Draft

A Roadmap for Exoplanets

presented by the

Exoplanet Roadmap Advisory Team
(EPR-AT)

appointed by the European Space Agency
(ESA)

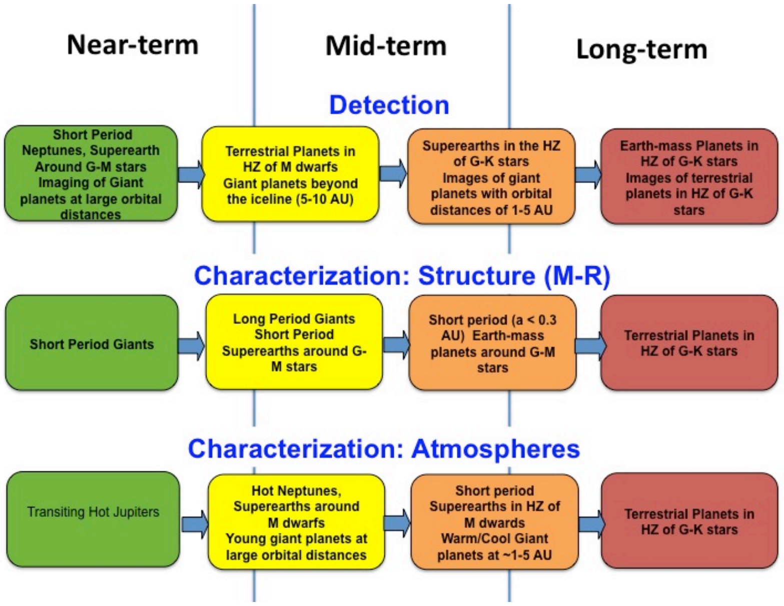
Executive Summary

1. Key Questions and Timeline

1. What is the diversity and architecture of exoplanetary systems?
2. What is the diversity of composition, structure, and atmospheres?
3. What is the origin of the diversity and how do planets form?
4. What makes a planet habitable?
5. Can we detect exo-life and if so, how common is it?

Approximate timeline:

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



Schematic showing the rough timeline for milestones in detection, characterization of internal structure (mass, radius, mean density) and the characterization of spectral atmospheres that are expected over the course of this roadmap. Color is coded from green (easy) to red (most challenging)

The figure is schematic showing expected milestones in the areas of detections, characterization with mass and radius, and the characterization of atmospheric that are expected during the course of this roadmap. Time as well as degree of difficulty proceeds from left to right.

2. Near-term Recommendations (~2011-2017)

The near term roadmap will focus on 1) a more complete census of exoplanets, 2) a better understanding of the architecture of exoplanetary systems, 3) determining the mass-radius relationship for exoplanets that are important for internal structure studies, 4) and to define a target list that can be used for more intense spectral characterization in the next phase of this roadmap, with ground-based and space-based facilities. In the near term it is expected that this spectral characterization will be possible for giant planets around relatively bright stars.

Anticipated Milestones

Detection:

1. More complete census of Planets around F-M stars.
2. A modest sample of terrestrial planets in the habitable zone (HZ) of M-dwarfs and the first HZ terrestrial superearch planet candidates around G-star.
3. Planets around stars more massive than the sun.
4. More direct imaging giant planet candidates at large orbital radii.
5. Planets in different environments, e.g. clusters.

Characterization:

1. Mass-radius relationship, mean densities of a large sample of planets down to Suprearths.
2. Planet light curves in optical and IR (Phase curves, secondary eclipses)
3. Strongest atmospheric signatures from short period Jupiter, Neptune, and possibly superearth planets. More spectra of long period planets (young, large a).
4. Debris disks

N1: *Stellar studies of all stars out to 50 pcs: understanding the host stars of exoplanet systems, statistics as a function of stellar properties.*

N2: *Radial velocity monitoring of several thousand nearby F-K main sequence stars and evolved, intermediate mass stars using optical spectrographs. Several thousands of stars will ensure a large enough statistical sample when trying to correlate planet properties with stellar properties (e.g. abundance, mass, age, etc.)*

N3: *RV Planet Searches in the Infrared with emphasis on short-period, low-mass planets around M dwarfs.*

N4: *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.*

N5: *A Search for Planets Among Stars in Diverse Environments*

N6: *Continued RV monitoring of all known exoplanet hosting stars in order to investigate the architecture of exoplanetary systems and to derive accurate orbital parameters.*

N7: *Securing the necessary telescope resources*

N8: *Characterization of Transiting Planets in the visible and IR with ground-based and on-going space based facilities*

N9: *Optimizing ground-based transit searches*

N10: *Continuation of the CoRoT and Kepler past the nominal mission life*

N11: *A study of exo-zodi systems and their influence on direct imaging of terrestrial planets.*

N12: *A search for radio emission from exoplanets*

N13: *Increase the sample size of pulsar planets*

N14: *Ground-based support of CoRoT, Kepler, and preparation for ground-based support for PLATO*

N15: *Continue ground-based microlensing searches*

N16: *Effective use of Planet finders for Exoplanets Studies*

N17: *Effective use of JWST for Exoplanets Studies (spectral characterization, imaging, photometry, phase curves, colors)*

N18: *Technological studies for Angularly Resolved Detections*

N19: *Theoretical studies on the spectroscopic signatures expected from exoplanets covering a wide range of masses (terrestrial to giant planets) and a wide range of temperatures*.

N20: *An investigation of the influence of stellar activity on habitability and anticipated atmospheric signatures*

N21: *Calibration of giant planet evolutionary tracks*

3. Mid-term Roadmarkers (~2015-2022)

During 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 define the mass-radius relationship of hot giant planets and possibly a sample of Hot Superearths. This should lead to the first studies of the internal structure of exoplanets. JWST may offer the spectral characterizations of several hot Jupiters and hot Neptunes.

Anticipated Milestones to be achieved:

Detection:

1. Giant planets beyond the snow line (3-5 AU) including the discovery of Jovian analog exoplanet systems
2. Planet masses down to an Earth mass.
3. First confirmed Superearths at 0.7-1 AU around a G-type star.

Characterization:

1. The mass-radius relationship down to the Earth-mass regime from transiting planets

2. Low to medium resolution (R=20-200) spectra from space taken visible to mid-infrared of Hot/Warm short-period Planets down to Superearth mass.
3. Low resolution (R=50) spectra taken from visible to near-infrared of Warm/Cool long-period (down to a fraction of an AU) Planets down to Superearth mass

M1. *Preparation for an M-class and/or smaller mission for characterization of exoplanet atmospheres from gas giants to superearths*

M2: *Transit Searches for Small Planets around solar-type stars*

M3*: Secure the ground-based support necessary for follow-up of PLATO transit candidates*

M4: *Obtain accurate stellar parameters using GAIA and PLATO*

M5: *Continue long term RV surveys to find planets at large orbital distances, multiple systems, and to refine orbital parameters of known exoplanets.*

M6: *Continue direct imaging studies from the ground (AO, coronography) to find large planets at large orbital distances.*

M7: *Keep facilities to determine radii of transiting planets found by RV surveys and to search for transit timing and transit duration variations.*

M8 *Devote time on ELT and JWST for key programs for in transit spectroscopy of transiting planets and direct imaging of Giant planets at large orbital distances.*

M9: *Continued technological Research & Development studies into the various Angularly Resolved Detections.*

M10: *Use of ALMA to study exoplanets in their birth environments*

M11: *True mass determination of known giant planets with GAIA: Deriving the true mass function for giant exoplanets..*

M12: *Astrometric Searches for Terrestrial Planets with SIM-lite*

M13 *Obtain a sample of Terrestrial planets in the Habitable Zone of G-K type stars*

4. 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 6.1

L1: *Begin work on a flagship mission to characterize all the known terrestrial planets in the habitable zone of F-K type dwarfs.*

L2: *An astrometric Search for Giant planets using GAIA combined with RV ground-based follow-up observations*.

L3: *Astrometric detections of terrestrial planets with SIM and ground-based ultra-precise RV measurements: This along with L2 should complete the mass function of planets down to the low mass end and to fully characterize planetary system architectures.*

L4: *Use SKA for the detection of radio emission from exoplanets*

L5: *Planning and technological development for the construction of Hyper-telescopes*

L6: *Technological studies for extreme adaptive optics with Hyper Telescopes*

It is essential that technological studies of angularly resolved techniques continue so that these can exploit Hyper Telescopes should they be built.

5. General Comments and Recommendations with no timeline

G1: *Stronger International Cooperation*

G2: *Laboratory measurements to produce line lists, atomic and molecular transition probabilities, opacities, and equation of states.*

G3: *Better coordination between ESA and ESO*

G4: *Coordination between ESA, national space agencies, and universities*

G5: *Involve the Planetary Community*

G6: *A Rigorous Public Outreach*

G7: *Keep a vibrant exoplanet community going*

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The Exoplanet Roadmap (DRAFT)

0. Preamble

This roadmap is a working draft that should not be considered to be the final product. It will be completed and revised after the EP-RAT workshop 7-8 April 2010 and after which we have received additional input from the community. This draft does not have references, but these will be included in the final version. Please note that the role of the EP-RAT is advisory in nature and its recommendations and suggestions by no means preempt or substitute the peer review process and the relevant call for mission proposals.

The recommendations are listed in the executive summary and in the following roadmap we highlight the status of the field and provide justifications for our recommendations.

1. Introduction

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 scientific discipline that attracts some of the brightest young scientific minds as well as enchanting the public. The progress in this field has been phenomenal. A scant 20 years after the first discoveries of giant exoplanets with the Doppler method, we now have discovered over 400 planets in orbit around other stars including the first terrestrial mass objects. We have characterized exoplanets in terms of their mass, radius, and mean density and thus have been able to construct the first crude 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 by those of us who were working in this largely unnoticed field. Although significant progress has been made, the community has to travel a long way before we can truly do comparative planetology, fully understand the process of planet formation, and know, ultimately, how our own solar system formed and how life originated on one of its terrestrial planets.

The detection of exoplanets is a field that requires a diverse range of astronomical measurements that are pushed to the extreme limits: radial velocity precisions of 0.1 – 1 m/s, 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 most of these “extreme” measurements often require expensive space missions.

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. As part of this effort 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.

Although the EPR-AT is making a recommendation to a space agency, a complete roadmap involves surveying the landscape of not only on-going and planned space missions, but ground-based efforts as well. An effective roadmap must take into account all of these. The knowledge gleaned from ground-based studies and previous space missions is essential for the effective planning of future space missions. Given the complexity and expense of space missions we should also have in mind the budgetary and institutional landscape over the course of our proposed roadmap.

2 The Exoplanet Landscape

2.1 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) Micolensing, and 6) Timing variations. To date, all of these techniques have been successful at detecting extrasolar planets. The explanet discoveries/detections are shown in Fig. 1. 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. The symbol "SE" represents a superearth (5 M_{earth}) at 1 AU. The other letters mark the location of planets of the solar system. Note that current disoveries dominate the upper left of the diagram. To date we have found relatively few extrasolar planets that have direct analogs to planets in our solar system. A major goal of detections for this roadmap is to fill the lower right of the mass-distance parameter space and to determine just how unique are the properties of our solar system.

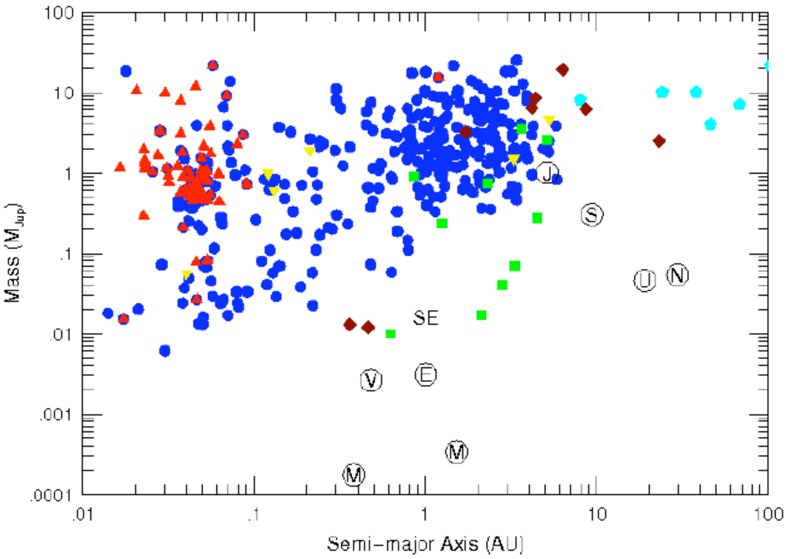

Fig. 1 Exoplanet discoveries from the various search methods in the Mass-Semi-major axis plane. Blue dots: Radial velocity detections; Red triangles: Transit detections; Inverted yellow triangles: astrometric detections; Green squares: Microlensing detections; Blue Pentagons: Imaging detections; Red diamonds: Timing detections. The letters mark the location of the planets in the solar system. "SE" denotes a Superearth with 5 M_{Earth}.

2.1.1 Radial Velocity Method

To date over 400 extrasolar planets have been discovered and 43 stars are are known to have multiple planet systems. The vast majority have been discovered with the radial velocity (RV) technique (see Fig. 1). Not only is the RV method the most successful at detecting exoplanets, but 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 exoplanetary studies 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 $m_pP^{-1/3}$ 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 (semimajor axis < 5 AU) to the star. The Doppler method has detected a planet as light as 1.94 M_{earth} (GL 581e, but at a distance of 0.02 AU. To date the lightest exoplanet detected by RV at 1 AU from a G-type star (nominal habitable zone for a G-type star) is 0.39 M_{Jup} (HD 74156 d) or more than a factor of 100 more massive than an Earth-mass planet.

High precision RV measurements are currently made using two techniques: simultaneous 1) Th-Ar calibration of gas absorption cells (predominantly molecular iodine). Both methods produce comparable precision. The iodine absorption cell has a demonstrated RV precision of 1-2 m/s and the Th-Ar technique exemplified by the HARPS spectrograph has a precision of better than 1 m/s.

A major goal of any exoplanet search is the discovery of an Earth-mass planet in the habitable zone of a G-type star. This goal is clearly driven by the solar system paradigm. We want to understand how life forms and the only example of a habitable planet is that of an Earth-mass object 1 AU from a G2 main sequence star. When searching the possible parameter space for habitable planets this is an obvious region to search. For the RV method this requires an RV precision of about 10 cm/s over a period of several years. 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 “Superearth”. The RV method is within a factor of 3 of being able to detect a superearth of 5 M_{Earth} at 1 AU from G-type star, but more than an order of magnitude away from having the precision to detect an Earth analog. There are two limiting factors hindering the method from detecting such planets: 1) Improved wavelength calibration that is needed to achieve an RV error of at least 10 cm/s, 2) Improved instrument stability, and 3) overcoming the intrinsic variability of the star (stellar noise). Efforts are currently underway to overcome these limiting factors. Laser frequency combs have shown promise as an excellent wavelength calibration that may achieve an RV precision of a few tens of cm/s. Repeated measurements of stars over a long time span may be able to beat down the intrinsic stellar noise.

2.1.2 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 which 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 the radial velocity method it allows us to determine the planet mass and to derive the mean planet density. Transiting planets, furthermore, provide targets for detailed planet characterization by spectroscopic observations of their atmospheres during primary and secondary eclipse.

Up to today, more than 70 confirmed transiting planets are known. From these, 7 were first detected by radial velocity measurements. So far, most of the transiting planets were detected by wide-angle transit surveys from ground (e.g. Super-WASP, HATNet, MEarth, STARE, OGLE) and from space (CoRoT (CNES) and Kepler (NASA)). Key for successful transit searches is high photometric precision since the photometric signal is small (~1% for a Jupiter around the Sun, ~0.01% for an Earth-sized planet). The transit geometry imposes additional constraints, like a high number of surveyed target stars to overcome the low geometrical probability for the transit viewing geometry (~1/a) and long-term, continuous observations not to miss the short transit event. Most modern ground-based transit surveys therefore use wide-angle multi-telescope facilities and networks around the globe to obtain a wide field-of-view (FOV) with high star number and to overcome data gaps due to the day/night cycle. Recently, the MEarth project chooses another search strategy. The project targets planets around M dwarf stars. Since M dwarfs are sparsely distributed in the sky, a wide-field survey would be very inefficient. The project instead uses a one-by-one approach to scan the target stars.

Photometric limitations of ground-based observations due to Earth atmosphere are overcome in space by wide-angle photometric telescopes. The first space mission searching planets via transits was CoRoT (CNES), launched in Dec. 2006. It was followed by the Kepler mission (NASA), operating since March 2009. CoRoT so far detected 7 extrasolar planets and one brown dwarf. The high photometric precision of space telescopes allows detecting small, terrestrial transiting planets. For example, CoRoT-7b is the smallest known terrestrial exoplanet with measured basic parameters so far. Kepler just announced its first 5 planet detections, including a hot Neptune. Both missions are still operating and further planet detections are expected soon.

The low geometrical transit probability leads to a detection bias of the transit method towards low orbital distances (Fig. 1). The most distant planet yet detected by transits has been found by CoRoT (CoRoT-9b with 95 day period). Space missions clearly allow for wider detection coverage of the planet orbital distance parameter space due to their continuous observations. Further distant planets are expected from Kepler, which targets at transiting planets as distant as the habitable zone of G stars.

The PLATO mission under definition study at ESA plans to expand the future search domain by targeting on brighter stars. Its goal is to significantly increase the statistics of confirmed small, terrestrial planets in different stellar environments together with a good characterization of their central stars to put planets into a well characterized context.

Transit planet candidates in stellar lightcurves always require an extensive follow-up programme, since other phenomena like eclipsing binary stars or starspots can also produce a periodic dimming of stellar. Follow-up observations include high-resolution imaging and photometric observations to confirm the signal on the target star with medium to large telescopes as well as medium- and finally high-spectral resolution radial-velocity observations to derive the planet mass. 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. In future, ground-based radial-velocity follow-up could be a bottle-neck 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 project with two, equally important parts: photometric detection of the transit signal and confirmation of its planet nature by determination of the planet mass.

2.1.3 Astrometric Detections (To be completed)

2.1.4 Imaging Detections

The attempt to directly image extrasolar planets was undertaken as soon as their existence was proven in 1995. Facing large contrasts and short separations was often considered a show-stopper for current instruments motivating the development of new technologies. In reflected light, the planet 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 works on evolutionary models have shown early that these characteristics are much more relaxed for young systems since planets can be self-luminous. Then they can also be searched farther form the stars as their intrinsic light is distance-independent. The first successful direct image of an extrasolar planet was obtained in 2005 at VLT for a peculiar system, a young (12 Myr) very low mass star (M8). Since then, several detections of low mass objects were made in young systems (1-700 Myr) with 8-10m class telescopes on the ground and 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. 2, 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. Orbital distances that can be probed are quite large so far (tens of AUs) due to the bias of the detection method (see Fig. 2) while at the same time young systems are relatively distant except for a few cases (β Pic for instance).

As for spectral characterization some of these planets have been observed in several broad-band filters (mostly in the near IR) which allow 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. They are sharing the same properties of L and T type stars.

Another interesting point is that the latest detections (HR 8799 b,c,d, Fomalhaut b, β Pic b) were made around massive A type stars with circumstellar disks suggesting, as suspected, that more massive stars tends to form more massive planets. This result is consistent with the results of RV surveys of intermediate mass evolved stars. One interest of direct imaging is precisely to probe a range of physical separations that is quite large and hence to detect giant planets formed by different ways either by “core-accretion”, or gravitational disk instabilities. For instance, it is very likely that most planets in the Fig. 2 & 3 have been formed like stars. β Pic b could be the first detected object formed as planets since it is located at a distance that is compatible with the core-accretion model.

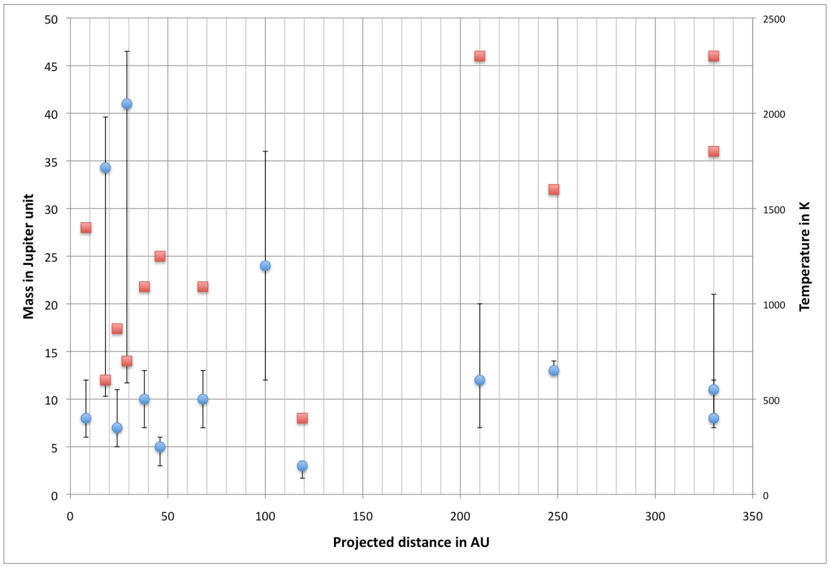

Fig. 2 : Estimated mass (blue dots) and temperature (red squares) vs. separation diagram of young planet candidates found by direct imaging. Objects significantly more massive than planets have been included because unconstrained parameters (like age) can still place them in the planetary regime. Error bars are shown for the mass estimates.

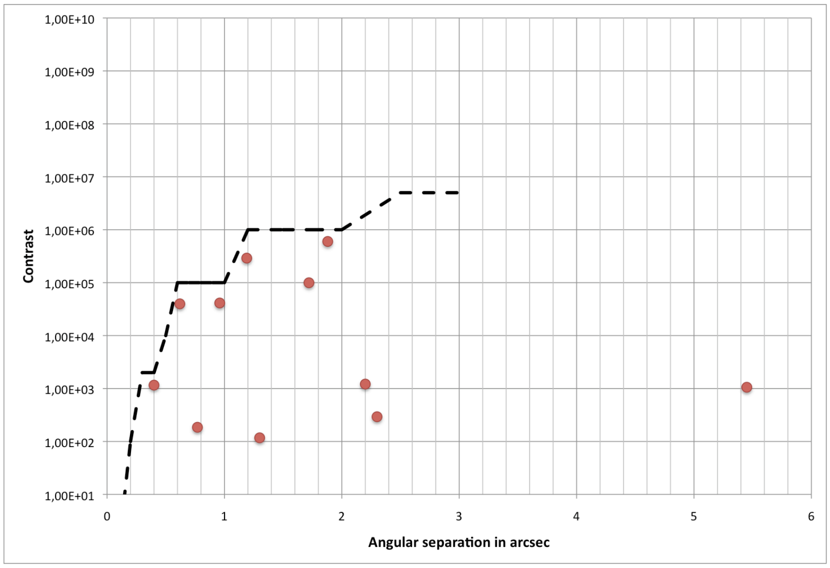

Fig. 3 : Measured contrasts of young planet candidates found by direct imaging. The dotted line is illustrative of the detection limit with current instruments

2.1.5 Microlensing

Gravitational microlensing detections exploits the phenomena that when a foreground star (the “lens”) is aligned with a more distant star (the “source”) gravitation bends the source light into two images (or a ring in the case of a perfect alignment). The resulting magnification is time variable as the projected separation between the source and lens varies. Microlensing events occur on timescales of months. If the source image passes close to the planetary companion of the lens star a further perturbation of the magnification occurs. These timescales for these planetary events are ~1 day for Jupiters and ~1.5 hours for Earths. Hence, microlensing detections require 24 hour photometric monitoring in order to detect any microlensing events due to planetary companions.

Microlensing has several advantages over other techniques:

a. It is more sensitive to low-mass planets and even earth-mass planets can be detected.
b. Microlensing is most sensitive to planets that have a projected distance within a factor of 1.6 of the Einstein ring. For typical lensing stars in our galaxy this corresponds to a projected distance of about 2 AU which is within the habitable zone of certain stars.
c. The microlensing event from a planet occurs regardless of whether it orbits a host star or not. It is the only method that is sensitive to free-floating planets. (Note: free-floating planets have been claimed by imaging studies, but these rely on theoretical evolutionary tracks and the planet mass cannot be directly determined.)
d. Since microlensing surveys are best carried out against the galactic bulge where stellar densities are highest they find planets around stars at large distances and in different regions of our galaxy compared to the other search techniques.
e. Planetary microlensing events are independent of the type of host star. So, unlike say the Doppler method which is only sensitive to late-type stars, microlensing can detect planets around stars all along the main sequence.
f. Microlensing searches, can detect multiple planets in a single event, unlike other methods which require repeated measurements to detect multiple signals.
g. Microlensing programs survey a large number of stars they can quickly provide statistics on the frequency of planets down to terrestrial masses.

There are, however, disadvantages to the microlensing method. 1) These are once only events, so it is not possible for follow-up observations. 2) The lens star is faint, and often not even dectected so follow up observations of the host star are not possible, 3) accurate orbital parameters (period, eccentricity, etc) of the planet(s) are not well derived, and 4) the host stars are distant so these are not well suited for space missions for planet characterization.

To date 10 planet candidates have been found via the microlensing method, mostly from the OGLE and MOA programs. These planets have masses in the range of 0.02 – 3.5 M_{Jup}.

2.1.6 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 as 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 time variations provided by milli-second pulsars (Wolszczan & Frail, 1999).

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 V 391 Per to infer the presence of a 3.2 M_{Jup} planet at 1.7 AU of the star. Because V 391 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 dwarf to search for planetary companions, but with no confirmed detections.

Eclipsing binary stars also can be used to search for timing variations in the eclipses caused by planets either around on companion, or circumbinary planets. Planetary companions in eclipsing binaries found by timing variations have been claimed for QS Vir (Qian et al. 2010a), 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, Szilard et al. 2009). Timing variations of transits can also be used to search for additional planets to known transiting planets.

2.2 Characterization

2.2.1 Fundamental Planetary Parameters (M, R, density, internal structure, orbital parameters)

For a basic characterization of extrasolar planets it is essential to derive their fundamental parameters: radius, mass, density and orbit. Radius, mass and density determine the overall nature of a planet (e.g. gas giant, Neptune-like, terrestrial) and allow first insights into their interior structure. The planetary orbit determines the dynamical evolution of the planet and the energy it received from its host star. Examples for the understanding of planet nature we already gain from the fundamental planet parameters are e.g. 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 of physical 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 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 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. In future, comparative planetology can include, for the first time, not only planets of our Solar Systems, but allows us to compare our system to planets in different environments and evolutionary stages. We are today just at the beginning of opening this research area. Looking back at the enormous surprises we already had when detecting exoplanets at all kinds of unexpected configurations (hot giant planets, large excentricities, large inclinations, etc.) we can not underestimate the scientific impact of increasing the sample of planets with known prime parameters might have.

An important near future goal is therefore to expand the range of planets with known fundamental parameters as wide as feasible with current technological and financial constraints towards smaller planet sizes. The fundamental planet parameters must be known with sufficient accuracy before statistics and comparative planetology on a larger scale can be made. It is therefore important to develop and maintain photometric facilities allowing us to determine planet radii, especially for small, terrestrial planets in the future, in addition to detection methods providing their mass. 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. Furthermore, since the uncertainty of planet parameters is often constraint by our knowledge of the host star, an accurate determination of stellar parameters forms the basis for planet parameter determination.

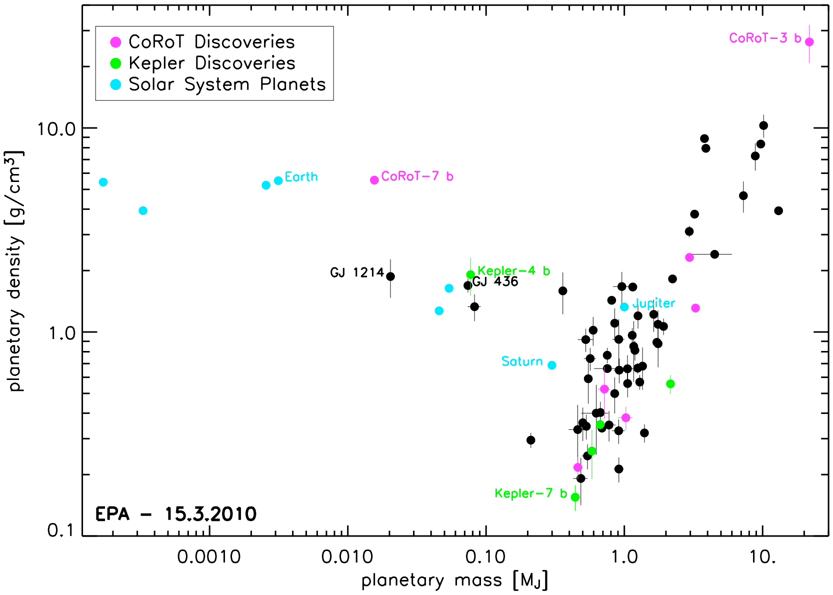

Fig. 4: Density versus mass of known transiting planets.

2.2.2 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 extrasolar planets orbiting very close to their parent star, we can already probe their main atmospheric constituents using transit techniques. With primary transit method, we can indirectly observe the thin atmospheric ring 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 influence 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. This technique was pioneered by two different teams 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. 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 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 can not be measured, but we can appreciate the temperature or albedo variations through time (depending if the observation is performed in the visible or infrared).

The problems that we can tackle with current telescopes are :

- Detection of the main molecular species in the hot transiting planets’ atmosphere (water vapour, methane, CO2, CO, ammonia etc.).
- Constraint of 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) Broad band 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 micron.

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).

But there are many more exoplanets known, albeit that they do not transit or they orbit at large separation from their parent star, making impractical the use of transiting techniques to observe them. Most recently the first spectrum of a hot Giant planet at projected separation of 38 AU was observed from the ground with VLT/NACO (Janson et al., 2010). Spectroscopy in the shorter wavelength range of JHK-band will likely start soon with dedicated integral field units on VLT (SPHERE) and Gemini (GPI).

2.3 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, that 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, for which imaging of the planetary system will be possible, and finally planetary atmospheric measurements will be focused on nearby, and bright objects, to maximize the planetary signal and the signal to noise simultaneously. In light of above considerations it is clear the relevance of a good knowledge of stellar populations in the stellar neighborhood. 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 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 star intrinsically bright, 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. 5 (left panel). Intrinsically bright stars distributions flatten because we have imposed a maximum distance of 300 pc, while faint stars number increases with a power of 1.5. Analogously, for comparison, we report on the right panel the apparent magnitude distribution of stars within 30pc, 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 specially true in the 300 pc volume samples. For example within this volume a number of star forming regions and young stars (e.g. Gould Belt population) are present. These young nearby stars are of considerable interest for the study of the planetary systems formation mechanisms.

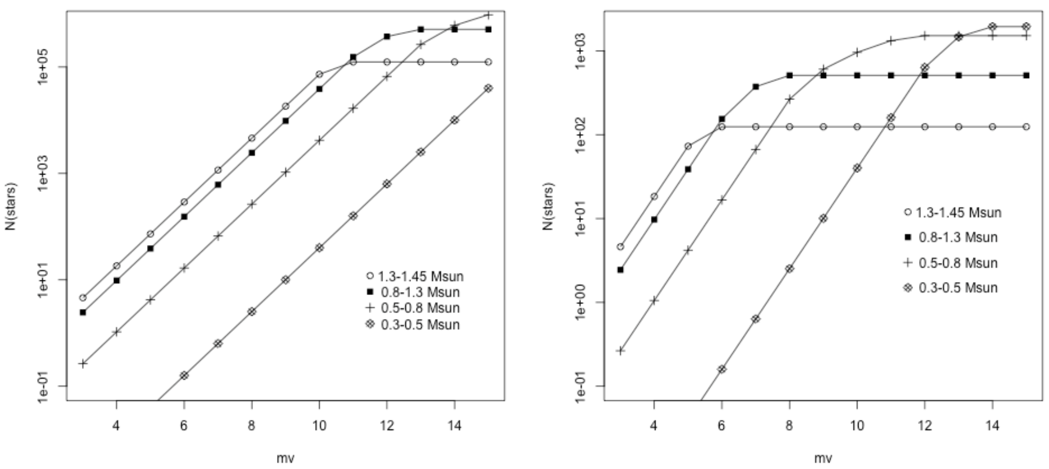

Figure 5: Number of solar-like stars in four mass bins as function of apparent magnitude expected in the solar neighborhood in a volume of radius of 300 pc (on the left) and of 30 pc (on the right)

2.4 Theory: News on the Evolving State of the Art

The long-lasting scientific debate on whether extra-solar giant planets formed 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 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, but Levison et al. (2010) 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, probably the most relevant one, is that of migration reversal in the inner part of disks with inefficient cooling (Paardekooper and Mallema, 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 planets 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 Jupiters 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 extra-solar planets, 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 a 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 mecanism 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 focussed 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., 2006). 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).

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; a few planets at large distances have been detected too. But we have a lack of 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 birth places: the disks. 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? Do super-Earth 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.

3 The Facility Landscape

Figure 5 shows the current and planned major facilities which 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.

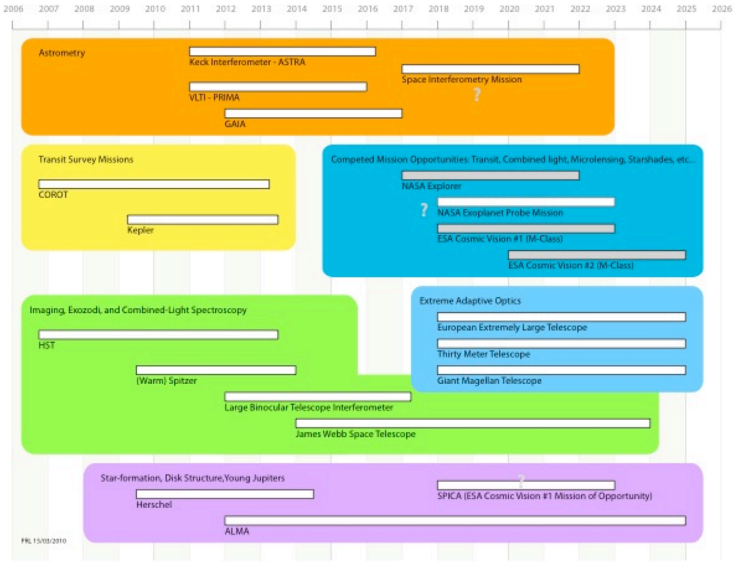

Figure 5: Timeline of current and planned large facilities. Green indicates facilities that are primarily used for exoplanet studies (courtesy Peter Lawson).

4 The Institutional Landscape

The two premier agencies for launching large space missions are ESA and NASA. Our U.S. colleagues have also had to devise roadmaps and to draft recommendations to NASA regarding exoplanet research. Although scientists on both sides of the Atlantic are making recommendations to their respective space agencies in Europe we must recognize that there are institutional differences between NASA and ESA. In the U.S. there is one space agency that is funded by one government. ESA on the other hand is a space agency that is funded by many nations, each with individual government, funding agencies, and political agendas. Furthermore, unlike the U.S. there are strong space agencies in many of the ESA member states (e.g. CNES, DLR) that have funded space missions independent of ESA. NASA funds laboratories like the Jet Propulsion Laboratory in cooperation with universities that can make the necessary technological research and development studies for future space missions. There is no equivalent laboratory funded by ESA. Finally, NASA, in the past has supported ground-based efforts in support of its space mission and has even funded the construction of facilities (e.g. Keck II). Traditionally ESA has not offered the community such ground-based support as these nominally fall under the auspices of ESO. Finally, NASA supports both observational and theoretical studies in exoplanets (e.g. “Origins of the Solar System Program”). In drafting a European roadmap one must also take into account the institutional differences between ESA and NASA.

5 The Budgetary Landscape

A space mission is expensive. The preparation and planning requires 5-10 years and with a final cost of 200-1000 million Euros. Unfortunately, any proposed space mission comes in very challenging budget times. The major countries of the world have spent trillions of Euros (or the equivalent) avoiding a world economic crisis and the recovery looks to be a long and slow one. It seems doubtful that countries in Europe will have the political will to increase funding for space research for the foreseeable future. This will impact the ESA budget for the next 10-15 years, or the time frame of this roadmap.

This budgetary landscape was in the mind of the EPRAT as we drafted this roadmap. The study of exoplanet requires a diversity of space missions: astrometry, direct imaging, characterization, etc. The exoplanet community would love to fly all of these missions. It cannot. The choice and number of space missions the exoplanet community should fight for must be chosen carefully and be ones that provide significant advancement to the field. Large missions of the class of the James Webb Space Telescope that cost upwards of several billion Euros will not be possible in the next 15 years, if not longer.

Whereas in the past it was easier to fund M-class missions (~400 MEuros), in the current budget climate makes it more favorable for the approval of small (~200 MEuros). The operative words for the next decade may well be “small and few”. The exoplanet community should “scale back” its ambitions and give serious thought to what science can be done on a small class missions. The science goals for such a mission will clearly not be as ambitious as a M-class mission, but may still provide significant milestones to the exoplanet roadmap.

6 The Exoplanet Roadmap

6.1 Goals and Key Questions

The goal of this roadmap is not merely to detect another “Pale Blue Dot”, but rather 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 stars. This comparative planetology includes not only the detection, but 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 range from the detection to the characterization:

1. Architecture: multiple planets, accurate orbital elements
2. Mass, radius, and mean density of exoplanets
3. Spectroscopic features of exoplanetary atmospheres
4. Exo-magnetospheres
5. Possible biosignatures.

The key questions we hope to answer by the end of this roadmap are

6. What is the diversity and architecture of exoplanetary systems?
7. What is the diversity of composition, structure, and atmospheres?
8. What is the origin of the diversity and how do planets form?
9. What makes a planet habitable?
10. Can we detect exo-life and if so, how common is it?

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 can 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 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 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 a dispassionate and unbias recommendations as far as possible.

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

The near term roadmap will focus on 1) a more complete census of exoplanets, 2) a better understanding of the architecture of exoplanetary systems, 3) determining the mass-radius relationship for exoplanets that are important for internal structure studies, 4) and to define a target list that can be used for more intense spectral characterization in the next phase of this roadmap, with ground-based and space-based facilities. In the near term it is expected that this spectral characterization will be possible for giant planets around relatively bright stars.

Anticipated Milestones

Detection:

1. More complete census of Planets around F-M stars.
2. A modest sample of terrestrial planets in the habitable zone (HZ) of M-dwarfs and the first HZ terrestrial superearch planet candidates around G-star.
3. Planets around stars more massive than the sun.
4. More direct imaging giant planet candidates at large orbital radii.
5. Planets in different environments, e.g. clusters.

Characterization:

1. Mass-radius relationship, mean densities of a large sample of planets down to Suprearths.
2. Planet light curves in optical and IR (Phase curves, secondary eclipses)
3. Strongest atmospheric signatures from short period Jupiter, Neptune, and possibly superearth planets. More spectra of long period planets (young, large a).
4. Debris disks

N1: *Stellar studies of all stars out to 50 pcs: understanding the host stars of exoplanet systems, statistics as a function of stellar properties.*

Any characterization mission (imaging, spectroscopy, etc) will have target stars at distances no greater than about 50 pcs. 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 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 which 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 2-4 m class telescopes.

N2: *Radial velocity monitoring of several thousand nearby F-K main sequence stars and evolved, intermediate mass stars using optical spectrographs. Several thousands of stars will ensure a large enough statistical sample when trying to correlate planet properties with stellar properties (e.g. abundance, mass, age, etc.)*

The major goals of such surveys should be to detect the smallest mass planets possible, to extend detections of giant planets at large orbital distances, and to understand the role of stellar mass in planet formation. Such surveys should strive to remove some of the biases of current RV searches. One such bias is in the stellar mass. Over 80% of known planet hosting stars have masses less than 1.4 M_{sun}. The reasons for this are clear: Early RV planet search programs were driven by the solar system paradigm and thus focused on G-types stars. More importantly, early-type more massive stars are ill-suited for RV searches (too few lines and high rates of rotation). Recently a number of programs have focused on searching for planets around evolved intermediate mass stars (1.5-2 M_{sun}). These should be continued and expanded.

Another bias of RV searches are against long-period exoplanets. Even giant planets at large orbital radii induce a small amplitude reflex motion of the star and require a very long time base line to detect. RV surveys should commit to monitoring a large enough sample of stars over a long enough time span to detect solar system analogs and to find giant planets beyond the ice line.

N3: *RV Planet Searches in the Infrared with emphasis on short-period, low-mass planets around M dwarfs.*

The RV amplitude of an M dwarf stars due to a planet in the habitable zone of the star is ~ m/s, a precision achieved by current methods. The reflected/irradiated light signal from such planets will can 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.

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. An ulitimate precision of 1 m/s or better may be achieved in the near future. To achieve this level work it is required to:

a) Find the most effective wavelength for RV searches: Near, Mid-, or Far-IR?
b) Suitable wavelength calibration: Th-Ar, absorption cell, or laser frequency comb?
c) Advancement in IR detector technology. Currently IR detectors lag far behind with their optical CCD counterparts in terms of noise and stability. To achieve a 1 m/s RV precision will require higher quality IR detectors. *The astronomical community should encourage industry to pursue such developments.*

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. The RV variations due to a planet should have the same amplitude in the optical and infrared. A recent example of this was the discovery of the purported planet around TW Hya, a star that also has a disk (Setiawan et al. 2008). Recent RV measurements in the infrared with the CRIRES spectrograph on ESO's Very Large Telescope (Figueria et al. 2010) detected the RV variations in the IR, but at one-third the optical amplitude. This provides strong evidence that surface spots as the origin of the radial velocity variations. This only underscores how RV measurements in the Infrared are essential for confirming important exoplanet discoveries among stars where the intrinsic RV signal from the star is suspected to be large.

N4: *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.*

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 characterize 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 superearths in the habitable zone of solar types stars.

There are 3 challenges RV measurements must overcome in order to be able to detect terrestrial planets in the habitable zone of solar-type stars:

1. *Improved wavelength calibration*. 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. 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.
2. *Instrument stability*. 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 can be achieved. CCD detectors with low, and invariant noise characteristics that are stable over a long time period are also essential.
3. *Beat down the Stellar Noise*. Although great strides have been made in improving the *precision* of RV measurements the ultimate *accuracy* of RV measurements will be set by the intrinsic variability of the star. This stellar noise component includes 1) solar-like oscillations with amplitudes of ~1 m/s and time scales of 5-15 min, 2) rotational modulation from surface structure with RV amplitudes of up several m/s (depending on the activity level) and times scales of days to weeks, and 3) changes in the convection pattern of the star which can have amplitudes of up to 10 m/s and time scales of ~10 years. Solar like oscillations have amplitudes of 0.3-0.5 m/s and timescales of 5-15 minutes. The most problematical is 2) due to the time scales involved. It may be difficult to find solar-like stars that have intrinsic variability better than 1 m/s. Investigations of **N1** are important for establishing such a sample.

Studies are currently underway on points 1. and 2. ESPRESSO is a high resolution spectrograph which may use a laser frequency comb and that is proposed for the VLT. Its goal is to achieve an RV precision of 10 cm/s. Point 3. can only be solved with telescope resources. It is possible to detect signals with amplitudes much lower than your measurement precision *if* one has sufficient measurements. Even with a current RV precision of 1 m/s it is possible to detect a terrestrial planet at 1 AU from a G-type star with intrinsic noise of ~1 m/s. This would require several thousands of observations over 5-10 years.

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 helping to find the most intrinsically RV quiet stars for scrutiny by the premier RV facilities (e.g. HARPS, ESPRESSO).

N5: *A Search for Planets Among Stars in Diverse Environments*

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 which is not seen in the transit discoveries and this may indicate an effect of the sample choice. There are other evidences that the 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. Why are Hyades stars different? Planets around binary stars also can provide important clues to planet formation. The wide binary system 16 Cyg A,B have identical stars that are solar twins. Component B has a giant planet while 16 Cyg A does not. What accounts for the differences?

A search for planets in a wide range of environments can provide a better understanding of the process of planet formation. Such environments include 1) planets in binary stars with a wide range of binary orbital periods, 2) planets in clusters with different properties, 3) planets around very young stars, and 4) planets around stars in different regions of the Milky Way.

N6: *Continued RV monitoring of all known exoplanet hosting stars in order to investigate the architecture of exoplanetary systems and to derive accurate orbital parameters.*

Planets most likely all 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 dymanical stability in the habitable zone of multiple systems.

Accurate orbital parameters are also needed for photometric searches for transits of long period systems. For example, a giant planet in a 100 day 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 type 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 be able to make a classification of planetary systems concerning the architecture of planetary systems. The question is whether there exists 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.

N7: *Securing the necessary telescope resources*

The telescope resources needed to carry out the proposed recommendations N1-N6 are exorbitant. 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. (As an example, the confirmation of CoRoT-7b and the detection of CoRoT-7c required over 80 hours of HARPS time). 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, sufficient for a large portion of the survey work (see Table 1 in appendix). Others can be 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 handfull 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 encourage 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 encouraged to devote a fraction of their telescope time to RV planet work if there is monetary compensation similar in line with the OPTICON program).

N8: *Characterization of Transiting Planets in the visible and IR with ground-based and on-going space based facilities*

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

- Detection of the main molecular species in the hot transiting planets' atmospheres (water vapour, methane, CO2, CO, ammonia etc.).
- Constraint of 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) Broad band or low resolution spectroscopy from a space or ground-based observatory. This can be accomplished by 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:

- Detection of minor atmospheric species and constraint of their abundance.
- More accurate spectral retrieval to map thermal and chemistry gradients in the atmospheres, distribution/characteristics of clouds/hazes.
- Cooler and smaller planets. With current telescopes we can already approach the case of warm Super Earths and Neptunes transiting bright, later type stars, e.g. Gliese 1412b, GJ 436b, etc.

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.

N9: *Optimizing ground-based transit searches*

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 Neptunes and Hot Superearths around M dwarfs, especially in the habitable zone are especially important. Current radial velocity techniques can measure the mass of the star 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 for planets found by the RV method, including long period systems.
4. A search Transit timing variations (TTVs) and transit duration variations (TDVs). Both of these give indications of additional bodies in the system and possibly moons around the known giant planet.

N10: *Continuation of the CoRoT and Kepler past the nominal mission life*

Both CoRoT and Kepler are producing exciting new results on exoplanets. CoRoT has found the first hot Superearth (CoRoT-7b). Kepler has demonstrated a performance that can find an earth radius planet in the habitable zone of a G-type star (and it will surely shortly 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, and for Kepler, 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 Superearths. This is important because for the very low-mass (i.e. radius) objects one will have to rely on this relationship for inferring the planetary mass.

Currently, CoRoT and Kepler are the only functioning space missions 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.

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

N11: *A study of exo-zodi systems and their influence on direct imaging of terrestrial planets.*

A study of exo-zodiacal light around nearby stars should establish whether this exo-zodi light will 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. However, space-based missions are probably best suited for such studies. The proposed Fourier Kelvin Stellar Spectrometer (FSKI). FSKI has the primary science case to detect exo-zodis down to the 1 zodi level. If FSKI is not funded then exo-zodi studies must rely on ground-based interferometric facilities most likely the LBT.

N12: *A search for radio emission from exoplanets*

Planetary magnetospheres may play a key role in protecting terrestrial planets from high energy particles from activity of the host stars. An investigation of magnetospheres around exoplanets will help in our understanding in the formation and evolution of magnetospheres.

The first challenge will be to detect the magnetospheres of giant exoplanets. This 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.

N13: *Increase the sample size of pulsar planets*

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. In either case, pulsar planets gives 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 severely limited by the small sample size. This must be increased.

LOFAR due to its all-sky survey capabilities will be able to search for milli-second pulsars which can then be the subject of more intense studies to search for pulsar planets.

N14: *Ground-based support of CoRoT, Kepler, and preparation for ground-based support for GAIA.*

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.

Prepare for follow-up of Gaia detections. 1) High-resoluion, 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 characterize 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.

N15: *Continue ground-based microlensing searches*

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 micro-lensing searches require a network of telescopes the community should strive to ensure that these microlensing searches have adequate infrastructure. This infrastructure includes sufficient telescopes. Microlensing events from planets have duration of hours, so a network of telescopes are essential for capturing these events.

N16: *Make Effective use of Planet finders for Exoplanets Studies*

The progress of observational techniques now allows the detection of a few masses of Jupiter down to 10 AU with age of about 10-50 Myr. Ground-based telescopes (VLT, Gemini and Subaru) will soon (2011) be equipped with “planet-finders” (SPHERE, GPI and HiCIAO) making use of extreme adaptive optics, achromatic coronagraphy and differential imaging. These instruments will achieve contrasts of 10^6 to 10^8 in the near IR and will be able to probe the region within 5-10 AU to 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 analysis. 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 (see M1).

N17: *Make effective use of JWST for Exoplanets Studies (spectral characterization, imaging, photometry, phase curves, colors)*

JWST is also very promising for the exoplanet spectral characterization as NIRCAM, MIRI and TFI include high contrast imaging devices offering a large spectral coverage from about 2 to 15 μm then 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 (2.5-25μm) then allowing the identification of ammonia, methane, CO_2.

The same instruments will allow transit spectroscopy and potentially have the ability to detect small planets. A number of instrumental choices have been driven by this science case.

JWST will a valuable facility for performing characterization studies of exoplanets, but 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 small (only MIRI is a 50-50 US-Europe collaboration). *The community must move fast and organize itself so as to effectively use its small share of the time effectively on exoplanet studies. ESA should consider having an Open Time Key Programs for Exoplanets on JWST, a concept that worked well with Herschel.*

N18: *Technological studies for Angularly Resolved Detections*

The angularly resolved detection of a terrestrial planet in the habitable zone of a sun-like star is arguably the greatest technological challenge for this roadmap. This with high probability will require a large flagship space mission. Given the technological challenges, but more importantly the dire budget landscape for the foreseeable future, the planning for such a mission is at least ten years away, and a possible launch in 20 years or more.

It is important that technological studies in the area of Angular Resolved Detections continue. In particular, it is still not known which proposed technique: coronagraphy, nulling interferometry, occulters, Fresnel interferometers, etc. is the best suited for the characterization of terrestrial planets in the habitable zone of solar-type stars. Technology development must continue so that given a change in the direction of the budgetary wind in the hopefully not that distant future, the community can effectively propose missions to study earth like planets.

It would be difficult, if not impossible for ESA to support the technological development of angularly resolved detections over the time span before the possible launch of such a mission (10-15 years). Clearly such research and development will have to be carried out at the grass roots level: at universities and national institutes and laboratories. These technologies should be tested at ground-based facilities. Not only will these testbed facilities provide technology advancement, but would produce observational results on easy targets (e.g. bright giant planets at large orbital distances). These could provide key milestones to this roadmap.

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 space mission. This 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.). At this stage, it will be valuable for a comprehensive comparison of the techniques for direct detection.

N19: *Theoretical studies on the spectroscopic signatures expected from exoplanets covering a wide range of masses (terrestrial to giant planets) and a wide range of temperatures*.

In the mid-term part of this roadmap we expect that space missions will be proposed to perform spectral characterization of exoplanets. 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 are 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 Jupiters → Hot transiting Neptunes → 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.

N20: *An investigation of the influence of stellar activity on habitability and anticipated atmospheric signatures*

Stellar activity will definitely have an influence 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 on the surface.

Theoretical work investigating such influences should be undertaken and to assess whether biosignatures 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.

N21: *Calibration of giant planet evolutionary tracks*

The masses of giant planets at large orbital radii as well as free-floating planets found by imaging surveys rely on theoretical models to get the planet mass. This mass determination, and thus the nature of the object is 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, ELT, GMT).

6.3 Mid-term Roadmarkers (~2015-2022)

During 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 define the mass-radius relationship of hot giant planets and a sample of Hot Superearths. This should lead to the first studies of the internal structure of exoplanets. JWST may offer the spectral characterizations of select hot Jupiters, hot Neptunes and hot-Super-Earths. GAIA for late-type stars within 25 pc Gaia will be sensitive to planets with M~ 15-20 Earth masses, or smaller (depending on spectral sub-type).

Anticipated Milestones to be achieved:

Detection:

1. Giant planets beyond the snow line (3-5 AU) including the discovery of Jovian analog exoplanet systems
2. Planet masses down to an Earth mass.
3. First confirmed Superearths at 0.7-1 AU around a G-type star.

Characterization:

1. The mass-radius relationship down to the Earth-mass regime from transiting planets
2. Low to medium resolution (R=20-200) spectra from space taken visible to mid-infrared of Hot/Warm short-period Planets down to Superearth mass.
3. Low resolution (R=50) spectra taken from visible to near-infrared of Warm/Cool long-period (down to a fraction of an AU) Planets down to Superearth mass

M1. *Preparation for an M-class and/or smaller mission for characterization of exoplanet atmospheres from gas giants to superearths*

Efforts to characterize the atmospheres of exoplanets should span the entire parameter space from hot, close in planets, to the cooler ones at large distances that 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:

Transiting planets: The spectral investigation of Hot Jupiters, Hot Neptunes, and Hot Superearths using in-transit spectroscopy and radiated light (secondary eclipse). Spitzer has already demonstrated the feasibility of such work and it is expected that in the near term JWST will produce similar results for a small sample of targets. The proposed should be dedicated to exoplanets and thus investigating a much larger sample of stars and with greater sensitivity.

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 to Superearth at distances > 1 AU from the host star.

The decision on which type 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 these methods 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 2 techniques mentioned here are not exclusive and could be implemented in parallel possibly in the same mission. Although more challenging the scientific return is high and the cost is reduced on the longer term.

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

1. A small mission with a total cost of ~200 Million Euros and with reduced science objects. Such a mission would be able to characterize Hot/Warm plants possibly to masses comparable to a Superearth, but not in HZ. The sample size would probably be more limited
2. A medium class mission with a total cost of ~400 Million Euros. Such a mission would be more ambitious and with a larger sample size and should be able to obtain spectral characteristics of planets down to a masses of Superearths and in the HZ of stars (M-dwarfs and late-type stars).

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

M2: *Transit Searches for Small Planets around solar-type stars*

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 (Superearths, Neptunes) 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 = 10-15 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 subgiant 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 characterize 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.

M3*: Secure the ground-based support necessary for follow-up of PLATO transit candidates*

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 object cannot be confirmed, and the companion mass determined. *Both* the planet mass and radius are crucial for models of the internal structure of the stars. The ground-based program should be in place prior to the launch of PLATO. Unlike NASA (e.g. Kepler follow-up program), ESA does not support 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 the EU. *ESA can aid in this effort by stressing the need for this ground-based follow-up and supporting these efforts (through words if not funds).*

M4: *Obtain accurate stellar parameters using GAIA and PLATO*

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 dearf and subgiants in a large fraction of the sky, including many known planet hosting stars. This will build on the knowledge obtained from **N1**.

M5: *Continue long term RV surveys to find planets at large orbital distances, multiple systems, and to refine orbital parameters of known exoplanets.*

M6: *Continue direct imaging studies from the ground (AO, coronography) to find large planets at large orbital distances.*

The next generation of planet finders (EPICS in Europe or PFI in the US) is already planned for Extremely Large Telescopes (30-40m) with the goal to extend the parameters space to lower masses, older planets and to access fainter stars. Exploring 10^9 contrast 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 first regarding the manufacturing/operation of 30-40 meters telescopes, second for what concern atmospheric compensation with AO, and third for the optimization of high contrast instruments. However ELTs will nicely complement a large space mission dedicated to spectral characterization of exoplanets (whatever a visible telescope or an IR interferometer). Therefore, space and ground projects should be harmonized and 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 be very 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.*

M7: *Keep facilities to determine radii of transiting planets found by RV surveys and to search for transit timing and transit duration variations.*

With the successful launch of CoRoT and Kepler, and the fact that PLATO has reached the definition phase, it is easy to overlook the continued need for ground-based facilities to continue studies of known transiting planets to investivgate TTVs, TDVs, etc. To search for transits discovered by other methods (e.g. RV).

M8 *Devote time on ELT and JWST for key programs for in transit spectroscopy of transiting planets and direct imaging of Giant planets at large orbital distances.*

M9: *Continued technological Research & Development studies into the various Angularly Resolved Detections.*

Several technological concepts have to be developed to reach higher TRLs. As for direct imaging, the question of wavefront control in space is crucial for achieving very high contrast close to 10^9-10^{10}. Deformable mirrors have to be qualified for space environment. 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. These solutions have to be matured and compared at some point. Coronagraphic masks have been already manufactured for space onboard JWST (NIRCAM, MIRI, TFI). These are based on various techniques, opaque masks, amplitude variable masks, and phase masks. The next step is the achievement of simple solutions for achromatic coronagraphs. Several prototyping are undergoing and have to be further developed. Qualification for space is not an critical issue.

M10: *Use of ALMA to study exoplanets in their birth environments*

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 birth places: 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. More effort in this direction should be made. 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 of 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

M11: *True mass determination of known giant planets with GAIA: Deriving the true mass function for giant exoplanets.*

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.

M12: *Astrometric Searches for Terrestrial Planets with SIM-lite*

The astrometric detection of terrestrial planets not only requires a precision of a few micro-arcseconds, better than what is offered by GAIA, but also dedicated observations on few targets. Such a program can only be accomplished with missions like SIM-lite, and as such it marks an important milestone in any exoplanet roadmap.

The fate of SIM-lite as of this writing is unknown and has to await the U.S. Decadal Review due in June 2010. The EPRAT fully supports the efforts of our U.S colleagues efforts to get this important mission approved. Given the unfavorable budget climate SIM-Lite may request a European contribution to ensure its success. The channel for such a request a formal proposal to ESA from the exoplanet community that would go through the peer review process. If the European contribution is at a modest level of 100-200 MEuros then this would have merit. A more expensive contribution may seriously compromise the funding for other high priority missions. For example, the EPRAT considers a space mission for the spectral characterization of exoplanets as one of these high priority missions. Such an expensive contribution should be carefully considered by the European exoplanet community,

M13 *Obtain a sample of Terrestrial planets in the Habitable Zone of G-K type stars*

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 these studies have to be extended to the habitable zone of other 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 around G-K main sequence stars that can serve as targets for spectral characterization in the long term.

Radial Velocity Searches

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 Superearths) in the habitable zone of G-K type stars.

Astrometry

SIM-Lite also has the ability to detect terrestrial planets in the habitable zone of G-type stars. It should thus also be able to deliver a sample of terrestrial planets in the habitable zone of G-type stars.

6.4 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 6.1

L1: *Begin work on a flagship mission to characterize all the known terrestrial planets in the habitable zone of F-K type dwarfs.*

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, 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.

L2: *An astrometric Search for Giant planets using GAIA combined with RV ground-based follow-up observations*.

Although a flagship space mission to characterize habitable planets around solar-type stars will be a major milestone in the long term, other investigations in the field should continue. By 2020 the final GAIA astrometric results should be available. With an astrometric precision of 6 μas (bright stars) to 200 mas (faint stars) GAIA should *discover* a large number of giant planets and planetary systems. It is essential that RV measurements are conducted from the ground to confirm the GAIA detections and to derive the true mass of these exo-planetary systems

L3: *Astrometric detections of terrestrial planets with SIM and ground-based ultra-precise RV measurements: This along with L2 should complete the mass function of planets down to the low mass end and to fully characterize planetary system architectures.*

Should SIM be approved it should be able to detect a number of terrestrial planets in the habitable zone of solar like stars. SIM should thus help prepare the final target selection for the characterization mission. RV measurements, if possible, should be performed from the ground in order to confirm the SIM results and to derive the true mass of the planetary objects.

L4: *Use SKA for the detection of radio emission from exoplanets*

In the long term the Square Kilometer Array (SKA) should be on line. This facility should be used to search for radio emission from planets and building on the experience from LOFAR.

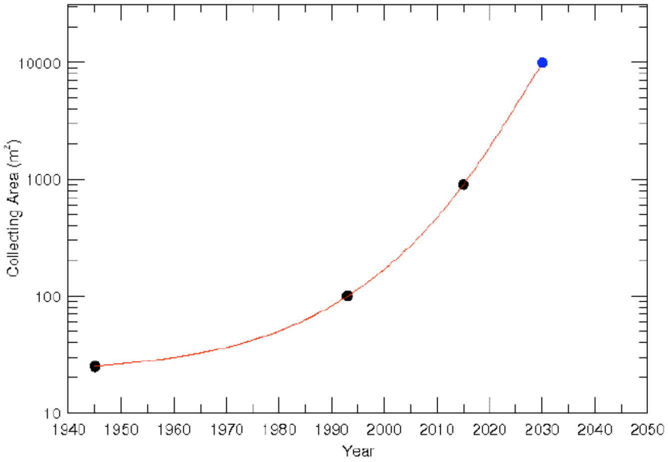

Fig. 8 Relative collecting area (diameter squared) of telescopes from 1940-2030. The first 3 points represent the development from the Hale 5m to Keck 10-m to extremely large telescopes. The red line represents the fit to these points. The blue dot represents the extrapolation to 100m class telescopes.

L5: *Planning and technological development for the construction of Hyper-telescopes*

In the long term the community should consider building Hyper-telescopes of 100-m diameter or larger for the spectral characterization Fig. 8 shows the development of relative telescope collecting area (diameter squared and ignoring a factor of π) over the past 60 years. It took almost 50 years between the construction of the Hale 5-m telescope to achieve a four-fold factor in collecting area of the Keck I telescope. The first extremely large telescopes (30-42m class) are expected to come on line around 2017, or approximately 25 years after the Keck 10-m telescope. This represents a nine-fold increase in collecting area. If technology continues at this pace, then it is reasonable to expect 100-m telescopes to be technologically feasible by 2030.

L6: *Technological studies for extreme adaptive optics with Hyper Telescopes*

It is essential that technological studies of angularly resolved techniques continue so that these can exploit Hyper Telescopes should they be built.

6.5 General Comments and Recommendations with no timeline

G1: *Stronger International Cooperation*

The next 15 years represents a rather sobering budget situation in regards to funding of space missions in particular, and astrophysical research in general. Ideally we would like to have fund all space missions: imaging, microlensing, astrometry, IR spectroscopy, interferometry, etc. Realistically, over the 10-15 year time span we will be lucky to fund one M-class mission for extrasolar planets. And this will be a hard sell, particularly among our non-exoplanet colleagues who could argue to the funding agencies that these missions serve a narrow slice of the community (e.g. the next generation X-ray telescope can be used by the broad community). Given the expense of these missions and the current lack of political will to fund these one country (U.S., Europe, Japan, China, etc.) cannot go it alone. These will have to be international efforts.

We recommend stronger international cooperation in the area of exoplanet space missions. This coorperation should extend beyond the traditional partners (e.g. U.S. and Japan) and should explore including working ties with the up and coming economies China and India. In 20-25 years these may be the dominant world economies and they may be willing to help fund missions in exchange for technological expertise. Also, efforts should be made to coordinate the development of M-class missions to achieve some diversity in the types of space missions that are flown.

The budget constraints of ESA in the next 10-15 years may make it more conducive to fund small space missions. With high probability the rest of the international community will also be faced with such budgetary limitations. 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. This may be easier said than done as one has to have a smooth and efficient interface between all the participating space agencies when funding is provided on a more or less equal basis. There have been successful joint ventures in the past (e.g. JWST) however one space agency (NASA or ESA) funded the vast majority of the mission and the other generally participated junior level. To our knowledge joint space ventures where costs were equally divided among participating countries have not yet been done. ESA and NASA (and other international space agencies), should find ways of improving the interface between the two agencies (and others) to make such joint ventures possible.

G2: *Laboratory measurements to produce line lists, atomic and molecular transition probabilities, opacities, and equation of states.*

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: laboratory studies form measuring 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 molecular transition probabilities, equations of state, and opacities 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 laboratory studies are supported during the course of this roadmap.

G3: *Better coordination between ESA and ESO*

Observations from ground-based facilities are becoming more and more an integral part of space missions as we have 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.

NASA, has a very pragmatic solution to this: It purchases telescope time (e.g. purchasing a part of Keck II) and funds the observational support (e.g. Kepler) for its space missions. It is not as easy for ESA to follow the NASA model. There seems to be a sharp division between science done in space (ESA) and science done from the ground (ESO). These agencies must recognized that the boundary between space and ground-based research for some programs (e.g. PLATO) are blurred and that both are required to make efficient and effective use of the taxpayers money that funds expensive space missions of fixed, and rather short lifetimes. Europe must find a European solution to the problem of providing adequate ground based support of 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.

G4: *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).

G5: *Involve the Planetary Community*

The exoplanet community has been traditionally dominated by astronomers. The early discoveries were made with the Doppler 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 vica 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" the "Protostars and Planets" Conference. The former is bi-annual meeting 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 the 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. 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.

G6: *A Rigorous Public Outreach*

ESA's budget depends on funding from the public sector. Whether the exoplanet community gets the funding to fly an M- or even L-class mission depends on political will and this is swayed by public opinion. Funding for exoplanet research will not be increased if the public does not deem it worthwhile. 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 and ESA must exploit this interest with a rigorous public outreach.

In terms of public outreach, NASA is far and above the industry standard. ESA is encouraged to build a significant staff for public outreach following the NASA paradigm. ESA press relations should also work more closely with national space agencies to ensure that important news, press releases, press packets are distributed to the local community in the language of the country. Astronomy is an international discipline where English is the lingua franca, but public support comes from the grassroots level and this means communicating to the public in the local language. Money spent on public outreach is well spent and will pay dividends in the future.

G7: *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 characterize 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 tourch 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 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 15-20 years. Young scientists need to build careers base on scientific achievements not promises.

European and National programs should be established to fund talented young planetary and exoplanetary scientists build 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.

Appendix

A1 Overview of Existing Facilities (To be completed)

A1.1 Radial Velocity Facilities

There are a number of high resolution spectrographs world-wide 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 1 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

A1.2 Large Telescopes

A1.2.1 European Southern Obsevatory

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

HARPS at La Silla

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 premier RV planet hunting machine in the world. It has discovered some of the lowest mass planets and is one of the "work horses" of the follow-up of CoRoT transit candidates. Recently, it provided the radial velocity confirmation of CoRoT-7b, the first transiting terrestrial "Superearth" discovered by CoRoT.

The Very Large Telescope

Instrumentation at the four 8.2m VLTs on Paranal include:

1. UVES: High resolution spectrograph operating in the 0.3-1.1 mm 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: Cryrogenic wide field imager covering J, H, K, Bracket gamma, CH4, H2, 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 system operating in the 1-5 mm range.

Planned or proposed Facilities:

ESPRESSO: (proposed) 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

PRIMA on the VLTI

A1.2.2 Keck Observatory

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

1. HiRes: A high resolution spectrograph operating in the 0.3 – 1 mm 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 3.6um), and the Nuller, working in N-band (10um). 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.

A1.2.3 Subaru 8.2m Telescope

Subara 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 longslit 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.

A1.2.4 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 wavelemngths 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 mm). It may work as a polarimeter and low amd medium resolution spectrograph
3. EMIR: A wide ield near-infrared (0.9 – 2.5 mm) 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)

A1.2.5 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 ppower of up to R = 120,000. An iodine absorption cell provides the wavelength reference for precise stellar RV measurements.

A1.2.6 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)
   - Longslit spectroscopy (seeing and diffration 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) provides 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

A1.3 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 and 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 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.

A1.4 (Warm) Spitzer and Herchel

Spitzer is a 0.85-m space telescope woriing 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.

A1.5 Transit Space Missions: CoRoT and Kepler

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 fullfilled the pre-launch technical specifications of photometric performances, and it is regularely 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 and CoRoT-3b: the first secure 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

A2 Planned and Proposed Facilities (To be completed)

A.2.1 Extremely Large Telescopes

The European Extremely Large Telescope (ELT)

The Thirty Meter Telescope (TMT)

The Giant Magellan Telescope (GMT)

A2.2 The James Webb Space Telescope (JWST)

A2.3 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 μas on faint stars. (Note the astrometric perturbation of a Jupiter analog around a solar-type star at 10 pcs is ≈ 500 mas.) 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.

A2.4 SPICA

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission is a Japanese astronomical 3.5-m telescope that is is optimized for mid- to far-infrared observations. ESA will decide in the next months on its participation with a modest contribution of ?? million Euros. Current instrumentation of interest in the exoplanet community includes

A2.5 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 modeling.

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 fov 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.

A2.6 Space Interferometry Mission

A2.7 ALMA

A2.8 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.