined-light spectroscopy. Spitzer, Hubble and large ground-based observatories have already demonstrated the feasibility of such work. While JWST and ground-based facilities will produce similar results for a select sample of targets, the proposed dedicated mission should provide repeated observations of a much larger sample of stars over a broader wavelength coverage.

2. Angular Resolved Detections. 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. In the midterm such spectral characterizations would be for mature giant planets down to maybe super-Earth size at distances > 1 AU from the host star.

The decision on which type of spectral characterization mission to undertake first should be defined by

1. Technological feasibility in the time frame of the proposed mission.
2. Suitable sample of target stars
3. Scientific return
4. Cost that can be accommodated in the current ESA budget

These four criteria should be defined during the near-term phase of this roadmap. Planning and feasibility studies for the other technique should continue since the full parameter space of spectral characterizations are needed. An M-class or smaller space mission using either of the two methods listed above, will help define which is more suitable for the spectral characterization of earth like planets in the habitable zone using a more expensive space mission in the distant future, (or possibly ground-based efforts with extremely large telescopes). We note that the two techniques mentioned here are not exclusive and could be implemented in parallel possibly in the same mission. Although more challenging the scientific return would be high and the cost reduced in the longer term.

In preparing for such a characterization mission the community should consider two options for space missions:

1. A small mission with reduced science objectives. Such a mission would be able to characterise hot planets down to masses comparable to a Super-Earth, but not in the HZ. The sample size would probably be more limited.
2. A medium class mission with more ambitious science goals. Such a mission have a larger sample size and should be able to obtain spectral characteristics of planets down to Super-Earth masses and in the HZ of stars (M-dwarfs and late-type stars).

The spectral characterization of a large number (N > 10) of targets for comparative planetology is an important milestone to be accomplished in the mid-term part of this roadmap.

MS-2: *Transit Searches for Small Planets around solar-type stars.* (**KQ1**, **KQ2**, targets for **KQ3**)

Ground-based transit searches among bright stars will only be able to achieve a photometric precision of 0.1%. By comparison, the photometric transit depth of CoRoT-7b is a mere 0.03% far below the capabilities of ground-based telescopes. Furthermore, because of the reduced photometric precision and poorer duty cycle ground-based facilities are not as efficient as space missions. Ground-based searches can only find small planets (super earths, Neptune's) around M-dwarfs (large R_{planet}/R_{star} ratio), but not solar type stars. Clearly the discovery of transiting terrestrial planets around bright stars, particularly G-type stars requires space-based efforts. Kepler may find transiting planets around G-type stars, but the magnitude range of Kepler targets, V = 11-15 precludes characterization observations to determine the planet mass and to search for atmospheric features.

The PLATO space mission would make a significant contribution to this. PLATO will survey a large fraction of the sky producing exquisite light curves of all stars in the field down to V=13, but most importantly all the bright dwarf and sub giant stars down to magnitude 11. PLATO should find a large number of transiting Hot Earths (the transit probability for a CoRoT-7 like system is ~15%) as well as a few terrestrial planets in the habitable zone. Because these stars would be relatively bright, there is some hope that RV measurements should be able to characterise the planet mass.

Obtaining a modest sample of transiting terrestrial planets around bright, especially F-K type stars, that are conducive for follow-up characterization studies is an important milestone that should be accomplished in the mid-term.

MS-3: *True mass determination of known giant planets with Gaia: Deriving the true mass function for giant exoplanets* (**KQ1, KQ2, KQ4**).

The single most important parameter characterizing a planet is its mass. Accurate masses for exoplanets are needed for internal structure studies, atmospheric modeling, and dynamical studies. The exoplanets can be measured by one of two ways 1) radial velocity measurements of transiting systems that have known orbital inclinations (for relatively few stars) and 2) astrometric measurements combined with radial velocity measurements. Astrometric measurements also hold the promise of being able to detect terrestrial planets in the habitable zone of G-type stars.

Towards the end of the mid-term period of this roadmap the first astrometric results of Gaia should become available. These, combined with the already obtained RV data, should be able to derive true mass for known giant exoplanets. With these we can begin to derive the true mass function for extrasolar planets.

MS-4: *Obtain accurate stellar parameters using Gaia and PLATO* (**KQ1**, **KQ4**).

During the mid-term part of the roadmap Gaia will provide with accurate stellar properties of the solar neighborhood such as distance, space motions, binarity, radius (from magnitude, distance, and effective temperature), etc. Accurate stellar parameters are needed in order to get accurate planet parameters and many of these require asteroseismology. If PLATO flies it will provide accurate stellar parameters (radius, mass, age, etc) for all bright dwarf and sub giants in a large fraction of the sky, including many known planet-hosting stars. This will build on the knowledge obtained from NG-1.

MS-5 *Devote time on ELT and JWST for key programs in spectroscopy of transiting planets and direct imaging of Giant planets at large orbital distances* (**KQ1**, **KQ3**, **KQ4**).

MS-6: *Astrometric Searches for Terrestrial Planets* (**KQ1**, targets for **KQ3**, **KQ4**, **KQ5**).

Astrometric measurements play important roles in this roadmap as they provide the key parameter for characterizing a planet – its mass. Ultra-precise astrometric measurements can also detect terrestrial planets in the habitable zone of solar-type stars and thus can provide targets for future missions to search for bio signatures from these exoplanets. The astrometric detection of terrestrial planets requires not only a precision of a few micro-arcseconds, but also dedicated observations on fewer targets.

During the preparation of this roadmap SIM-Lite was the only proposed space mission that could make astrometric measurements with a frequency and precision to detect terrestrial planets (Earth analogs). The U.S: Decadal Review did not support SIM-Lite, therefore there is now a gap in our roadmap in regards to astrometric measurements. The community should investigate whether "targeted" (as opposed to the "global") astrometry can achieve the exoplanet goals of SIM-Lite but at significantly reduced cost.

5.4.3 Technology Recommendations

MT-1: *Continued Research & Development studies into the various Angularly Resolved Detection technologies* (**KQ1, KQ3, KQ4, KQ5**).

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.

5.4.4 Anticipated milestones at end of term

1. Detections
   a. 2000 exoplanets around host stars with stellar masses 0.1 – 2 $M_{\odot}$
   b. 200 multiple systems
   c. Tens of Jovian and Neptune planets with semi-major axis, a > 5 AU
   d. ~100-200 candidate terrestrial planets in the Habitable Zone of G-type stars and ~10 of these around nearby bright stars → Target List for flagship mission
   e. Good estimate of η_{Earth}, the estimated fraction of stars with terrestrial planets in the habitable zone of stars
   f. Direct detections (imaging) of up to ~100 Giant planets at a > 10 AU
2. Characterization of the Internal Structure
   a. Mass-Radius relationship of giant planets with a < 1 AU
   b. Mass-Radius relationship of Terrestrial planets (1-5 M_{Earth}) with a < 0.1 AU
3. Characterization of Atmospheres
   a. Spectra of ~tens of giant planets with a = 1–5 AU
   b. Spectra of a many 10s of Hot Jupiters: m = 1–3 M_{Jup}, a < 0.1 AU
   c. Spectra of terrestrial planets (1–5 M_{Earth}) in the habitable zone
   d. Expected biosignatures and required instrumentation to detect these
4. Technological
   a. Technology for high contrast imaging suitable for space missions
   b. Ability to implement this technology in space

5.5 Long Term Road Markers (~2020 and beyond)

The focus of the long-term portion of the roadmap is the characterization of terrestrial planets in the habitable zone of G-type stars. The key questions to be answered are the ones posed in Section 4.1

5.5.1 Ground Recommendations

LG-1: *An astrometric Search for Giant planets using Gaia combined with RV ground-based follow-up observations* (**KQ1, KQ2, KQ4**).

By 2020 the final GAIA astrometric results should be available. With an astrometric precision of 6 mas (bright stars) to 200 mas (faint stars) it is expected that Gaia should *discover* ~ 8000 giant exoplanets and to characterise the mass and orbital parameters of about one-half of these (Casertano, Lattanzi, Sozzetti et al. 2008). It is essential that RV measurements be conducted from the ground to refine the orbital parameters from the Gaia detections and to derive accurate properties of the host stars. The recent astrometric measurement of the of the inclined orbits of υ And (McArthur et al. 2010) beautifully demonstrates how by combining astrometric and RV measurements one can determine fully the orbital parameters of planetary systems including their individual orbital inclinations. Once Gaia results are available Doppler efforts should focus on observing Gaia exoplanet discoveries.

5.5.2 Space Recommendations

LS-1: *Extend the life of the GAIA mission past its nominal lifetime* (**KQ1, KQ4**).

We recommend that the life of the GAIA mission should be extended for as long as possible. A longer time base will result in a better determination of orbital parameters as well as enable GAIA to detect planets of smaller mass.

LS-2: *Begin work on a flagship mission to characterise all the known terrestrial planets in the habitable zone of F-K type dwarfs* (**KQ3, KQ4, KQ5**).

The mid-term portion of this roadmap should have established 1) the technology suitable for the characterization of terrestrial planets in the habitable zone of G-type dwarfs, 2) the possible biosignatures that might be expected from the atmospheres of such planets, and 3) a sample of target stars with known terrestrial planets. In the long-term part of this roadmap the planning for such a mission should be made, and the funding for its launch secured.

LS-3: *Astrometric detections of terrestrial planets with space missions and ground-based ultra-precise RV measurements: This along with LG-1 should complete the mass function of planets down to the low mass end and to fully characterise planetary system architectures* (**KQ1, KQ2, KQ4, KQ5**).

5.5.3 Anticipated Milestones

1. Detections
    a. Complete census of exoplanets: good sampling of the mass/semi-major axis parameter space from $m = 1\ M_{Earth}$ to $10\ M_{Jup}$ and $a = 0.01 – 10\ R_{Jup}$
    b. Good understanding of the the structure of Exoplanetary Systems
    c. Excellent Targets for flagship missions to characterise
2. Characterisation of the Internal Structure of exoplanets
    a. Mass-Radius relationship of giant planets up to a = 100 AU
    b. Mass-Radius relationship of Terrestrial planets (1-5 M_{Earth}) with a < 1 AU
3. Characterization of Atmospheres of exoplanets

a. Spectra of few of Super-Earths in habitable zone of solar-type stars
b. Spectra of terrestrial planets (1–5 M_{Earth}) in the habitable zone of G stars

5.6 General Comments and Recommendations

G1: *International Cooperation/Coordination.*

Although competition is a healthy aspect of science, when it comes to expensive space mission's international cooperation will be needed. In the next 10-15 years the ESA budget may make it more conducive to fund small space missions and likewise for the international community. Such small missions will clearly have scaled-back scientific goals. An obvious consideration is for one or more countries to combine fiscal resources to fund a larger mission with more ambitious science goals. In this case there should be a smooth and efficient interface between all the participating space agencies.

G2: *Better coordination between ESA and ESO.*

The study of extrasolar planets, particularly terrestrial ones, is a key science goal of both ESA and ESO. Observations from ground-based facilities are becoming more and more an integral part of space missions as we have already seen with CoRoT and Kepler. For PLATO inadequate ground-based follow-up may compromise many of the important science goals of the mission. It is often not easy to get granted time for the ground-based support of space missions as this does not always produce an immediate scientific return. However, these relatively inexpensive ground based observations are essential for maximizing the scientific return of very expensive space missions.

We encourage ESO and ESA to enter discussions as to how ESO can better support space missions through its ground-based facilities. One solution is for ESA to outright purchase telescope time and to include such costs in the overall budget of a space mission. Alternatively, ESO could be convinced to reserve a fraction of its telescope time for support of space missions. In either case this dedicated time will not circumvent the peer-review process. The community will still have to submit proposals, but these will be competing for the reserved time and thus have a better chance of success. Such a model has worked well for the NASA Keck time.

G3: *Coordination between ESA, national space agencies, and universities.*

There are a number of strong national space agencies in Europe that have launched space missions largely independent of ESA (e.g. ROSAT, CoRoT). These national agencies can provide important resources to the exoplanet community. Good coordination between ESA and national space agencies would make effective use of these different resources. Such coordination could include national missions to test new technologies, or small science missions whose results can help the planning of future ESA flagship missions. ESA can encourage these national efforts by providing technical consultation or small amount of funding to ensure its success (e.g. ESA's small contribution to the CoRoT mission).

G4: *Involve the Planetary Community.*

Astronomers have traditionally dominated the exoplanet community. The early discoveries were made with the radial velocity method, a technique employed by stellar spectroscopists for studying binary stars. Unfortunately, the planetary community has been slow to embrace the field of exoplanets – most participants to major international conferences are still dominated by astronomers. There is much that the planetary community can learn from the exoplanet community, and vice versa. The exoplanet community should strive to include our planetary colleagues in order to make the field more inter-disciplinary.

Recently, there have been efforts to have a forum where participants from both fields can interact. The U.S. Division of Planetary Science, Europlanet, the European Geophysical Union, The German Physical Society (DPG), the AGU etc. all have sessions on exoplanets. The exoplanet *astronomical* community is encouraged to participate in these meetings that has been the traditional domain of planetary scientists and to make these exoplanet sessions large and well attended by both communities. But more can be done. One way is to hold a joint, bi-annual international meeting that attracts colleagues from both the exoplanet and planetary disciplines. Two models for this are the "Cool Stars, Stellar Systems, and the Sun" and the "Protostars and Planets" series of conferences. The former is a bi-annual meeting which was designed to bring the stellar and solar community together to explore the so-called "solar – stellar connection". It was realized that the active star community could learn from solar physicists and vice versa. In over twenty years Cool Stars has grown from a small meeting to one of the largest international meetings with strong participation from both solar and stellar scientists (interestingly, recent meetings have also included exoplanet studies). The "Protostars and Planets" meets less regularly and it brings together the star- and planet formation communities. It is also heavily attended (750 attending at PPV). A similar conference series "Solar and Exoplanetary Systems" could build a better synergy between the exoplanet and planetary community. A bi-annual meeting, alternating between Europe and the U.S., similar to what is done with Cool Stars, would also bring better collaborations between Europe and the U.S. Such a conference series would have a broader strategic goal in building a broader community base when it comes time to propose expensive flagship missions.

These efforts should not stop with planetary scientists. Understanding the conditions that create habitability on an exoplanets requires expertise from diverse fields: chemistry, biology, and geology. The exoplanet community should strive to make the field more interdisciplinary.

G5: *A Rigorous Public Outreach.*

A rigorous public outreach is essential for the survival of the field. Here the exoplanet community has a distinct advantage. Astronomy in general captures the public imagination, but more so exoplanets. Fifteen years after the discovery of 51 Peg b new exoplanet discoveries continue to make the headlines. The layperson as much as the professional astronomer wants to learn about worlds around other stars. The community must exploit this interest with a rigorous public outreach.

G6: *Keep a vibrant community going.*

The field of exoplanets is arguably well over 20 years old, dating back to the first attempts by Campbell and Walker in the early 1980s to search for exoplanets using precise stellar radial velocity measurements. Many of the early pioneers in the field will be well past retirement when a flagship space mission to characterise terrestrial planets in the habitable zone flies in 20-25 years. The characterization of terrestrial exoplanets is the destiny of our young scientists. To quote from the inaugural address of John F. Kennedy: "The torch has been passed to a new generation". This passing of the torch will occur in the lifetime of this proposed roadmap.

The exoplanet community is fortunate to have a vibrant field that attracts young scientists as witnessed by their attendance in large numbers at international exoplanet conferences. The community needs to build on this vibrancy and to nurture it. The exoplanet field, particularly in space missions, must strive to have achievable milestones and goals that produce tangible scientific results in the near- and mid-term that will help promote young careers and guarantee a healthy influx of the best and brightest into the field. It would be foolish to focus vast efforts and resources for a space mission that will yield scientific results in 20-25 years. Young scientists need to build careers based on scientific achievements not promises.

European and National programs should be established to fund talented young planetary and exoplanetary scientists in order to build cross disciplinary research groups. International and national "exoplanet" centers can help promote mobility and collaboration and to keep the field vibrant and competitive (in terms of space funding) with other scientific fields.

6 Summary

In our Exoplanet Roadmap we have proposed a number of milestones and recommendations that we feel will help turn exoplanet research into bona fide *exoplanetary science* – a field that compares the characterstics of exoplanetary systems to each other and to our own solar system. We have identified three major "paths" in our roadmap that are essential for this comparative planetology: 1) Detections – we must complete the census of planetary systems to ensure there are no major gaps in our knowledge. 2) Structure – knowing the true mass, radius, internal structure and composition of planetary bodies as a function of orbital distance and host stars is essential for understanding planet formation. 3) Atmospheres – the physical parameters, chemical composition, and evolution of exo-planetary atmospheres must be understood if we are eventually to interpret possible bio signatures from terrestrial exoplanets and to understand the conditions under which life can form.

Although all of our numerous recommendations contribute to our goal of comparative exoplanetology, we can identify several "priority" needs in each one:

Detections: The discovery space must be completed by extending the discovered exoplanets to the lowest possible mass and to the largest possible orbital distance around all types of stars. We also must find planetary systems like our own including terrestrial planets in the habitable zone of solar-type stars. We need to answer the question of how unique the properties of our solar system are, as well as if these special characteristics are essential for the development of life on its planets. Also of importance are detections of nearby exoplanets that are amenable to detailed characterization studies. All detection methods (Radial Velocity, transits, microlensing, astrometry, imaging, and timing variations) can contribute to these important goals.

Structure: CoRoT, Kepler, and ground-based surveys (e.g. SuperWASP, HATNet, MEarth) have greatly advanced our understanding of the structure of mostly giant plants in short period orbits. This knowledge must be extended to larger orbital distances and especially to the terrestrial mass regime.

Atmospheres: Progress in this path currently lags the other two, but there has been encouraging results in recent years. The reflectance, effective temperature, and first chemical species have been measured for a few transiting hot Giant planets. These types of data must be extended to lower mass planets and out to at least the habitable zone of F-G type stars.

With respect to possible future space missions that can be selected under CV2, we can identify 3 "high priority " mission types:

- A mission for the characterization of exoplanetary atmospheres down to Super-Earth masses (≈ 5 M_{Earth}), either as close in planets (transiting systems) or ones at large orbital distances (angularly resolved detections). A space mission that can characterise a wide range of planetary atmospheres will provide a major "boast" to this roadmap path.
- A photometric mission to characterise the internal structure of terrestrial planets. PLATO will largely accomplish this goal and thus this mission has high priority for this roadmap
- An astrometic mission to find terrestrial planets orbiting in their HZ. Astrometry provides a key parameter of exoplanets – their mass. Space-based astrometric measurements have the potential of finding those terrestrial planets which will form the target list for future missions aimed at determining other planetary parameters. Gaia will measure the mass of a large number of exoplanets, but only for giants. SIM-Lite would have done this for terrestrial planets, buts its "demise" has left a gap in our roadmap. An astrometric mission with the same precision as SIM-Lite but focussing on exoplanets may achieve the same "exoplanet" goals.

In terms of technological development, the highest priority is to assess which direct imaging technique (coronagraphy, nulling interferometry, external occulters) is the one to use for a future flagship mission in order to characterise habitable terrestrial planets.

The EPR-AT refrains from prioritizing these missions for we do not want to pre-empt, or influence the process of the peer review. An intelligent decision on the type of mission to fly must be based on a direct comparison of the proposals. This should take into account which provides the most scientific return for the cost, and if most of the science objectives cannot be accomplished with existing and future (i.e. funded) ground and space-based facilities.

7 References

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8 Appendix

8.1 Overview of Existing Facilities

Below is a brief summary of existing and proposed facilities that can be used for exoplanet studies. It is not intended to be exhaustive.

8.1.1 Radial Velocity Facilities

There are a number of high-resolution spectrographs worldwide that are capable of making high precision radial velocity measurements. These employ either the simultaneous Th-Ar calibration method or the iodine gas absorption cell. Table 2 lists the known instruments capable of making radial velocity measurements to an accuracy of better than 10 m s^{-1}. Most of these have already made exoplanet discoveries. RV searches for planets lack sufficient telescope time and such facilities can provide much needed observational data.

Telescope	Instrument	Wavelength Reference
1-m MJUO	Hercules	Th-Ar
1.2-m Euler Telescope	CORALIE	Th-Ar
1.8-m BOAO	BOES	Iodine Cell
1.88-m Okayama Obs,	HIDES	Iodine Cell
1.88-m OHP	SOPHIE	Th-Ar
2-m TLS	Coude Echelle	Iodine Cell
2.2m ESO/MPI La Silla	FEROS	Th-Ar
2.7m McDonald Obs.	2dcoude	Iodine cell
3-m Lick Observatory	Hamilton Echelle	Iodine cell
3.8-m TNG	SARG	Iodine Cell
3.9-m AAT	UCLES	Iodine cell
3.6-m ESO La Silla	HARPS	Th-Ar
8.2-m Subaru Telescope	HDS	Iodine Cell
8.2-m VLT	UVES	Iodine cell
9-m Hobby-Eberly	HRS	Iodine cell
10-m Keck	HiRes	Iodine cell

Table 2: Facilities with high resolution spectrographs capable of precise stellar radial velocity measurements to better than 10 m s^{-1}. All of these facilites have discovered exoplanets

8.1.2 Large Telescopes

8.1.2.1 European Southern Observatory

ESO currently operates two major facilities: the 3.6m Telescope on La Silla and the four 8.2m telescopes of the Very Large Telescope.

<u>HARPS at La Silla</u>

The High Accuracy Radial Velocity Planet Search (HARPS) spectrograph mounted on the 3.6m telescope is dedicated to the discovery of extrasolar planets. It has a radial velocity precision of 1 m/s and is the premier RV planet hunting machine in the world. It has discovered some of the lowest mass planets and is one of the "work horses" for the follow-up of CoRoT transit candidates. Recently, it provided the radial velocity confirmation of CoRoT-7b, the first transiting terrestrial "Super-Earth" discovered by CoRoT.

<u>The Very Large Telescope</u>

Instrumentation at the four 8.2m VLTs on Paranal include:

1. UVES: High resolution spectrograph operating in the 0.3-1.1 μm range and resolving power of R′= 80,000 – 110,000. It is equipped with an iodine absorption cell for precise stellar radial velocity measurements.
2. CRIRES: High resolution infrared spectrograph with resolving power of R = 100,000 operating in the spectral range 1-5 μm. It is equipped with absorption cells for precise stellar radial velocity measurements.
3. FLAMES: Multi-object spectrograph for intermediate and high resolution spectroscopy
4. ISAAC: Infrared imager operating in the 1-5 μm range. Spectroscopic modes offer resolving power of R = 500 – 3000.
5. HAWK-I: Cryogenic wide field imager covering J, H, K, Bracket gamma, CH_4, H_2, 1.061 μm, 1.187 μm and 2.090 μm.
6. XSHOOTER: Multiwavelength (300-2500 nm) medium resolution spectrograph.
7. SINFONI: A near-infrared (1.1 - 2.45 μm) integral field spectrograph fed by an adaptive optics module.
8. AMBER: A near-infrared, multi-beam interferometric instrument, combining simultaneously up to 3 telescopes.
9. NACO: Adaptive optics high contrast imaging system operating in the 1-5 μm range.

<u>Planned or proposed Facilities</u>

ESPRESSO: This is a high resolution spectrograph to work on single units of the VLT or in combined 4-UT mode. The instrument will be stabilized and use either Th-Ar or laser frequency comb for wavelength calibration. The goal is for a 10 cm/s measurement precision. Approved in July 2010 and expected to have first light in 2015.

PRIMA on the VLTI: Phased Referenced Imaging and Micro-arcsecond Astrometry facility is designed to provide 10 micro-arcsecond astrometry in the K-band.

SPHERE (2012): Planet finders combining extreme AO, coronagraphy, differential imaging from 0.95 to 2.3μm (narrow and band imaging, low and medium resolution spectroscopy)

8.1.2.2 Keck Observatory

The Keck Observatory operates two 10-m telescopes on the summit of Mauna Kea. Instrumentation that is pertinent to exoplanet studies includes:

1. HiRes: A high resolution spectrograph operating in the 0.3 – 1 μm region and with resolving power of R=25,000 - 85,000. It is equipped with an iodine absorption cell for precise radial velocity measurements (s~2-3 m s^{-1}).
2. NIRC-2/AO: NIRC2 is a near-infrared instrument that takes advantage of the adaptive optics on the Keck II telescope. In imaging mode it provides an image scale of 0.01, 0.02, and 0.04 arcseconds/pixel. In spectroscopic mode it provide resolving powers of R = 2580 – 11430 in J, H, and K.
3. NIRSPEC: NIRSPEC is a near-infrared cross-dispersed echelle grating spectrometer destined to operate at the Nasmyth focus on Keck II. It provides spectroscopy at resolutions of R=2,000 or 25,000 over the 1-5 μm wavelength range
4. Keck Interferometer: The interferometric mode of Keck combines light from the two 10m telescopes. The interferometer can reach high angular resolutions to a small fraction of an arcsecond. The Keck Interferometer has 3 modes: V2-science working in the near infrared (H&K band) and mid-IR (L-band at 3.6μm), and the Nuller, working in N-band (10μm), as well as the SPR (self-phase referencing for high spectral resolution) working in the K-band.

Planned instruments:

ASTRA is ASTrometric and phase-Referenced Astronomy upgrade extension of the Keck Interferometer. It will allow KI to observe two objects simultaneously, and to measure the distance between them with a precision eventually better than 100 μas.

8.1.2.3 Gemini Telescopes

Gemini observatory operates two 8-m telescopes respectively in the North hemisphere (US, Hawaii) and the South hemisphere (Chile, Cerro Pachon)

1. GMOS (multi object, long slit, IFU and imager (0.36-1.1μm).
2. NIRI and NIFS : imager and spectrograph (1-5μm) fed by AO.
3. Michelle : mid IR imager and spectrometer (7-26μm).
4. NICI : near IR coronagraphic imager (1-5μm) fed by AO.
5. T-ReCS : mid IR imager and long slit spectrograph.

Planned instruments:

GPI (Gemini Planetary Imager, 2011-2012) : extreme AO + coronagraph + differential imaging from 0.9 to 2.4μm (integral field spectrograph, low resolution).

8.1.2.4 Subaru 8.2m Telescope

Subaru is located at Mauna Kea. It currently has the following instruments:

1. MOIRCS: The Multi-Object Infrared Camera and Spectrograph provides imaging and low-resolution spectroscopy from 0.9-2.5 microns over a 4 arcmin x 7 arcmin field of view.
2. IRCS: Infrared Camera and Spectrograph provides imaging and low-resolution spectroscopy (R=100-2000) from 0.9-5.5 microns.
3. COMICS: The Cooled Mid-Infrared Camera and Spectrograph provides imaging and spectroscopy (R ~ 2500) in the 8-25 micron regime.
4. FOCAS: The Faint Object Camera And Spectrograph provides optical imaging and long slit and multi-slit spectroscopy over a 6 arcmin field of view.
5. SUPRIME-CAM: Subaru Prime Focus Camera -provides optical imaging over a large field of view with a mosaic of CCDs.
6. HDS: High Dispersion Spectrograph provides high resolution (R= 160 000) at optical wavelengths.
7. AO188 + HiCIAO : high order AO + coronagraph + differential imaging for high contrast imaging (0.9-2.5μm).

Planned instruments :

SCExAO (2010-2011): extreme AO + coronagraph (improvement of AO188+HiCIAO).

8.1.2.5 Grand Telescope Canarias (GTC) 10.4 m telescope

The GTC is a 10.4 m telescope operated on La Palma, Canary Islands. It saw first light in 2009. Planned instrumentation includes:

1. OSIRIS: OSIRIS is an imager and spectrograph (R=300-2500) for optical wavelengths from 0.365 to 1.05 μm with a field of views of 7.8 x 8.5 arcmin.
2. CIRCE: Canary Infrared Camera (1-2.5 μm). It may work as a polarimeter and low amd medium resolution spectrograph.
3. EMIR: A wide field near-infrared (0.9 – 2.5 μm) camera and multi-object and medium resolution spectrograph (R~4000).
4. FRIDA: InFRared Imager and Dissector for Adaptive optics is an integral field spectrograph with imaging capabilities with filters at ZJHK . It will have high spatial resolution (0.01”) and a range of spectral resolutions up to R=30,000.
5. NAHUAL: High resolution spectrograph (R > 50,000) for the near infrared. Gas absorption cells will be used to provide wavelength calibration for high precision RV work (goal: 1 m/s).

8.1.2.6 Hobby-Eberly Telescope 9.4m Telescope (HET)

The HET is a 9.4-m fixed-elevation telescope in West Texas. It operates in queue scheduling mode. The High Resolution Spectrometer (HRS) provides resolving power of up to R = 120,000. An iodine absorption cell provides the wavelength reference for precise stellar RV measurements.

8.1.2.7 Large Binocular Telescope 2x8.4m Telescope (LBT)

The LBT is composed by two 8.4 telescopes operating in Arizona. The instruments operating or planned are:

1. The LBC Large Binocular Cameras are two prime focus cameras approximate field of view of 27' x 27'.
2. Lucifer is a multi-mode instrument for seeing limited as well as for diffraction limited conditions, with the following observing modes:
   - Direct imaging over a 4x4 arcmin2 FOV (seeing limited)
   - Long slit spectroscopy (seeing and diffraction limited)
   - Multi-object spectroscopy with slit masks (seeing limited)
   - Diffraction-limited imaging over a 0.5’x0.5’ file FoV
   - Add-on capability for an integral field unit (IFU) spectroscopy and imaging with OH-avoidance
3. MODS (Multi-objects double Spectrograph) provide multi-object low- and medium-resolution spectroscopy (R=2000-8000) and imaging across the 330-1100nm band in a 6x6-arcminute field of view.
4. LINC-NIRVANA is an interferometric camera with a beam combiner that will operate at wavelengths between 0.6 and 2.4 microns. When coupled with the adaptive optics system of the LBT the instrument will deliver the sensitivity of a 12 m telescope and the spatial resolution of a 23 m telescope, over a field approximately 10-20 arcseconds square.
5. LBTI (Large Binocular Telescope Interferometer) is a thermal infrared imager and nulling interferometer for the LBT. The system is designed for high spatial resolution, high dynamic range imaging in the thermal infrared. Operating between 3.5 and 13 μ in a field of view of 40 x 60 arcsec.
6. PEPSI (Potsdam Echelle Polarimetric and Spectroscopic Instrument) is a fibre feed high-resolution echelle spectrograph with two polarimeters working in the 383 to 907 nm band.

8.1.3 LOFAR

The LOw Frequency ARray (LOFAR) telescope is an innovative European radio telescope that will observe in the relatively unexplored frequency range of 10-250 MHz. The LOFAR project is led by ASTRON in the Netherlands with European partners. Eighteen core LOFAR stations are planned for the Netherlands and international stations have been built in Germany (5 stations), and are others are being developed or planned for France, United Kingdom, and Sweden. LOFAR may have the sensitivity to detected radio emission from exo-magnetospheres. It will also increase the sample of milli-second pulsars, which can provide more pulsar planet candidates. Operation of the first stations began in 2010.

8.1.4 (Warm) Spitzer and Herschel

Spitzer is a 0.85-m space telescope working at Infrared wavelengths. After exhausting its liquid helium Spitzer can now use its Infrared Array Camera (IRAC) in “warm” mode at 3.6 μm and 4.5 μm wavelengths.

The Herschel Space Observatory was launched on 14 May 2009, and is now an operational ESA space observatory offering unprecedented observational capabilities in the far-infrared and submillimetre spectral range 55-671 μm. Herschel carries a 3.5 m diameter passively cooled Cassegrain telescope, which is the largest of its kind and utilises a novel silicon carbide technology. There are three instruments in the focal plane: two direct detection cameras/medium resolution spectrometers, PACS and SPIRE, and a very high-resolution heterodyne spectrometer, HIFI. The focal plane units of the instruments are contained inside a superfluid helium cryostat. Herschel is an observatory facility and is a partnership between ESA, the instrument consortia, and NASA. The mission lifetime is determined by the cryostat hold time.

Herschel is expected to make major contributions all across astronomy, but as what concerns exoplanets, studies of the processes of star- and planet-formation play a major role. Also detailed spatially resolved observations of debris systems are expected to contribute to our understanding. In the Solar System, the asteroid and Kuiper belts are examples of debris systems In particular, the Kuiper belt has an estimated dust luminosity $L_{\mathrm{dust}}/L_{\mathrm{Sun}} \sim 10^{-7}$–$10^{-6}$. Such debris systems orbiting nearby solar type stars are expected to be observable by Herschel. They could display a variety of structural features such as clumps, rings, belts, excentric distributions and spiral patterns depending on the geometry of other orbiting bodies in the system, and therefore spatially resolved multi-color observations are important. In most cases, these features are believed to be formed, shaped and maintained by the dynamical influence of planets orbiting the host stars. In a few cases, the presence of the dynamically important planet(s) should be able to be inferred from direct observation.

As an early result we can mention the solar-type star q^1 Eri which is known (from ground based observations, Liseau et al, 2008) to be surrounded by debris, extended on scales of ≤ 30”. Observations using the Photodetector Array Camera and Spectrometer (PACS) aboard the HSO have led to that for the first time the q^1 Eri disc been resolved at far infrared wavelengths (Liseau et al., 2010). The PACS observations at 70 μm, 100 μm and 160 μm reveal an oval image showing a disc-like structure in all bands, the size of which increases with wavelength. The observed emission is thermal and optically thin, and consistent with debris at temperatures below 30 K at radii larger than 120 AU. From image de-convolution, it is found that q^1 Eri is surrounded by an about 40 AU wide ring at the radial distance of ~85 AU. This is the first real Edgeworth-Kuiper Belt analogue ever observed.

8.1.5 Transit Space Missions: CoRoT and Kepler

8.1.5.1 CoRoT

CoRoT is a space mission launched in December 2006 whose operations are foreseen until March 2013. It consists of an afocal telescope with 27cm pupil and has two parallel main scientific programs: the asteroseismology study of a selected sample of relatively bright stars and the search for extrasolar transiting planets. CoRoT is a French national-lead program with the collaboration of the partners ESA, Austria, Belgium, Brazil, Germany and Spain. CoRoT has fulfilled the pre-launch technical specifications of photometric performances, and it is regularly providing light-curves of stars with unprecedented photometric quality, stability and duty cycle. Among the most relevant results provided so far are the study of the oscillations of giant and hot stars and the discovery of CoRoT-7b: the first Super-Earth with a measured radius, CoRoT-9b, a giant planet orbiting within the temperate zone, and CoRoT-3b: the first confirmed inhabitant of the brown-dwarf desert.

During its operation, CoRoT will discover many gas giant extrasolar planets with periods up to 100 days, which will provide fundamental information for the distribution of planets around main sequence stars in the galaxy and for studies of their atmosphere. Most interestingly, CoRoT has proved its capability of discovering planets down to two Earth radii, entering the domain of the rocky planets, which are of particular interest for the characterization of their internal structure

8.1.5.2 Kepler

The Kepler space telescope is a 0.95m diameter Schmidt telescope in an earth-trailing orbit. It will monitor approximately 100,000 stars over a 3.5 year nominal mission life in order to search for transiting planets in the habitable zone of stars with a wide range of spectral types. Kepler was successfully launched in March 2009. To date it has discovered 5 transiting extrasolar planets. (http://kepler.nasa.gov/)

8.1.6 Microvariability and Oscillations of Stars (MOST)

MOST is a 15cm space telescope launched in June 2003. Its primary science goals are the study of stellar oscillations. It has been used for observations of known transiting exoplanets, in particular to search for reflected light and to place contraints on the exoplanet albedo.

8.1.7 Microlensing Facilities (not exhaustive)

Event Detection:

OGLE: Dedicated 1.3m telescope in Chile run by the Unversity of Warsaw. It targets stars in the Galactic Bulge and Magellanic Clouds.

MOA: Japan/New Zealand collaboration using a 0.6m telescope at Mt. John Observatory in New Zealand.

Event Follow-up

PLANET: Five 1-m class telescopes distributed in longitude in the southern hemisphere.

μFun: Informal consortium of observers dedicated to photometric follow-up of microlensing events.

RoboNet II: global network of three 2-m robotic telescopes.

8.2 Planned and Proposed Facilities

8.2.1 Extremely Large Telescopes

8.2.1.1 The European Extremely Large Telescope (E-ELT)

1. EPICS (0.95-2.0 μm): extreme AO, high contrast imaging. Integral field spectroscopy with low resolution (R<100) + differential polarimetry in the visible (500-900nm)
2. Cosmic Dynamics and Exo-earth experiment (CODEX): A high very stable, high resolution (R > 120,000) spectrograph capable of achieving a radial velocity precision of 2 cm/s over decades

8.2.1.2 The Thirty Meter Telescope (TMT)

1. PFI: extreme AO, high contrast imaging (1.1-2.4 mm): extreme AO, high contrast imaging. Integral field spectroscopy with low resolution (a few hundreds).
2. High-Resolution Optical Spectrograph (HROS): An R=50,000 spectrograph operating in the 0.31 – 1.1 μm range that can be used for Doppler searches of exoplanets
3. Planet Formation Imager (PFI): 10^9 contrast ratio imager for the direct detection of exoplanets.
4. Near-IR AO-fed echelle spectrometer (NIRES): R=20000-100000 spectrograph operating in the 1-5 μm range for the detection of terrestrial planets around low mass stars.

8.2.1.3 The Giant Magellan Telescope (GMT)

A telescope consisting of seven segments of 8.4-m diameter that will provide the equivalent collecting area of a 24.5-m diameter telescope.

8.2.2 The James Webb Space Telescope (JWST)

Space observatory to be launched in 2015. JWST will allow direct imaging and transit spectroscopy of exoplanets in the IR (0.6 - 28 μm).

1. NIRCAM (0.6-5 μm): narrow and broad band imaging (coronography).
2. NIRSPEC (1-5 μm): multi-object spectrograph (low and medium resolution, R=100-3000).
3. TFI (1.6-2.6 / 3.1-4.9 μm): integral spectroscopy (R=100) including coronagraphy.
4. MIRI (5-28 μm): combines 2 modules, an imager with coronagraphs and slit spectroscopy (narrow and broad bands + low resolution R=100), in addition with a integral field unit (R=3000).

8.2.3 Gaia

Gaia is a space astrometric mission that it the successor to the successful HIPPARCOS mission. It will carry out an all-sky astrometric survey on all objects in the magnitude range V = 6-20 during the time span 2012-2017. Final results will be available in 2020. It will achieve an astrometric precision of 6 μas on bright stars and 200 mas on faint stars. (Note the astrometric perturbation of a Jupiter analog around a solar-type star at 10 pcs is ≈ 500 μas.) It has the capability of discovering a number of giant planets and multiple systems, as well as to derive the true masses of know giant exoplanets.

8.2.4 SPICA

The proposed JAXA/ISAS-led Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is designed to be the next generation long wavelength infrared astronomical observatory following on from the highly successful ESA Herschel Space Observatory. It will operate over the 5 to 210 micron wavelength range and employ a 3 m class telescope cooled to below 6 K allowing unprecedented sensitivity in the long wavelength infrared regime. SPICA will also be an essential pre-cursor to more futuristic facilities such as the proposed large space based infrared interferometers as it will demonstrate many of the technologies required for these missions. SPICA has been selected for inclusion in the next phase of the European Space Agency's Cosmic Vision program for future space science missions as a mission of opportunity and is currently awaiting approval by JAXA and ESA before entering Phase B. It is expected that the mission will be launched in 2018 with a guaranteed three year lifetime, however, because the cooling of the telescope and instruments is achieved using closed cycle mechanical coolers, it is expected that the actual operational life will be rather longer than this meaning that it should still be operational at the start of operations the second tranche of Cosmic Vision missions due for launch in 2022.

The instrument suite for the SPICA satellite will comprise the following instrument capabilities:

Mid-infrared camera and spectrometers: 5-37 micron imaging and spectroscopy. The grating spectrometers will have a resolving power of typically a few thousand and will cover the full MIR including the 27-37 micron band not accessible to JWST. As an option there will also be two immersion grating spectrometers operating in the short wavelength MIR (~5-15 microns) with resolving powers of up to 30000. These will allow, for instance, the study of the dynamics of protostellar disks.

Far Infrared Spectrometer and Camera: 34-210 micron imaging and spectroscopy. This instrument will be a Mach-Zehnder configuration Fourier transform spectrometer to provide imaging spectroscopy from 34-210 μm covering from the rest frame [Si]34 to [NII]205 micron lines over a 2x2 arcmin field of view.

Guidance Camera: NIR and visible focal plane camera with a scientific imaging and low resolution spectroscopy capability.

MIR Coronagraph: 5-27 micron coronagraph with medium to low resolution spectroscopy. This instrument will have an inner working angle of 3.3λ/D allowing it to image and take modest resolution (r~10-200) spectra of young gas giant planets orbiting as close as ~10 AU around stars at 10 pc distance. There is also an option to extend the wavelength range down to 3.5 micron.

SPICA will have the capability to directly detect and undertake detailed characterisation of a number of hot young gas giant planets using its coronagraph. Additionally the MIR spectrometers will be capable of undertaking transit spectroscopy on many targets with high efficiency and high sensitivity. The coronagraphic capabilities of SPICA will, in principle, exceed those of JWST as the PSF will be very much cleaner and the dedicated instrument will have a rather better contrast (10^{-6} compared to 10^{-4} for JWST). A unique feature of the coronagraph will be the ability to take direct spectra of a few target exo-planets. The far infrared region is unexplored territory for exo-planet research and it is anticipated that both transit photometry and, possibly, spectroscopy will be possible on some targets allowing us to probe to different depths into planetary atmospheres and opening a new discovery space in characterisation. Although not directly related to exo-planets *per se*, the detection and characterisation of exo-Zodi dust clouds is one of the prime goals for the SPICA FIR instrument, following up on the results of Spitzer and Herschel, and will, in combination with the presence or otherwise of planets in the same systems, allow a much more complete picture of planetary formation scenarios and the role of planetesimals.

8.2.5 PLATO

PLATO (PLAnetary Transits and Oscillations of stars) is one of the three M-class missions selected for definition study in the framework of the ESA Cosmic Vision 2015-2025 program. The scientific goals of PLATO are: 1) Detection and basic characterization of exoplanetary systems of all kinds, including small, terrestrial planets in the habitable zone; 2) Identification of suitable targets for future, more detailed characterization. If approved it will be a milestone for the determination of fundamental planetary parameters (M, R, density, internal structure, orbital parameters) and will contribute to the identification of targets for atmospheric characterization.

These goals necessitate photometric observations of bright targets, in order to obtain follow-up confirmation and mass determination by radial velocity monitoring, with the current and next generation telescopes. The physical characterization of exoplanets necessitates precise characterization of the host stars that will be obtained by PLATO through seismic analysis of the host stars, allowing to achieve the few percentage precision required for planet structure and formation modelling.

In order to reach the Earths in the HZ, PLATO will monitor about 20,000 late-type stars (dwarfs and subgiants) brighter than V=11 for 2-3 years. Furthermore PLATO will monitor all the dM stars in its field of view brighter than V=15 with the aim to detect terrestrial planets in their HZ. The total coverage of the PLATO pointings (long runs and step and stare phase), will cover more than half of the entire sky. The detected planets will be a very good sample for future atmospheric characterization missions.

8.3 Space Interferometry Mission: SIM Lite

The SIM Lite Astrometric Observatory is a Michelson interferometer with a 6-m baseline. It will have an astrometric precision of of 4 microarcseconds all over the sky and 1 microarcsecond for selected targets. For exoplanet studies it has three main gaols: 1) to perform the first census of nearby Earth-like planets, to determine the prevalence of Neptune and larger mass planets among a wide range of stellar types, and 3) to search for Jupiter-mass planets around young stars (http://planetquest.jpl.nasa.gov/SIM/).

8.4 Atacama Large Millimeter Array (ALMA)

ALMA is an array of up to 64 12 meter diameter antennae operating in the 31-950 GHz frequency range. It is located in the Atacama desert at an altitude of 5000 m. ALMA will be capable of imaging planetary systems in the earliest stages of their formation when they are still embedded in the protoplanetary disk. Start of early science is expected in 2011 (http://www.almaobservatory.org/).

8.5 Fourier Kelvin Stellar Interferometer (FKSI)

The proposed FKSI mission is a space-based, two-telescope (diameter ~ 0.5m) infrared interferometer having a baseline of 12.5 meter baseline on a boom. It is passively cooled to 60 K and will operate in the spectral range 3 to ~10 microns. The main scientific goals for the mission are the measurement and characterization of the exozodiacal emission around nearby stars, debris disks, and the atmospheres of known exoplanets, and the search for Super-Earths around nearby stars. (see Danchi et al. 2004).

9 List of Acronyms

ALMA: Atacama Large Millimeter/Sub-millimeter Array
AMBER: Imaging and spectroscopic VLTI focal instrument
AO: Adaptive Optics
CNES: Centre National d'Etudes Spatiales (France)
CoRoT: Convection Transits Rotation (space-based transit search, CNES, Austria, Belgium, DLR/Germany, Spain)
COMICS: Cooled Mid-infrared Camera and Spectrograph (Subaru)
CRIRES: Cryognic High-resolution Infrared Echelle Spectrograph
EPICS: Planet Imager and Spectrograph (E-ELT)
ESO: European Southern Observatory
ESA: European Space Agency
ELT: Extremely Large Telescope
E-ELT: European Extremely Large Telescope
ESPRESSO: Echelle SPectrograph for Radial vElocity Super Stable Observations
EUCLID: dark energy space mission (ESA)
FGS: Fine Guidance Sensors (HST)
FKSI: Fourier Kelvin Stellar Interferometer
FOCAS: Faint Objet Camera and Spectrograph (Subaru)
GAIA: ESA astrometric space mission
GMOS: Gemini Multi-object Spectrograph
GMT: Giant Magellan Telescope
GPI: Gemini Planet Imager
GRAVITY: Adaptive optics assisted two object beam combiner instrument for the VLTI
GTC: Grand Telescope Canarias
HARPS: Harps Accurate Radial Velocity Planet Searcher (Radial Velocity spectrograph)
HAWK-I : High Acuity, Wide field K-band Imaging
Herschel: 3.5m space telescope working in far IR and sub-mm band. Launched in 2009
Hipparcos: ESA astrometric satellite mission (1989-1993)
HiCIAO: High Contrast Instrument for the Subaru Next Generation Adaptive Optics
HDS: High Dispersion Spectrograph on Subaru
HiRes: High Resolution Spectrograph on Keck
HST: Hubble Space Telescope
HZ: Habitable Zone
IRCS: Infrared Camera and Spectrograph (Subaru)
IFU: Integral Field Unit
IR: Infrared wavelength region
IRTF: Infrared Telecsope Facility
JAXA: Japan Aerospace Exploration Agency
JWST: James Webb Space Telescope

Kepler: space-based transit search telescope (NASA)
LBT: Large Binocular Telescope
LBTI: Large Binocular Telescope Interferometer
HATNet: Hungarian-made Automated Telesope Network
KNTNet: Korean Microlensing Telescope Network (ground-based microlensing)
MOA: Microlensing Observations in Astrophysics
MicroFUN: Microlensing Follow-up Network
MiNDSTEp: Microlensing Network for the Detection of Small Terresrtrial Exoplanets
MOST: Microvariability and Oscillations of Stars
MoU: Memorandum of Understanding
NACO: NAOS-CONICA (Nasmyth Adaptive Optic System and Coude Near Infrared Camera)
NASA: National Aeronautics and Space Administration (U.S.)
NIR: Near Infrared wavelength region
NICI: Near infrared coronagraphic imager
MOIRCS: Multi-object Infrared Camera and Spectrograph (Subaru)
OGLE: Optical Gravitational Lens Experment (ground-based microlensing)
OPTICON: Optical Infrared Coordination Network for Astronomy
pc: parsec
Phoenix: High resolution IR spectrograph on Gemini South Observatory
PLATO: Planetary Transits and Oscillations of Stars (space-based transit mission, ESA)
PRISMA: Swedish space mission to test formation flying
PRIMA: Phase-referenced Imaging and Microarcsecond Astrometry Facility (VLTI)
RoboNet: Microlensing follow-up network
ROSAT: ROentgen SATellite X-ray observatory
RV: Radial velocity
SIM-Lite: Space Interferometry Mission (NASA astrometric space mission)
Super-WASP: Wide Angle Search for Planets (ground-based transit search)
SPITZER: Infrared space telescope
SPHERE: Spectro-Polarimetric High-contrast Exoplanet Research
STARE: Stellar Astrophysics & Research on Exoplanets (ground-based transit search)
SUPRIME-CAM: Subaru Prime Focus Camera
TFI: Tunable Filter Imager
TMT: Thirty Meter Telescope
TPF-C: Terrestrial Path Finder Coronagraph
TRL: Technological Readiness Level
T-ReCS: mid IR imager and long slit spectrograph on Gemini
VLT: Very Large Telescope (ESO)
VLTI: Very Large Telescope Interferometer