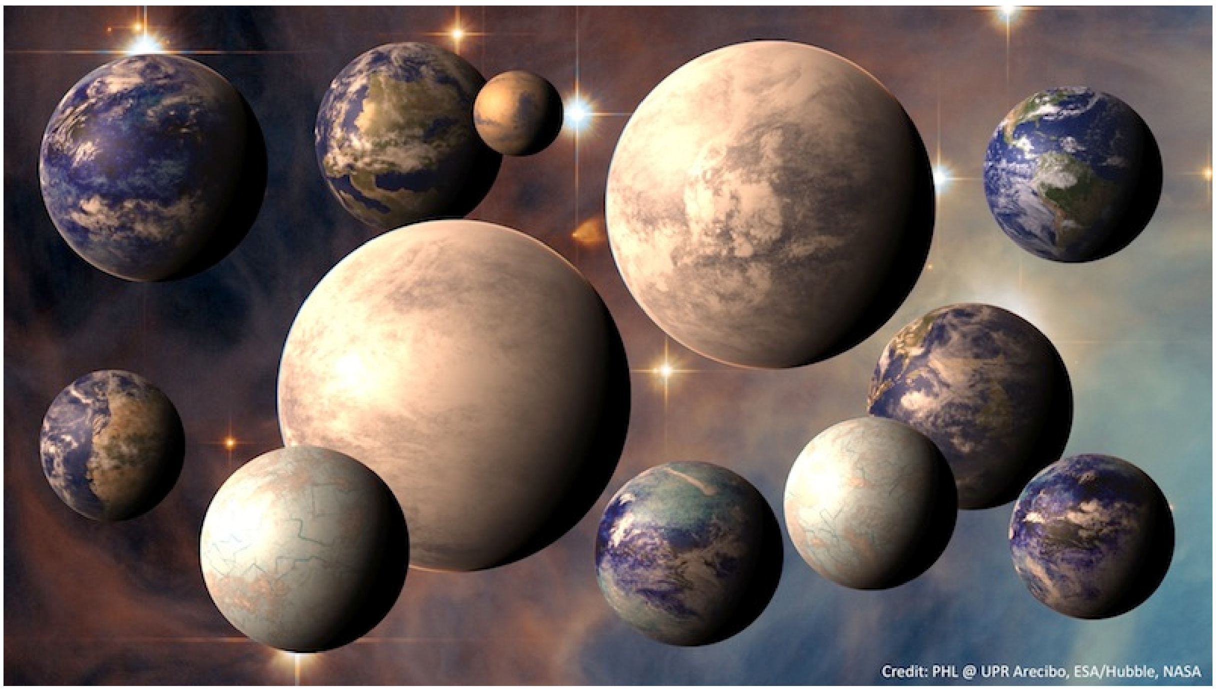
Exploring Habitable Worlds beyond our Solar System

White paper submitted in response to ESA's call for science themes for the L2/L3 missions of its Cosmic Vision program



Coordinator / spokesperson: Andreas Quirrenbach

Contact details:

Prof. Dr. Andreas Quirrenbach
Landessternwarte, Zentrum für Astronomie der Universität Heidelberg
Königstuhl 12
D-69117 Heidelberg
Germany

A.Quirrenbach@lsw.uni-heidelberg.de

+49-6221-54-1792

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2. Executive Summary

We are now at a unique moment in human history. For the first time, we are able to build instruments that allow us to investigate directly how unique the Earth is and whether or not we are alone in the Universe. Discovering Earth's sisters and possibly life is the first step in the fundamental quest of understanding what succession of events led to the emergence and survival of life on Earth. For this, we need to know how, where and when stars form from gas and dust and how, where and when planets emerge from this process. This is certainly one of the most important scientific goals that ESA and Europe could set themselves. [ESA, Cosmic Vision, 2005]

Triggered by the discoveries of the first planets outside the Solar System twenty years ago, the study of planetary systems associated with other stars and of the properties of exoplanets has grown into one of the most vibrant fields of astrophysics. Surveys covering thousands of stars have yielded nearly 1000 confirmed planet discoveries, and steady progress is being made from Jupiter-size objects towards Neptune- and now Earth-size planets, driven by refinements in instrumentation and observing techniques.

Thanks to the ubiquity of planetary systems and the broad diversity of exoplanets, in terms of size, composition, temperature, and orbits, we have already begun the exploration of some distant worlds by remote sensing. The population of gaseous exoplanets at short orbital periods (the so called hot Jupiters or hot Neptunes depending on their size/mass) that includes a significant fraction of transiting objects has provided us with the data to expand comparative planetary science beyond our own Solar System. Transmission and emission spectroscopy achieved during primary transits and secondary eclipse, respectively, as well as orbital spectrophotometry for transiting and non-transiting planets have made possible the detection of atmospheric species and clouds, and the measurement of atmospheric temperatures, vertical/longitudinal thermal structures and wind speeds. First applied to the most favorable hot Jupiters, these techniques are now providing results on smaller and cooler planets. The trend towards the observation of terrestrial exoplanets will continue, but characterizing them, assessing their habitability and searching for signs of biological activity implies an ambitious space program that will aim, beyond the next decade, at the direct imaging of exoplanets that do not necessarily transit, which represent the vast majority of exoplanets and include our nearest neighbors.

The stunning progress in exoplanet science during the past years has broadened our view, and changed the perspective we had on these questions when they were framed within the Cosmic Vision program. Whereas previous proposals for large space missions, informed solely by our own Solar System, focused strongly on the possibility of detecting “Earth twins”, we are now in a position to formulate questions about habitability and ultimately extraterrestrial life in the more general context of comparative planetology, with a large number of systems available for study.

Among the remarkable feats of the exoplanet community has been the ingenuity with which new observing techniques have been invented and put into successful use over the past twenty years. We now have a diverse set of tools at our disposal, with which we can explore different aspects of exoplanetary systems. A number of complementary approaches have been identified that can address habitability from different angles. Coronographs and infrared interferometers have been studied at some level of detail, and other more recent concepts (external occulters and integrated-light telescopes) also show considerable promise. While none of these is ready yet for flight, the rapid progress over the past few years in the development of the key enabling technologies gives confidence that an exoplanet exploration mission will become viable technically and financially in time for implementation in the middle of the next decade.

Ever since the first discovery of a planet around a Sun-like star (Mayor & Queloz 1995), Europe has been playing a leading role in exoplanet science, with arguably the best ground-based instruments and the first dedicated exoplanet space mission (CoRoT). Future plans include the small mission CHEOPS, as well as two strong contenders for M3 (PLATO and EChO). The adoption of “Exploring Habitable Worlds beyond the Solar System” as the theme for a large mission will enable ESA to secure its leading role in this endeavor into and beyond the next decade.

3. The Science Case of Exoplanet Characterization: Atmospheres, Surfaces, Habitable Environments

Probably for as long as humans have looked up to the night sky, they have tracked the wanderings of the brightest specks of light across the background of seemingly unmoving stars. Observed through the first telescopes, these planets appeared to be physical bodies with their own moons around them, orbiting the Sun just like the Earth; a discovery that triggered the upheaval of the commonly held view of the place of the Earth and mankind in the Universe. With the increasing quality of ground-based telescopes, and, since the 1960's, with space-based telescopes and dedicated spacecraft, the Solar System's planets and moons changed from merely slightly differently colored, fuzzy dots into unique and stunning worlds of their own.

3.1. The Diversity of Planets

One of the lessons of Solar System exploration is diversity. Since the 1990's, an even broader perspective has emerged with the discovery of exoplanets, as planets around other stars are called. And these worlds present an even greater diversity than those of our Solar System, in terms of observed masses (from $0.67M_{\oplus}$ to $30M_{Jup}$ and beyond), orbital range (from 0.006 AU to more than 1000 AU), orbital eccentricity, and host star properties.

One of the key drivers for Solar System exploration has been the search for life elsewhere. Finding life forms on another planet or moon would help to shed light on the formation and evolution of life on Earth. A prerequisite for life appears to be liquid water. The search for life is therefore closely linked with the search for liquid water and habitable conditions. So far, we haven't found liquid water on other planets or moons. Venus was long suspected to harbor water, because while this planet is closer to the Sun than the Earth, and thus receives a much larger solar flux, its clouds reflect most of this flux back to space. It was only in the 1960's that Venus's surface temperature was found to be close to 500°C, due to the extreme greenhouse effect in its thick carbon dioxide atmosphere, and in the 1970's, it was discovered that its clouds consist of sulfuric acid instead of water (Hansen and Hovenier 1974).

Mars orbits on the outer edge of the Sun's so-called habitable zone – the region around a star where the stellar flux that is incident on a planet would allow liquid surface water to exist. While water-ice is abundant on Mars (e.g. Plaut et al. 2007), the surface pressure and the temperature are too low for liquid surface water to be in equilibrium with the atmosphere. Mars shows evidence for the geologically recent presence of liquid surface water, indicating that in the past, the Martian atmosphere might have been much thicker, the climate much warmer and wetter, and more favorable for life (Solomon et al. 2005). Traces of ancient life, and even subsurface pockets of current life, will be searched for by ESA's upcoming Exomars mission. ESA's L-class mission JUICE will get a close-up of moons of the gas giant Jupiter where thick crusts of water-ice are predicted to cover deep, possibly habitable, oceans of liquid water (Grasset et al. 2013).

While the search for life elsewhere in the Solar System is still ongoing, it has become clear that there cannot be evolved life, beyond very primitive micro-organisms, and then only on a very few bodies (Mars and some of the giant planets' moons). However, we know that there are many more observable habitable exoplanets and that no present observation excludes evolved forms of life on them. Therefore, to find abundant life as we know it on Earth, we have to look beyond our own planetary system. Only a search for life on planets around other stars would answer the longstanding question whether we are alone.

3.2. Reaching beyond the Solar System

After two decades of hunting for exoplanets, we have identified almost 1000 of them, and we now know that there are at least as many planetary companions as there are stars in our galaxy. And thanks to the increased sensitivity of instruments and analysis methods, it has also become apparent that small exoplanets are in fact much more common than giant, gaseous ones. Indeed, according to recent estimates, at least 10% of stars could have a small planet orbiting in their habitable zone.

We know very little about these exoplanets, apart from their masses (and often only a lower limit is known), sizes, and the diameters of their orbits. As we know from the terrestrial planets in the Solar System, whether or not a planet in or near the habitable zone of a star has surface conditions compatible with life will depend strongly on the chemical composition and thickness of its atmosphere. The next step in the thriving field of exoplanet research should therefore be studying the physical properties, atmospheres and surfaces of exoplanets. This search for habitable conditions, i.e. conditions that are compatible with the presence of liquid water, or for actual signatures of life as we know it, i.e. spectral features due to vegetation (Fuji et al. 2010) or gases like O_2 and CH_4 (Rauer et al. 2011), does not have to be confined to small, rocky exoplanets around solar type stars. Other types of stars have planets, too (indeed, several of the known small exoplanets orbit red dwarfs). And, just like Saturn's largest moon, Titan, moons of gas giants that are located in or near a star's habitable zone could also have atmospheres and habitable conditions (Heller 2012).

Apart from the search for life outside the Solar System, studying exoplanets' physical properties, atmospheres and surfaces, will provide us with a wealth of knowledge on the formation and evolutionary processes that shape not only planetary systems as a whole, but also the interiors, atmospheres, and surfaces of individual planets. The large diversity exhibited by the Solar System planets in, amongst others, their atmospheric chemical composition and structure, the radiative and dynamical processes governing their climates and weather patterns, their internal composition and structure, their magnetic fields, and even in the properties of their moons and ring systems, has allowed us to significantly broaden our understanding of how planets work. These fields of study are now being enriched even further by discoveries of exoplanets with properties that are not found within the Solar System. We are thus at the dawn of a new science: comparative exoplanetology.

3.3. Physical Properties of Exoplanets: A Rich Field for Exploration

The diversity in physical properties of exoplanets, such as size, mass, composition, and orbits, and the paucity of information about the formation and evolution of these planets and their atmospheres, provide many opportunities for discoveries and new insights. Meaningful comparative planetology that connects these systems to the Solar System is now becoming possible. Indeed, more detailed observations, observational baselines long enough to cover several orbital periods and/or seasonal changes, and the relentless growth in computing power for data analysis and numerical modeling of physical processes have revealed significant and important gaps in our knowledge and understanding. As an example, a general circulation model that satisfactorily simulates the Earth's current climate and weather patterns will not do the same for Venus upon changing the solar irradiation or the planet's obliquity, rotation period, or atmospheric thickness and composition. As another example, we don't know whether Venus and the Earth started off with very different atmospheres, or with similar ones. If they were similar: when and why did the divergence start? How stable are such atmospheres anyway? And what was the Earth's atmosphere like when there was liquid surface water while the Sun was young and faint?

Exoplanet characterization will shed new light on these important questions and enable new approaches to the open problems (e.g., Medvedev et al. 2013). Although the detection methods that have harvested the vast majority of exoplanets known today all have peculiar biases towards planetary sizes, orbital distances, or temperatures, it can safely be concluded that exoplanets cover a huge parameter space: from young and hot to old and cold, from small and solid to giant and gaseous, from tight to wide orbits, and from circular to eccentric orbits that give rise to extreme temperature changes and hence to extreme dynamical processes in planetary atmospheres. Differences in types of parent stars – their composition, size, and activity – could also result in differences in types of planets. Exoplanet characterization will fill the gaps in our knowledge and understanding because it changes the universe around us into a huge physics laboratory where arguably enough planets can be probed to tackle a range of variables, including habitability and life (e.g. Grenfell et al. 2007).

Comparative exoplanetology is thus undoubtedly among the most exciting areas in all of science in the 21st century. The questions raised by the extreme complexity of this field will keep challenging space- and ground-based technologies for decades to come. By scheduling a large mission for launch in 2034, ESA will further energize the field and take a large step forward towards a fuller understanding of habitable worlds beyond our Solar System.

4. Exoplanet Characterization: Present and Near Future

The study of extrasolar planets is presently one of the fastest-growing areas of astrophysics. While surveys with different techniques (radial velocities, transit photometry, microlensing, coronographic imaging, and soon astrometry with GAIA) are discovering planets and planetary systems at an accelerating pace, we are also moving progressively into the era of exploration and characterization with photometric and spectroscopic methods. With increasing instrumental sophistication, each technique progresses from large to small planets, and most of them from hot to cool. This is particularly important in the context of the quest for habitable planets, which are within reach of the discovery programs now, but whose characterization will require larger and more advanced observing tools.

4.1. Studies of Exoplanet Atmospheres with Transit Spectroscopy

Out of the nearly 1000 exoplanets discovered so far, the ~300 transiting planets represent a unique opportunity to access spectral features of exoplanetary atmospheres. Transiting exoplanet properties for which we have spectroscopic information are particularly diverse, with star-planet distances ranging from 0.014 to 0.45 AU, equilibrium temperature ranging from 540 to over 3000 K and orbital eccentricity ranging from 0 (for the circularized hot Jupiters) to 0.93. The Spitzer Space Telescope has led to great advances in the understanding of the composition of transiting giant planets. The infrared spectra as observed with secondary eclipse data of hot Jupiters are believed to be shaped predominantly by water absorption (Burrows et al. 2005, Seager et al. 2005), but other molecules such as methane also play a role (Swain et al. 2008). While methane in particular could become more important for cooler planets, its abundance in GJ 436b is still controversial (Line et al. 2011, Stevenson et al. 2010, Knutson et al. 2011, Beaulieu et al. 2011). For close-in planets orbiting luminous stars, strong irradiation could flatten the temperature gradient and weaken absorption features in the spectrum at the time of eclipse (Fortney et al. 2006). The results on HD 189733b from Spitzer/IRAC (Tinetti et al. 2007, Ehrenreich et al. 2007, Beaulieu et al. 2008, Désert et al. 2009) and HST/NICMOS (Swain et al. 2008, Sing et al. 2009, Gibson et al. 2011) provide the first glimpses at the atmospheric composition of this hot Jupiter, revealing the signatures of molecules and the presence of haze. Important observations of primary transits have also been made using Spitzer (Richardson et al. 2006, Gillon et al. 2007, Nutzman et al. 2009). Large ground-based telescopes have also been used successfully to obtain spectra of a few bright exoplanets (Snellen et al. 2008), recently even of some that do not transit (Brogi et al. 2012).

A new chapter in exoplanetary science began with the discovery of the first transiting super-Earths (Léger et al. 2009; Charbonneau et al. 2009), for which measurements of mass and radius are possible. GJ 1214b is an especially interesting object since its spectrum has also been measured, giving us constraints on the nature of its atmosphere. Spectra have been obtained in transmission during primary transit and in emission during secondary eclipse, from the ground and from space. The flatness of the spectra can have several interpretations, but it definitely rules out a clear atmosphere with solar composition. Possible explanations are depletion of CH_4 or a dense cloud layer (Bean et al. 2010, Croll et al. 2011, Crossfield et al. 2011, Berta et al. 2012). Alternatively, the planet might be significantly smaller than indicated by the best present estimates and not possess a substantial atmosphere at all (Bean et al. 2011). These conclusions emphasize the diversity of the planetary conditions but also the need for consistent, reliable observational constraints.

Transit surveys like NGTS from the ground, and TESS and PLATO (if selected for M3) from space, will discover new interesting targets for transit spectroscopy. With missions such as the James Webb Space Telescope (JWST), we should be able to acquire better quality spectra of transiting Hot Jupiters and Hot Neptunes, to access atmospheric signatures of a few super-Earths, and to start characterizing such planets. Additionally, the EChO mission (currently under consideration by ESA as a candidate M3 mission) aims at measuring the largest technically and financially feasible part of the planetary spectrum (from 0.4 to 11 or even 16 μm). This mission is also optimized for time-sequence studies of these planets, thus providing access to meteorological phenomena through observations of temporal variability. High-resolution near- and mid-infrared spectroscopy with the next generation of extremely large telescopes will provide further insight into the composition and dynamics of giant and possibly even Super-Earth planet atmospheres (Hedelt et al. 2013,

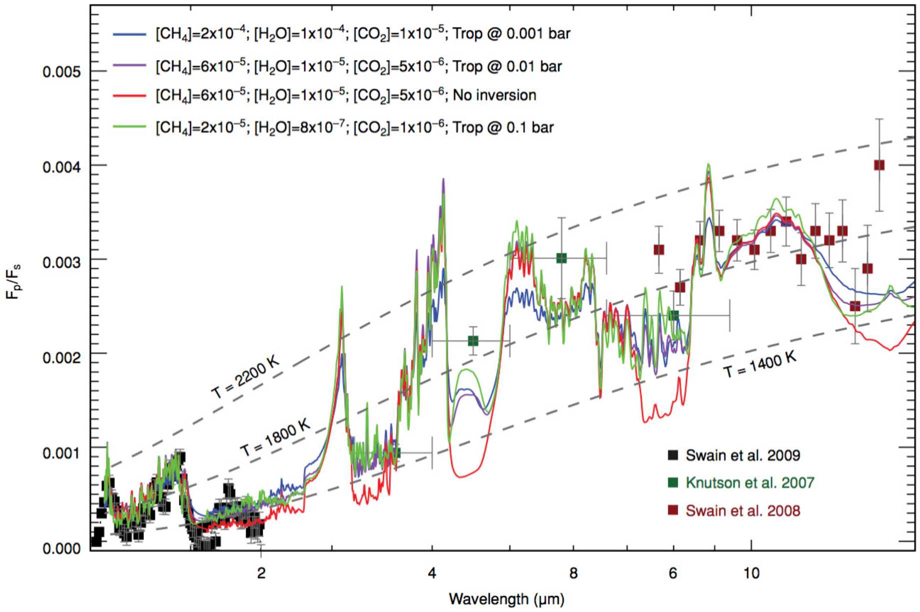

Figure 1: Synthetic emission spectra of the hot Jupiter HD209458b together with various observational data points (Swain et al. 2009). The data are from various sources, and there are gaps in the spectral coverage. Despite over a decade of study, the sparse data shown here represent the highest-quality exoplanet spectrum obtained to date.

Snellen et al. 2013). By the end of the next decade we will thus have acquired experience with the observational and theoretical tools needed for the analysis of exoplanet atmospheres. The logical next step will be the extension of such observations to potentially habitable planets.

4.2. Direct Detection with Coronographic Imaging

While radial velocity (RV) and transit searches are pushing towards the discovery of lighter planets down into the Super-Earth regime, direct imaging so far has revealed only a handful (about 30) of planetary-mass objects due to the high contrast that is needed at small separations (less than 1 arcsec). Nevertheless, a few emblematic objects have been discovered and studied, like β Pic b (Lagrange et al. 2009, 2010), the four planets around HR 8799 (Marois et al. 2008, 2010), and the intriguing supposedly planetary object in the Fomalhaut system (Kalas et al. 2008, 2013). In this respect, young systems offer a reduced star-to-planet contrast, as the planet's high, early luminosity decays slowly with age. The imaged planets are all located at physical separations larger than about 10 AU (β Pic b being the closest) and have masses (estimated from their luminosities) larger than 5-10 M_{Jup}. These systems are also very young, with ages ranging from a few Myr to a few hundred Myr. Overall, current ground-based instruments are now able to reach contrasts as large as 10^6 at typically 10 AU for the closest stars (10-20 pc), while the detection of more mature planets would require a dynamic range of more than 10^9.

Still, these few objects provide crucial information for understanding the physics of exoplanets, in particular the diversity with respect to the planets found by RV and transits, which has important implications regarding their formation and evolution. We have learned that planets can be much more massive than those in the Solar System, that they form relatively quickly (β Pic has a well-constrained age of 12 Myr), and that different mechanisms could be required to explain their formation at large distances (gravitational instabilities as opposed to core accretion). This knowledge is inaccessible by indirect detection because RV and transit photometry concentrate on the inner part of old systems, which have certainly lost memory of initial conditions due to migration and/or planet scattering. In addition, we are starting to obtain atmospheric properties through photometry (temperature and surface gravity, Bonnefoy et al. 2011, 2013) and low resolution spectroscopy (composition, Janson al. 2010, Konopacky et al. 2013, Oppenheimer et al. 2013). Finally, imaging is the only technique that provides a global picture of planetary systems including the distribution of the dust in protoplanetary and debris disks, which allows us to study the disk-planet connection (Lagrange et al. 2012) and to infer the presence of planets (Wyatt 2003).

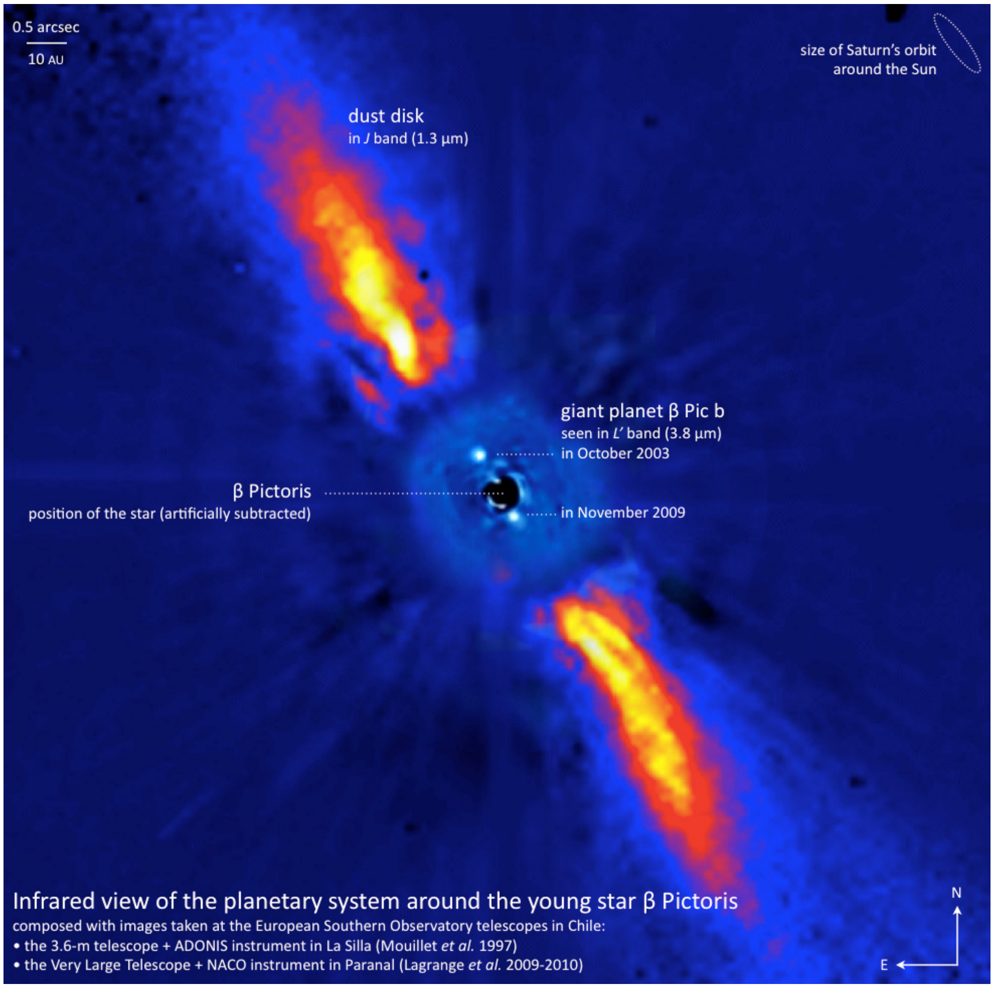

Figure 2: View of the β Pic system showing the debris disks superposed with the planet images in Nov. 2003 and Nov 2009 (Mouillet et al. 1997, Lagrange et al. 2009, 2010).

In the coming decade, several instruments optimized for direct imaging (extreme adaptive optics and coronographs) will be installed at large ground-based telescopes, starting with the series of planet finders like GPI (Macintosh et al. 2008) and SPHERE (Beuzit et al. 2008). These are designed to reach contrasts of 10^6 – 10^8 very close to the star (>1 AU) and detect a new population of young giant planets with masses similar to that of our Jupiter. Characterization of their atmospheres will become feasible with low resolution spectrographs in the near IR (1 – 2.3µm). SPHERE and GPI will also put important constraints on the frequency of giant planets at large orbital periods. Towards the end of this decade, JWST (and possibly SPICA) will come with a suite of IR instruments, all having coronographic observing modes. JWST's NIRCAM, MIRI and NIRISS will allow detailed atmospheric characterization (mostly photometry but also low resolution spectroscopy) of the planets discovered by SPHERE but at longer wavelengths (2.5 to 16µm), and will likely push the detection limit to the range of ice giants with long periods.

5. The Landscape in 2034

5.1. Further Developments in Exoplanet Detection and Characterization

Over the past two decades, the field of exoplanet research has grown faster than any other in astrophysics, both in terms of objects to be studied (from zero to at least one thousand), and in terms of active scientists (from a handful of part-timers to a large vibrant community). This growth has been driven by a strong diversification and many refinements of the available observing techniques and facilities. As it is likely that many of these developments will continue in the foreseeable future, it is not easy to extrapolate the state of the field over another twenty years, or to predict some of the major discoveries that will undoubtedly be made during that period. Nevertheless, we can foresee major features of the landscape of exoplanet exploration around the envisaged launch date of the L3 mission:

- Radial-velocity surveys will have performed exhaustive searches for terrestrial planets orbiting nearby stars. ESPRESSO at the 8.2m VLT, CARMENES at the Calar Alto 3.5m and SPIRou at the 3.6m CFHT will be able to detect $1M_{\oplus}$ planets in the habitable zones of "quiet" Sun-like stars and M dwarfs.
- TESS will have detected the brightest targets harboring transiting terrestrial planets in orbits up to ~30 days, and a small sample of longer-period planets. PLATO, if selected for M3, will expand the parameter range with a catalog of temperate terrestrial planets in orbits up to the habitable zone of Sun-like stars, where they are likely able to retain their atmospheres, and to develop habitable conditions.
- Thanks to the combination of radial velocities with transit observations (CHEOPS), the mass-radius relation will have been established down to Earth-size planets; consequently the bulk composition of these planets will be understood (Sohl et al. 2012). Note, however, that strong degeneracies exist for planets with an atmosphere (Adams et al. 2008).
- High contrast imaging surveys (SPHERE, GPI, JWST, SPICA, ELTs) will have discovered many young Jupiters and Neptunes; spectroscopic follow-up will have provided more detailed information on a subset of them.
- ALMA and LBTI will have imaged debris disks and determined the prevalence of zodiacal dust disks around solar-type stars.
- Astrometry with GAIA will have discovered most of the giant planets between 15pc and 150pc, but it will still miss nearby low-mass planets. The latter could be found by a dedicated astrometric mission, which would be an attractive candidate for a medium-size mission (M4).
- Transit spectroscopy is already a rich field for hot giant planets orbiting close to their stars, and will expand towards cooler and smaller planets with data from many complementary facilities, including JWST, EChO (if selected for M3), and infrared instruments at extremely large telescopes (including the E-ELT).

However, and significantly, spectroscopic investigations of potentially habitable planets will still be lacking, because none of the facilities that are presently foreseen for construction during the next twenty years will provide data with sufficient scope and quality to make meaningful statements about habitability. Thus, even if the status of exoplanet exploration around 2034 cannot be foreseen in detail at present, **it is logical for ESA to focus its L3 mission on the characterization of habitable worlds**. Missing this chance would in fact endanger the leading role that Europe has been able to establish in the field of exoplanets from its inception. In contrast, an early adoption of this topic for L3 would provide a framework in which the scientific focus and output of intermediate investments in space and on the ground can be optimized.

5.2. Targets for Habitable World Exploration

The design and optimization of any exoplanet exploration mission depends critically on the number and properties of the targets it is to observe. From the preceding discussion it follows that important progress will be made in this regard within the coming years:

- Kepler and microlensing surveys are establishing $\eta_{\oplus}$, the fraction of stars with planets in their habitable zones. This will tell us on a statistical basis the number of planets available for exploration within a certain volume.
- Next-generation RV surveys (e.g. ESPRESSO in the visible, CARMENES and SPIRou in the near-IR) will discover Earth-like planets in the habitable zones of "favorable" Sun-like stars and M dwarfs, i.e., in a subset of stars with rather quiet photospheres. This will provide an actual sample of target planets within 15pc that are amenable to spectroscopic

characterization. PLATO, which has been proposed as the M3 mission, would provide a sizeable sample of additional targets (the closest transiting planets).

- An astrometric mission, which could for example be flown as ESA's M4 mission, could conduct an exhaustive search of the habitable zones of all nearby stars down to 1 $M_\oplus$, thus establishing the "ultimate" target sample for further exploration.
- ALMA and LBTI will characterize debris disks, which could manifest themselves as "noise" for planet characterization missions.
- Ground-based long baseline interferometry (VLTI, CHARA, NPOI), as well as asteroseismology from space with TESS, PLATO (if selected as the M3 mission) and from the ground, combined with parallaxes from GAIA, will establish precise values for the most important properties of the host stars (mass, radius, distance, age), which are needed to determine the corresponding properties of their planets.

In summary, one can be confident that the present uncertainties about the number and properties of potential targets, which are sometimes seen as impediments for the implementation of a cost-effective planet characterization mission, will largely be removed within the next decade. Furthermore, specimens representing different categories of exoplanets – including potentially habitable ones – will be known 20 years from now. While an exhaustive census of the solar neighborhood would certainly be desirable (and possible), it is by no means a prerequisite for starting the in-depth characterization of those planets that we know.

While it is thus still premature to define a possible mission target catalog, we can estimate the number of potentially habitable planets using current Kepler and Corot results that suggest a value of $\eta_\oplus$ of 10 to 20% for F, G, and K stars (Batalha et al. 2013, Fressin et al. 2013). The corresponding value for M dwarfs may even be as high as ~50%. Based on these numbers, a variety of mission architectures are capable of characterizing samples of tens of potentially habitable planets.

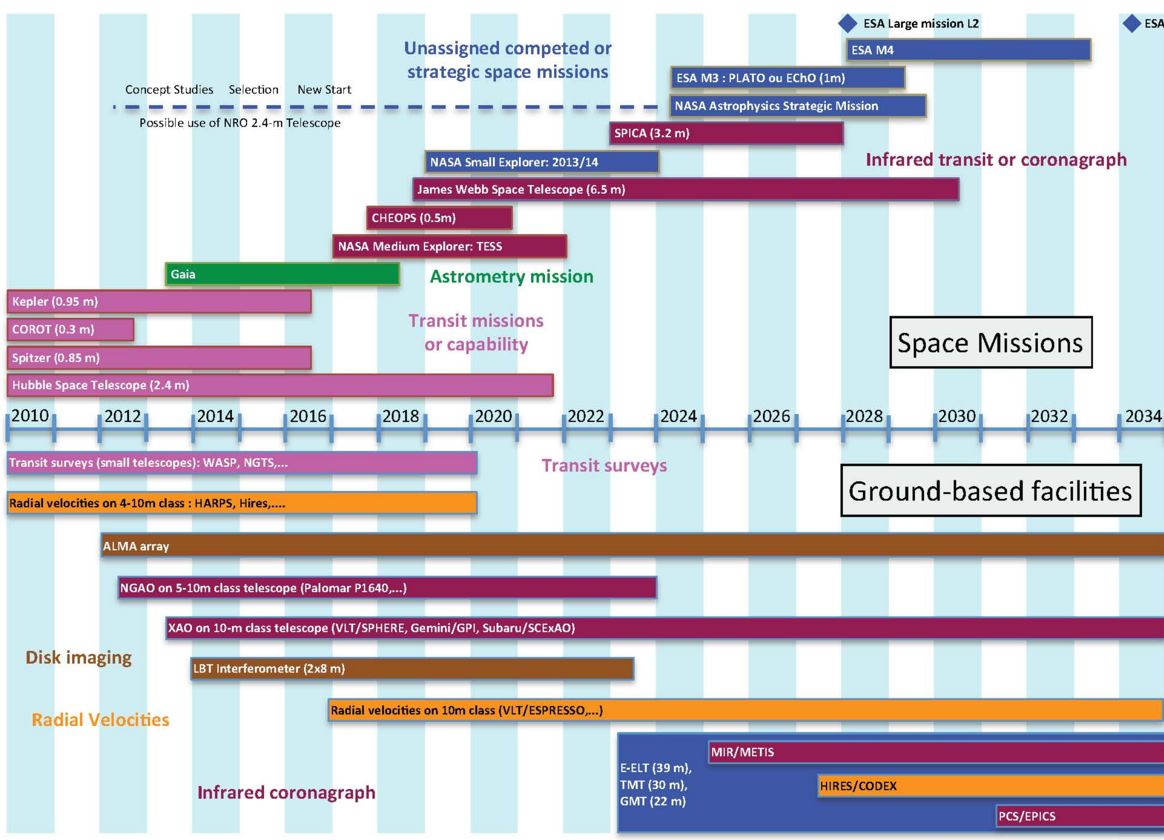

Figure 3: Chart summarizing the instrumental landscape up to 2034 both in space (upper part) and on the ground (bottom part). Bars of same color correspond to similar techniques.

6. Key Science Questions and Required Observations

The in-depth characterization of the physical and chemical properties of terrestrial exoplanets is a long term goal. It will require spectroscopy with sufficient resolving power and SNR at both thermal and scattered wavelengths. A broad spectral coverage from visible to mid-IR is necessary to assess the radiative budget of the planet, which is the key to understanding its climate. In addition, it also enhances the number of observable spectral molecular signatures, making the identification of molecules more robust and minimizing the uncertainty on their abundances. Observations will also have to be spread over several orbital periods, with different sampling frequencies, in order to characterize the signal variability associated with climate, rotation, seasons, phases and variations in the stellar luminosity. Polarimetry combined with visible spectroscopy would also constitute an additional way to derive the atmospheric gaseous/particle content. Techniques to constrain the mass and radius of the planet will not only contribute to understanding the nature of the planets but will also strongly increase the information content of the spectra whose interpretation depends on both the gravity and the radius. The radius, in particular, allows converting observed fluxes into albedos (scattered light) and brightness temperatures (thermal emission). The radii and masses of non-transiting planets can be constrained from spectra, although at reduced accuracy and with reliance on suitable models.

The general goals of obtaining an in-depth understanding of the physical and chemical properties of terrestrial exoplanets, and of developing the notion of habitability in the broader frame of comparative planetology, can be broken down into these more specific questions:

1. **What are the physical characteristics of the atmospheres (composition, temperature and pressure profiles, haze, clouds, winds)?**
2. **What is the internal structure of those planets?**
3. **What is the nature and composition of the surface (rocky, liquid, icy...)?**
4. **What is the time (and seasonal) variability of those features? Which roles do dynamics and photochemistry play?**
5. **What are the key processes which govern the chemistry in those exotic atmospheres?**
6. **If we discover chemical disequilibria – could they be caused by life?**

The information needed to address those questions can be provided by remote sensing observations. In particular:

Bulk planetary composition and internal structure:
The planetary composition and internal structure can be constrained in several ways. Measuring the planetary radius and mass will determine the mean density directly. Measuring the atmospheric composition will allow us to distinguish a Neptune-like planet from a terrestrial planet. In addition, finding traces of volcanic gases in the atmosphere may provide insight about the composition of the interior. Finally, an indirect estimate of the planet's surface gravity may be made through primary transit observations of the atmosphere, which give an indication of the atmospheric scale height.

Atmospheric composition:
The molecules which are most abundant, or have the strongest signatures, can be detected at low to medium spectral resolving power (e.g. H_2O, CO_2, O_2, O_3), from the UV to the IR, depending on the absorption properties of the molecular species (Des Marais et al. 2002). To detect less abundant or weaker molecular signatures a spectral resolving power of ~100 or higher is needed (e.g. C_2H_2, HCN). Most atoms and ions can be found in the UV-VIS-NIR (e.g. Na, K, H_3^+). Very high spectral resolution is needed to resolve these lines. To estimate the elemental and molecular abundances, a combination of appropriate spectral resolving power *R* and wavelength coverage is desirable. The required *R* will mainly depend on the molecule/element, on the wavelength interval and atmospheric region we are probing. To estimate chemical gradients (spatial and temporal) we need to be able to spatially resolve the planet (e.g. through observations at different planetary

phases) and/or monitor the atmosphere with a cadence and integration time which are shorter than the specific chemical reaction rate.

Thermal structure:
The effective temperature of the planet can be calculated knowing the flux from the host star, the orbital parameters and the planetary albedo. However the planetary albedo depends not only on the reflectivity of the surface but also on the opacity of the atmosphere and on the cloud properties. The atmospheric opacity is also responsible for a greenhouse effect that increases the surface temperature beyond the effective temperature, with obvious consequences for the habitability of the planet.

The infrared is the best interval to probe the vertical thermal structure of a planetary atmosphere through spectroscopic absorption signatures of molecules. The higher the spectral resolution, the higher the altitude we can probe: for example with Spitzer and Hubble low resolution spectroscopy and photometry, we typically sound the atmospheric region between the bar and millibar levels.

Horizontal thermal gradients require the ability to probe the planet at different phases. This can be attempted by monitoring light curves of transiting and non-transiting planets.

Indirect constraints on the temperature can be obtained through the temperature dependence of molecular and elemental absorption properties, or through measurements of the atmospheric scale height with transit data (provided other parameters such as gravity and the main atmospheric components are known).

Atmospheric dynamics and variability:
Atmospheric dynamics and temporal variability can be monitored by repeated observations of the thermal structure of the atmospheres. Observations of variations can also provide information on the rotation rate and on seasonal changes. In any case, the integration time of the observations needs to be sufficiently short to sample the variations; in the case of periodic processes like the diurnal rotation of planets, phase binning can also be employed.

Clouds and aerosols:
The presence of clouds and/or hazes in a planetary atmosphere profoundly influences the radiation balance and the climate of a planet. The optical properties of clouds and hazes depend on the size, shape and distribution of the particles. Spectroscopic observations in the visible and the infrared of the planetary atmosphere can provide constraints on those parameters. Polarized light in the visible is well-suited for detecting and characterizing clouds and hazes. Repeated observations are necessary to detect temporal variability, formation processes, and typical patterns.

Albedo and surface:
Spectral and photometric observations of the planet in the visible and near-IR spectral range provide constraints on the planetary albedo and the surface type of a planet (provided there is a surface, and the atmosphere is transparent enough at least at some wavelengths to get a glimpse of it). Also in this case, polarization may be the key for retrieving the type of surface. The presence of liquid water at the surface might be detected thanks to its glint (Robinson et al. 2010).

Magnetic field and upper atmosphere:
Observations of ionized species mainly in the UV (notice though that H_3^+ is detectable in the NIR) offer the possibilities of sounding the upper atmospheres of exoplanets, exploring star-planet interactions, and investigating escape processes.

Moons and rings:
Moons of transiting exoplanets will probably be detected rather soon, as they induce characteristic distortions in the light curves as well as timing variations. Photometric observations might also reveal the presence of prominent Saturn-like ring systems. Large moons have been hypothesized to stabilize a planet's obliquity and improve climate stability (Williams & Kasting 1996).

Planetary system architecture:
For a full understanding of the conditions on the surface of an exoplanet one must also take into account the context provided by the whole planetary system. The dynamical stability of the orbital parameters and the obliquity, as well as impact rate and history, depend on the presence of other large bodies in the system, and may have profound implications for the planet's habitability. Ideally one should thus seek to obtain complete sets of orbital parameters for all planets in the system; the presence and distribution of interplanetary dust may also provide crucial information on these issues.

Links to the Solar System:
Exoplanet science has a strong link to Solar System research. However, one cannot use the Solar System as a blueprint for exosystems, because each system and its evolving planets has a unique history and different end products. The Solar System planets should be used as "test-cases" in exoplanet studies. They are the only planets that can be studied in situ. Data, expertise and sophisticated numerical models have been collected and developed. Therefore Solar System studies and exoplanetology will ultimately merge into the broader field of comparative planetology.

7. Strawman Concepts

From the discussion in the preceding section it is apparent that the characterization of exoplanets and the exploration of habitable conditions on them comprise a very rich diversity of specific questions that can be addressed by an equally diverse set of observational approaches. Consequently, one cannot define a single mission concept that will provide a comprehensive and definitive picture of the habitable worlds in the solar neighborhood. In this Section, we will therefore describe a number of very different concepts that approach the quest for habitable worlds with common objectives based on different observing techniques in different parameter ranges. Each concept is capable of advancing the field of exoplanet exploration in a very significant way, as each can discriminate between hostile and potentially habitable worlds. We will thus have a choice between these concepts that can be based primarily on technological maturity and financial considerations later in the mission definition process.

7.1. Viable Mission Architectures

The biggest challenge in exoplanet exploration is the enormous contrast between the planet itself and its host star. There are two basic approaches to distinguishing planetary and stellar photons: spatial and temporal separation.

An instrument that aims at spatially resolving the planet from its host stars needs to provide sufficient angular resolution, i.e. of order 0.1" for a habitable-zone planet at a distance of 10pc. At visible wavelengths, this corresponds roughly to the resolution limit of a meter-sized telescope; in the thermal infrared an interferometer is needed to keep the unit telescope size reasonable. Working at very high contrast means that the starlight has to be rejected efficiently with a coronograph or nuller, and this in turn requires extremely precise control of the wavefront.

A variation on the concept of coronographic imaging is the idea of placing an occulter in front of the telescope, blocking the starlight even before it can enter the optical system. This obviates the need for precision wavefront control and decouples the inner working angle (IWA, the minimum accessible angular separation between star and planet) from the telescope size, but requires a complicated mission scenario with telescope and occulter spacecraft separated by thousands of km.

Concepts relying on temporal separation between star and planet obtain time series of the integrated light of the system. If the orientation of the observed system is nearly edge on, transits (when the planet is in front of the star) and eclipses (with the planet behind the star) lead to a dimming whose wavelength dependence contains information on the planetary spectrum. Even if a planet does not transit, its contribution to the integrated light varies with the orbital phase. Instruments aiming at detecting the ensuing changes of intensity, polarization, or wavelength of absorption lines are conceptually relatively simple, but require extremely high signal-to-noise and excellent stability.

7.2. Coronographs

High contrast imaging has been intensively developed in the last decade in particular for ground-based instruments like SPHERE and GPI (currently under construction for the ESO VLT and Gemini, respectively), but also for space with JWST. The fundamental challenge is obtaining high contrast at a small inner working angle (measured in multiples of the diffraction limit, λ/D). A lot of effort has been put into manufacturing various sorts of coronographs (apodization, phase masks, shaped pupils, among others; see Guyon et al. 2006 for a description). Most of these designs have been tested in the lab and some are currently implemented in real instruments. When used with good optics or with adaptive optics, these devices are able to deliver contrasts of 10^4 to 10^5 at a fraction of an arcsecond from the star, and soon planet finder instruments will reach even higher contrast (10^6 to 10^8) on the ground, which is sufficient for science programs focusing on young planets. The realm of mature planets, giants as well as terrestrial, will require even larger contrasts: 10^9-10^{10} in the visible and near-IR at closer separations of only a few times the telescope diffraction limit (corresponding to ~1 AU at 10-20pc). This means that a capability to suppress the starlight with an additional factor of 100 to 1000 with respect to SPHERE and GPI is needed. Such a challenging objective cannot be simply attained from an extrapolation of SPHERE and GPI, and hence calls for the development of new instrumental concepts and new strategies. In this respect, lab experiments have been built both in US and Europe to tackle coronography and wavefront control with large spectral band passes (Trauger & Traub 2007, Guyon et al. 2012, Baudoz et al. 2012). The achieved contrasts are very close to the requirements but still require some efforts to increase achromaticity and performance at the system level. The key points that are at the focus of current research are: 1) the capacity to control the optical wavefront in real time along the whole optical path to the science image in both phase and amplitude, 2) the achromaticity of the coronograph, and 3) the ability to recover the planetary signal embedded in the residual stellar light.

Moving from ground to space, in 2002 the NASA Terrestrial Planet Finder project studied a large coronographic telescope (6 to 8m in size) whose objective was to detect and characterize Earth twins in the solar neighborhood. Although abandoned in 2006, TPF-C has identified the key technologies for a space-based coronograph (Quirrenbach 2005). Smaller, 2-4m class coronographic telescopes have also been studied, and SEE-COAST and SPICES (with a 1.5m telescope) were proposed as an M class mission for Cosmic Vision (Schneider et al. 2009, Boccaletti et al. 2012). Maire et al. (2012) investigated the astrophysical potential of such a small coronograph in the context of exoplanets (Fig. 4). It can take spectra in the visible (0.45-0.90 μm) of mature planets from about 1 to 10 AU (depending on planet size and stellar spectral type) in the solar vicinity (<20pc). A few Super earths (about 2.5 $R_\oplus$), the most challenging targets, could be observed if present around the nearest targets (4-5 pc). To be efficient, such a mission needs an input catalog of targets, which will be provided by radial velocity surveys from the ground as well as astrometry with GAIA. Surprisingly, a 1.5m telescope with 10^{10} contrast capability can even perform low resolution spectroscopy of an Earth twin planet around the nearest star (about 1 pc).

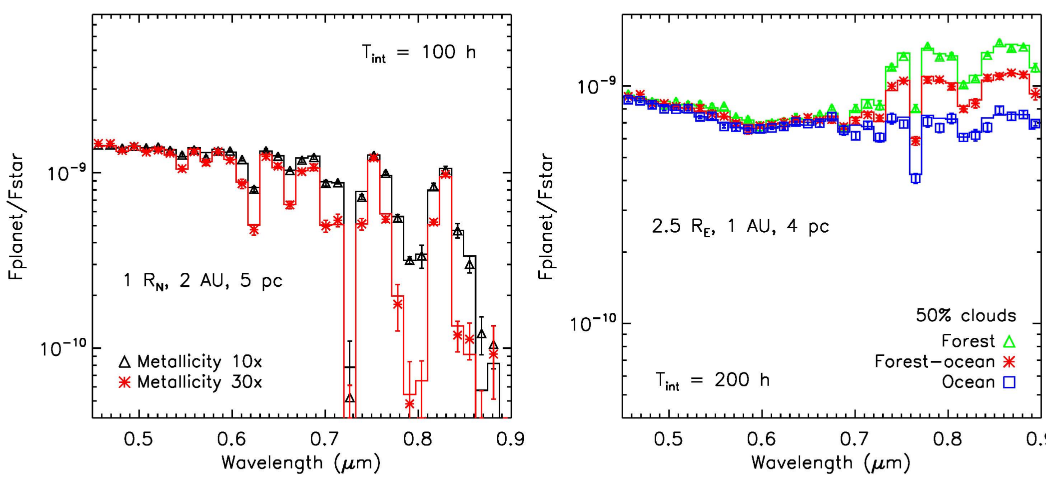

Figure 4: Simulated spectra across the SPICES spectral range, of Neptune-like (left) and Earth-like planets (right) with various properties demonstrating the ability of comparative planetology: spectral features vary at a detectable level with planet properties (Maire et al. 2012).

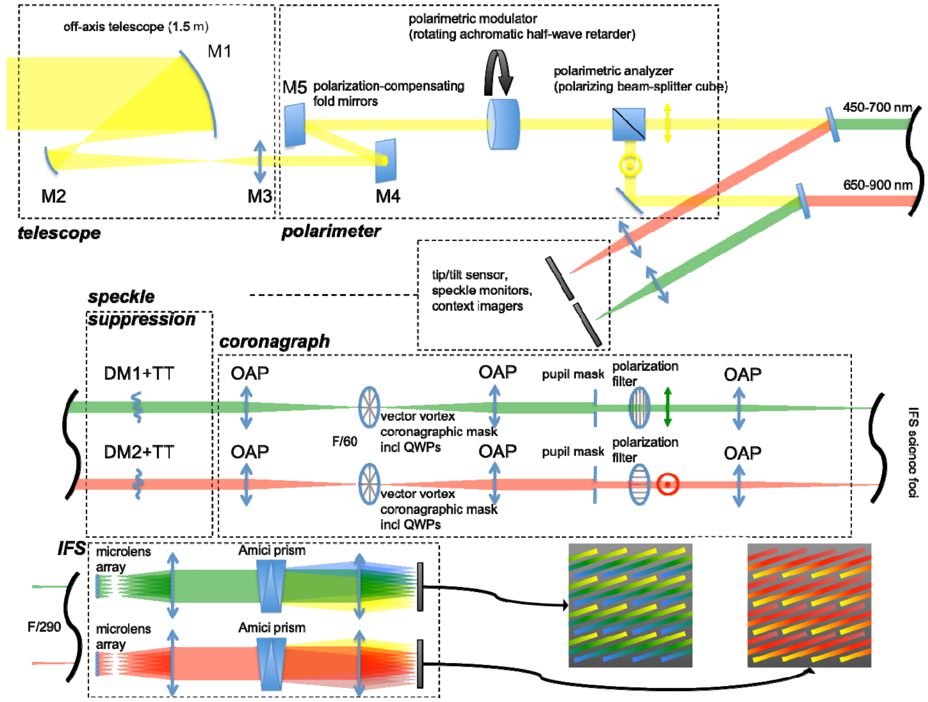

Figure 5: Conceptual design of the SPICES payload showing the main blocks: telescope, polarimeter, coronagraph and IFS. Only the main optics are shown here for sake of clarity.

To extend the mission capabilities to cover the appealing science case of spectroscopy of terrestrial planet atmospheres, beyond the marginal access provided by SPICES, a larger telescope (but with the same contrast capability) is required. A telescope diameter of 2-3 m is suitable for the science objectives proposed in this White Paper and is compatible with an ESA L class mission. In addition, an extension further into the near-IR is desired, although this imposes stronger limits on the angular resolution (equivalent to about 1 AU at 10 pc in the near-IR). With a suitable system design, it may even be possible to include the capability of sub-microarsecond astrometry, and thus to measure the planetary orbit (Guyon et al. 2013).

The concept of SPICES (for details see Boccaletti et al. 2012; see also Fig. 5) can be considered as a starting point for a study of an L class mission and is described here to provide an example of the present state of coronographic concepts and technologies. SPICES is a 1.5-m off-axis telescope consisting of a coronographic system combined with wavefront correction, which feeds an integral field spectro-polarimeter covering the 450-900 nm band and measuring two linear polarizations (Stokes Q, U). The requirement on the telescope optical quality is not drastic, but 10nm rms must be achieved at mid-frequencies. The instrument consists of two channels to mitigate the problem of chromaticity. Each channel is assigned a direction of polarization and half of the spectral band while it contains a single deformable mirror and a polarimetry-compliant coronograph. Wavefront sensing can be performed with a variety of techniques, such as the Self-Coherent Camera (Galicher et al. 2010), which also provides discrimination between speckles and planets (based on coherence) as a second stage (in the post processing). A deformable mirror (DM) provides a wavefront quality and stability on the order of tens of picometers. A Xinetics 48x48 actuator DM component has been tested at TRL5 by JPL (Trauger et al. 2010) and meets the contrast requirement. The coherent light is suppressed by a Vector Vortex Coronograph, a derivation of the phase mask concept which can be made potentially achromatic with a 50% bandwidth (Mawet et al. 2009). A raw contrast of ~10^9 over 20% bandwidth has been demonstrated at JPL (Trauger et al. 2011, Mawet et al. 2011). The backend instrument is a microlens-based integral field spectrograph (IFS) similar to those being developed now for SPHERE and GPI. Polarimetry is implemented in this design by using a rotating half-wave retarder as a modulator and a polarizing beam-splitter cube as an analyzer. For the purpose of thermal stability, target accessibility, and high data rate for the full mission, the satellite must be on an orbit around the Sun-Earth L2 Lagrangian point.

7.3. External Occulters

A different type of starlight suppression, first proposed by Lyman Spitzer, combines a telescope and a starshade (or occulter) in space for discovery of planets (Spitzer 1960). The size of the shade and the inter-spacecraft separation were enormous and thus impractical, but over many years refinements in starshade design have reduced the required starshade dimensions and improved the level of suppression. The technology developments and mission studies for external occulters have mainly been done in the US; a serious effort to build up similar expertise will be required in European academia and industry.

Though the original concepts for the starshade have used transmitting sheets with graded transmission for apodization, the most recent work has focused on optimizing the shapes of serrated-edge binary masks. Petal shapes have been found (e.g. Vanderbei et al. 2007) that permit operation at IWA < 100 milli-arcsec at wavelengths from 0.5-1.1 μm, using a shade with a nominal diameter of 40 meters at a telescope-starshade separation of 40,000 km. The telescope can be an ordinary diffraction-limited space telescope, and its diameter is determined mainly by the integration time required to detect faint planets ($\propto D^{-4}$), and by the need for planet-star astrometry ($\propto \lambda / D$). It can observe the planet in the entire passband from 0.5 to 1.1 μm in a single integration. Slewing from one star to the next requires that the starshade travel several thousand kilometers. To accomplish this within a few weeks requires large starshade velocities and Δ-velocities. With conventional thrusters, this would take a hefty amount of fuel; advanced electric propulsion eliminates this concern, but requires substantial electrical power. A substantial engineering effort has been dedicated to minimizing the time between observations and the resources required, and some mission scenarios have been found that yield satisfactory efficiencies with one occulter, and much better with two occulters. For modest telescope sizes (up to ~4m), these mission concepts outperform internal coronographs in terms of the number of planets that can be observed, as the smaller IWA more than compensates for the poorer agility. External occulters are particularly suited for long integrations on a small number of “cornerstone systems” that can be studied in exquisite detail, including monitoring of seasonal changes.

The most difficult technological issue is ensuring that the edge shape of the occulter is made well enough and maintained that way. Managing scatter and diffraction of sunlight off the edges, and deployment of the large starshade also need to be addressed. A NASA-funded technology program has demonstrated the manufacture of an occulter with flight quality edges, and a current one is intended to demonstrate deployment. Conventional prelaunch end-to-end testing – i.e., demonstrating stellar suppression at typical mission distances – is impossible. Thus it will be necessary to rely on diffraction models validated by subscale testing.

7.4. Interferometers

A space-based interferometer with starlight rejection capabilities – i.e. nulling (Bracewell 1978, Angel & Woolf 1997) – offers simultaneously the sensitivity, angular resolution and dynamic range needed to isolate and spectroscopically characterize the light of an exo-Earth in the ~6–20μm mid-infrared spectral domain.

As the faint planetary signal needs to be disentangled from the bright stellar one, the system must be spatially resolved typically at the 50–200mas level. A space-based nulling interferometer is able to spatially resolve and discern the faint planetary photons from the 10^6 times brighter stellar flux, as well as from spurious sources like stellar leaks (due to resolved stellar disk), our own local Zodiacal cloud, the exozodiacal light, and the thermal emission produced by the instrument. Luckily, the mid-IR range is also where the otherwise huge flux contrast of the system is reduced.

A 10-year long activity on both sides of the Atlantic to select the optimal array geometry converged in 2005 into the so-called *Emma X-array* configuration. The baseline concept is an X-shape configuration of four 2-m collectors flying in formation at L2 over a 5-year duration. The beams are combined within an additional centrally positioned spacecraft, where destructive interference cancels out the light from the central star. The long and short baselines of the rectangular configuration are tunable from tens to hundreds of meters in order to uniquely optimize the transmission map of the interferometer to the size of the habitable zone, which directly depends on a given stellar spectral type.

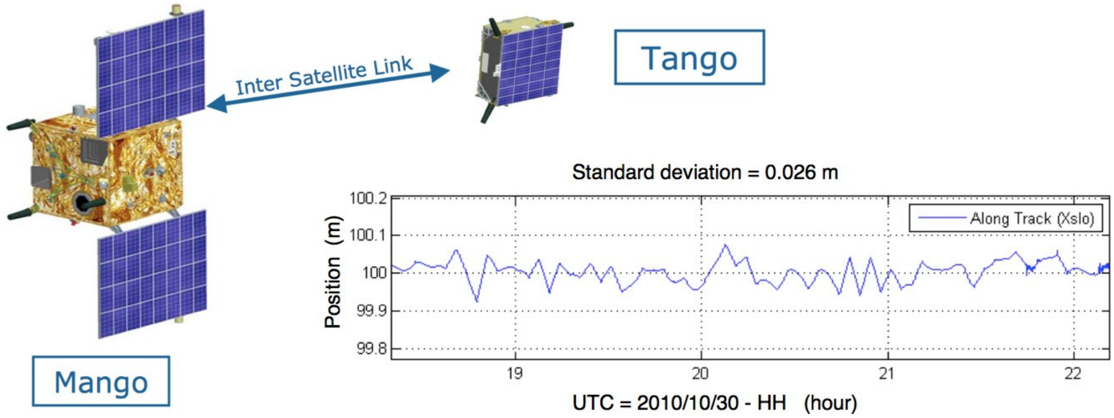

Figure 6: Demonstration of Formation Flying by PRISMA, 30 Oct. 2010. Two spacecraft, Tango and Mango, were successfully maintained at a distance of 100 m during 4 hours. The standard deviations were a few cm, limited by the accuracy of the radio frequency sensors. Laser based sensors will reduce this error to circa 100 µm (ESA's Proba 3 project). © Swedish Space Corporation, CNES and DLR

In the X-array arrangement, the respective destructive outputs of the two short-baseline Bracewell interferometers are combined with opposite phase shifts (±90°). This results in an internal "phase chopping" process (Mennesson 2005), which efficiently removes the thermal background and any emission from centro-symmetric sources around the nulled star.

A large effort in Europe has developed extensive expertise on nulling interferometry, both in academic and industrial centers. This has led to the publication of 34 PhD theses and 40 refereed papers. Built on the strong heritage of the Darwin/TPF studies (Cockell et al. 2009), progress has been achieved in various key technological areas, giving additional credit and technical readiness to this instrumental approach in the horizon of an L3 launch in 2034.

A key aspect is the deployment of a space interferometer based on a distributed array involving formation-flying operation. With the successful launch in 2010 of the PRISMA mission (OHB (S), DLR (D), CNES (F), DTU (DK), CDTI (E); Fig. 6) a crucial step has been made with the validation of the "Optical Arm" building block composed of two free-flying units, whose shape (length, orientation, rigidness) is controlled by the GNC/AOCS system. Extending the flight-tested building-block functionality from a distributed 2-S/C instrument to a 5-S/C instrument (i.e. 4 "optical arms" around one A-Unit) mainly relies on the replication of the coordination functionality and does not present additional complexity in terms of procedures according to the PRISMA navigation team. The current positioning accuracy is sub-cm, limited by the metrology system (GPS and RF). The launch of the PROBA-3 mission in 2017 will provide further valuable free-flyer positioning accuracy results (sub-mm). However, it should be noted that the requirement on the S/C positioning for interferometry is only at the sub-cm level, as the additional accuracy for co-phasing the array is provided by nanometer-accuracy servo delay-lines with few cm stroke, as demonstrated by TNO-TPD (NL).

The Planet Detection Testbed (Martin et al. 2010, 2012) has demonstrated the deep nulling needed for the detection and spectroscopy of Earth-mass planets. At 10µm with 10% bandwidth, it has achieved nulling of $8x10^{-6}$ (the flight requirement is 10^{-5}), starlight suppression of 10^{-8}, and planet detection at a planet-to-star contrast of $2x10^{-7}$, the Earth-Sun contrast. The *phase chopping* technique (Mennesson 2005) has also been implemented and validated on-sky for the Keck Nuller Interferometer (Colavita 2009).

In parallel, the operation of ground-based interferometers such as the VLTI has permitted to develop a strong European competence in the field of fringe sensing, tracking and stabilization.

7.5. Alternative Concepts

The recent stunning progress in the field of exoplanet detection and characterization has been mostly due to the exploitation of temporal rather than spatial differencing (see Section 4.), with Spitzer, HST, Kepler, and from the ground. It is particularly remarkable that many new "tricks" have been invented and put into practice that only ten years ago were not considered feasible: analyses of secondary transits (eclipses), out-of-eclipse light curves (phase curves), ground-based detections of molecular bands, and inspired applications of transit timing variations, to name just a few. CHEOPS, TESS, JWST, and hopefully EChO and/or PLATO will build on this legacy and offer many opportunities for the development of new strategies, perhaps even including studies of habitable super-Earths around bright M dwarfs. While it currently appears that the thorough characterization of habitable planets will likely require spatial rejection of the starlight to reach the required contrast, innovative temporal-differencing concepts might become serious alternatives in the coming years, on time for implementation as the L3 mission.

8. Sketch of Possible Implementation Plan

Considering that the scope of the present solicitation encompasses two decades from adoption of the science theme to envisaged launch date, care has to be taken to plan for technology development, and to maintain sufficient flexibility for identifying the mission concept most suitable for attaining the science goals, within the budgetary and technological constraints. For this decision, the proper yardstick clearly is not technology ready for a flight project today, but technology that can be brought to sufficient maturity within one decade. The existence of several viable concepts using very different observing strategies and therefore very different basic technologies should thus be viewed as a strength rather than a weakness, as several years are still available for technology development, risk mitigation, and to match the cost of each concept to the L mission envelope.

While considerably detailed preliminary studies have already been carried out on some of the concepts discussed above, much less has been done on others. In particular, careful system-level industry studies of coronographic missions have not yet been carried out in Europe. Moreover, even the more exhaustive studies involving industry were done ~10 years ago, and under the assumption of a much shorter time line available for technology development than currently envisaged. It is thus necessary to take a fresh and uniform look at the system level, to identify the key enabling technologies and the path to advance their maturity, before a sound decision can be made about the concept selection.

Assuming that the exoplanet theme is selected in 2014 for a 2034 L3 mission, a tentative timeline leading to the mission definition could therefore appear as follows:

2014-2015: Initial system-level assessment study for each concept family, identifying key enabling technologies which need maturity enhancement

2016-2020: Intensive R&D program to boost critical key technologies to a TRL level > 5; industry studies including cost estimates where needed

2019: Call for proposals for L3 mission

2020: Selection of mission concept for implementation

2020-2024: Further technology advancement to flight readiness, main trades and system analysis for the selected mission

2026-2034: Phase B

2034: L3 Launch

Preparatory science programs will proceed in parallel with these technical activities. As explained in Section 5., programs to search for target planets in the solar neighborhood and to characterize exozodiacal dust disks will proceed largely independently of the L3 mission anyway. However, the adoption of exoplanet exploration as a Large Mission by ESA will provide an added incentive for scientists and funding agencies to intensify their research efforts in these areas.

With the discovery of exoplanets, fiction and dream have become science. Observational exoplanetology has developed with extraordinary rapidity, and will continue to do so, attracting the efforts of our brightest minds, producing results which change the way we perceive the universe and ourselves. It is now realistic to address the great questions about habitable worlds other than Earth. Those questions will never be answered without instruments such as described here. A strong program of exoplanet missions is an essential component of the path ahead.

9. References

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