



**HAL**  
open science

## Detecting life outside our solar system with a large high-contrast-imaging mission

Ignas Snellen, F. Snik, M. Kenworthy, S. Albrecht, G. Anglada-Escudé, I. Baraffe, P. Baudoz, W. Benz, J.-L. Beuzit, B. Biller, et al.

► **To cite this version:**

Ignas Snellen, F. Snik, M. Kenworthy, S. Albrecht, G. Anglada-Escudé, et al.. Detecting life outside our solar system with a large high-contrast-imaging mission. *Experimental Astronomy*, 2022, 54, pp.1237-1274. 10.1007/s10686-021-09803-y . hal-03432566

**HAL Id: hal-03432566**

**<https://hal.science/hal-03432566v1>**

Submitted on 24 Nov 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



# Detecting life outside our solar system with a large high-contrast-imaging mission

Ignas A. G. Snellen<sup>1</sup> · F. Snik<sup>1</sup> · M. Kenworthy<sup>1</sup> · S. Albrecht<sup>2</sup> · G. Anglada-Escudé<sup>3,4</sup> · I. Baraffe<sup>5</sup> · P. Baudoz<sup>6</sup> · W. Benz<sup>7</sup> · J.-L. Beuzit<sup>8</sup> · B. Biller<sup>9,10</sup> · J. L. Birkby<sup>11</sup> · A. Boccaletti<sup>6</sup> · R. van Boekel<sup>12</sup> · J. de Boer<sup>1</sup> · Matteo Brogi<sup>13,14,15</sup> · L. Buchhave<sup>16</sup> · L. Carone<sup>12</sup> · M. Claire<sup>17</sup> · R. Claudi<sup>18</sup> · B.-O. Demory<sup>19</sup> · J.-M. Désert<sup>20</sup> · S. Desidera<sup>18</sup> · B. S. Gaudi<sup>21</sup> · R. Gratton<sup>18</sup> · M. Gillon<sup>22</sup> · J. L. Grenfell<sup>23</sup> · O. Guyon<sup>24,25,26</sup> · T. Henning<sup>12</sup> · S. Hinkley<sup>5</sup> · E. Huby<sup>27</sup> · M. Janson<sup>28</sup> · C. Helling<sup>29</sup> · K. Heng<sup>13,20</sup> · M. Kasper<sup>30</sup> · C. U. Keller<sup>1</sup> · O. Krause<sup>12</sup> · L. Kreidberg<sup>12</sup> · N. Madhusudhan<sup>31</sup> · A.-M. Lagrange<sup>6,27,32</sup> · R. Launhardt<sup>12</sup> · T. M. Lenton<sup>33</sup> · M. Lopez-Puertas<sup>34</sup> · A.-L. Maire<sup>35</sup> · N. Mayne<sup>5</sup> · V. Meadows<sup>36</sup> · B. Mennesson<sup>37</sup> · G. Micela<sup>38</sup> · Y. Miguel<sup>1,39</sup> · J. Milli<sup>32</sup> · M. Min<sup>39</sup> · E. de Mooij<sup>40</sup> · D. Mouillet<sup>32</sup> · M. N'Diaye<sup>41</sup> · V. D'Orazi<sup>18</sup> · E. Palte<sup>42</sup> · I. Pagano<sup>43</sup> · G. Piotto<sup>44</sup> · D. Queloz<sup>45</sup> · H. Rauer<sup>46</sup> · I. Ribas<sup>3,4</sup> · G. Ruane<sup>37</sup> · F. Selsis<sup>47</sup> · A. Sozzetti<sup>14</sup> · D. Stam<sup>48</sup> · C.C. Stark<sup>49</sup> · A. Vigan<sup>8</sup> · Pieter de Visser<sup>39</sup>

Received: 22 July 2020 / Accepted: 27 September 2021

© The Author(s) 2021

## Abstract

In this White Paper, which was submitted in response to the European Space Agency (ESA) Voyage 2050 Call, we recommend the ESA plays a proactive role in developing a global collaborative effort to construct a large high-contrast imaging space telescope, e.g. as currently under study by NASA. Such a mission will be needed to characterize a sizable sample of temperate Earth-like planets in the habitable zones of nearby Sun-like stars and to search for extraterrestrial biological activity. We provide an overview of relevant European expertise, and advocate ESA to start a technology development program towards detecting life outside the Solar System.

## 1 The exoplanet revolution

Since the first discovery of planet-mass bodies orbiting a pulsar [155] and the first gas giant orbiting a solar-type star [97], thousands of extrasolar planets have been found, exhibiting an enormous diversity in mass, size, composition, and orbital properties. Some gas giants are in such tight orbits that they are hotter than most

---

✉ Ignas A. G. Snellen  
snellen@strw.leidenuniv.nl

Extended author information available on the last page of the article.

stars in the Milky Way, while others are found at hundreds of astronomical units (AU) distance. Many planets are unlike those in our own Solar System, with still to be determined bulk compositions. We do know by now that rocky planets are very common, particularly around red dwarf stars, and temperate planets – like Earth – are expected to orbit many of our nearest neighbors. This puts us in a position to start addressing existential questions about the place of humanity and Earth in the Universe.

Much of the scientific progress is fuelled by enormous improvements in instrumental capabilities and precision, and a steep learning curve on how to optimally utilize both space and ground-based telescopes. The rapid sequence of milestones is amazing: after the discovery of the first transiting planet [21, 59], the first atmospheric feature was detected only two years later [22], followed by the first thermal emission measurements [23, 32], the discovery of the first exo-Neptune [18] and hot rocky planets [6, 78], a planet thermal map [70], the first direct image of a planet [74, 90], planet spin [131], culminating in the exciting discoveries of the first nearby temperate rocky planets Proxima b and those in the TRAPPIST-1 system [3, 52] – a true scientific revolution.

We can expect that in the next decade, by means of radial velocity, transits, astrometry, and microlensing surveys including ESA's Gaia, CHEOPS, and PLATO missions, a general census of the exoplanet population will be largely completed. Atmospheric characterization, however, requires different measurements, since most exoplanets are discovered without identifying photons from the planets themselves. Both transit spectroscopy and high-contrast-imaging techniques have already delivered a string of very exciting results, both from space and from the ground. Transit and dayside spectroscopic observations have constrained the climate and temperature structure for a range of hot Jupiters, and have revealed molecular, atomic and ionic absorption features, Rayleigh scattering by hazes, constrained global circulation patterns, and provided evidence for clouds and global winds. High-contrast imaging has provided such evidence for around a dozen directly-imaged massive young gas giants, including their spin rate and cloud-deck variability. Many endeavors are under way to push these measurements to smaller and cooler planets, and the future is bright. In the next decade, the James Webb Space Telescope (JWST), Ariel, and the Extremely Large Telescopes (ELTs) will come online. They are expected to extend atmospheric characterization to a few of the most favorable temperate rocky planets, such as Proxima b and those in the TRAPPIST-1 system, to address whether such planets have atmospheres, whether they are wet, and potentially habitable. Characterizing true Earth analogs that are in the Habitable Zones (HZs) of Sun-like stars (except for the Alpha Centaurus system) is outside the realm of both the JWST and the ELTs. This requires a large high-contrast-imaging telescope mission, e.g. such as the HabEx and LUVOIR missions currently under study by NASA.

Our ultimate goal is to understand the place of Earth and the Solar System in the Universe. How do planets form? What ranges of architectures of planetary systems exist, and how does the Solar System fit in? How unique is the Earth as a planetary host of biological activity? To address such existential questions, a broad framework is needed that explains the formation and evolution of planets as a function of mass,

composition, birth-orbit, and migration history. This will need to be coupled to a thorough understanding of geological processes, atmospheric physics and chemistry for a wide range of planets. Only at that point we will be in a position to identify biomarker gases (e.g. [100]) as unambiguous proof for biological activity.

In this White Paper, we advocate ESA to start a global collaboration to develop and build a large, high-contrast-imaging space telescope, to be launched in 2040. Only a handful of temperate rocky-planets around mid/late M-dwarfs – the low-hanging fruit – will have been characterized by that time. This mission will conduct a large characterization census of twin-Earths around solar-type stars in the solar neighborhood, and the many other planets in these systems, and assess their climate, habitability, and whether they are inhabited. This can only be done with a space telescope. In Section 2 we describe the current status of the field, and in Section 3 the outlook for the 2020–2035 period. Section 4 discusses the science case for this mission and the resulting instrument requirements. Section 5 describes the current HabEx and LUVOIR designs and provides a non-exhaustive list of potential areas for Europe to participate, and a roadmap for a technology development program towards detecting life outside the Solar System.

This direct imaging White Paper joins two other papers in this issue that are advocating interferometry (Quanz et al.) and a starshade (Janson et al.) for the detection of biomarkers. This paper has benefited greatly from excellent recent reviews, notably the *Exoplanet Science Strategy*<sup>1</sup> (2018) and *Astrobiology strategy for the search for life in the universe*<sup>2</sup> (2019), both from the National Academy of Sciences.

## 2 Current status of the field

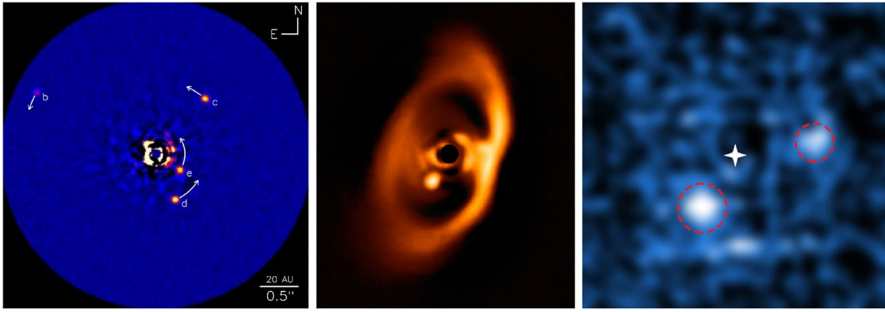
### 2.1 Finding planets

Most exoplanets have been discovered using the radial velocity (RV) technique, which measures the host star's reflex motion around the system's center of mass, or with the transit method, which targets the regular and temporal dimming of a star caused by a passing planet.

*The RV technique* requires spectrographs with a resolving power of  $R \sim 10^5$ , and has so far been utilized only on ground-based telescopes. The ultra-stable HARPS spectrograph [98] on the 3.6-m telescope of the European Southern Observatory (ESO) has played a pioneering and leading role. The RV signal induced by an unseen planet scales with the planet mass, square-root of the orbital distance, and the sine of the orbital inclination. Massive planets in close orbits, such as hot Jupiters, are therefore the easiest to detect and produce RV signals of up to 150–200 m/s. An Earth-mass planet in an Earth orbit around a solar-mass star induces an RV signal of 9 cm/s.

<sup>1</sup> NAS Exoplanet Science Strategy (2018) available at <http://nap.edu/25187>

<sup>2</sup> NAS Astrobiology strategy for the search for life in the universe (2019); <http://nap.edu/25252>



**Fig. 1** The two directly imaged systems with multiple planets so far, with HR 8799 (left) and PDS 70 with SPHERE (middle; [69]) and in H $\alpha$  [54]. Image credits: NRC-HIA/C.Marois/W.M.Keck Observatory; ESO/Müller et al.; ESO/S. Haffert, Leiden Observatory

*The transit method* relies on wide field CCD photometry to monitor the flux of thousands of stars simultaneously. The transit signal scales with the square of the ratio of planet to star radius, which corresponds to 1% for a Jupiter-size planet transiting a solar-type star and around 0.01% for an Earth-size planet. The duration of a transit is typically one to a few hours for a close-in planet, to half a day for a planet in an Earth-size orbit. Transit surveys are strongly biased to planets with short orbital periods, because those in wider orbits have a lower probability to transit, and if they do, produce transits less frequently. Ground based transit surveys have resulted in hundreds of hot and warm gas-giant planets (e.g. [1, 4, 142]). The CoRoT and NASA Kepler space mission have probed down to rocky planet sizes, albeit mostly for relatively faint and distant stars. In particular, Kepler has resulted in thousands of discoveries, reaching down to Earth-size planets in Earth-size orbits around solar type stars (e.g. [114]).

*High-contrast imaging* is currently exclusively performed by ground-based instrumentation, and relies on adaptive optics techniques that can correct the stellar wavefront from atmospheric turbulence, and coronagraphy to enhance the achieved contrast by blocking the starlight as much as possible, while letting the planet light pass through. Planets that are relatively bright and far enough from their host star are the most accessible, and current discoveries are mostly limited to young (10–100 Myr) self-luminous gas giant planets orbiting at tens of AU or more. Particularly remarkable examples are Beta Pictoris b in a nearly edge-on 10 AU orbit [75], the four-planet system of HR8799 [91], and the two planets in the PDS 70 system which still contains a gas and dust disc apparently feeding the (proto-)planets [54, 69, 104] - see Fig. 1. The few dozen gas giants and sub-stellar companions known so far are seen at contrasts of typically  $10^{4-5}$ . At mature ages of a billion years or more, these planets will have faded by several orders of magnitude below current detection limits.

*Microlensing* provides additional information on the architecture of planetary systems as the observational biases are very different from the other techniques. A foreground star with accompanying planet can act as a gravitational lens of a background star and significantly boost its flux. Although this technique does not provide precise measurements of a planet's mass and orbit, a large ensemble can provide statistics on planets in relatively wide (4–10 AU) orbits that are otherwise inaccessible

with the other methods. Microlensing surveys are currently conducted by ground-based telescopes mostly monitoring very wide star fields towards the bulge. As soon as a week- to month-long stellar microlensing event is identified, the target is then intensively monitored to identify short-duration amplifications due to planets in the system.

Finding planets through *astrometry*, which measures the reflex motion of the star in the plane of the sky, has held tremendous promise from the earliest days in the exoplanet field. Only now --- with ESA's Gaia mission --- is this technique expected to deliver [113]. Interestingly, the observational bias on orbital radius is opposite to those for the RV and transit techniques, generating a larger signal for planets in wider orbits (with a limit set by the total mission duration). Astrometric signals are inversely proportional with distance, making the technique most sensitive to the most nearby stars.

Red dwarf stars are particularly interesting for finding planets. Since stellar masses are up to an order of magnitude smaller than that of solar-mass stars the RV signals are correspondingly larger - and since stellar radii are up to a factor ten smaller, the corresponding transit signal for a given radius planet can be up to two orders of magnitude larger. Their luminosities can be a thousand times lower meaning that temperate planets can be found in smaller orbits - making even small, rocky planets accessible through both the transit and the RV technique. This is called the *red dwarf opportunity*.

Several, relatively small, ground based projects are currently targeting transits of mid-M dwarfs (e.g. M<sub>Earth</sub><sup>3</sup>) and late M-dwarfs (TRAPPIST; SPECULOOS<sup>4</sup>; [52]), and significant observing time is being invested in RV surveys targeting the nearest red dwarf population (e.g. Pale Red Dot<sup>5</sup>). The most thrilling discoveries are those of Proxima b, a planet with a minimum mass of 1.3 M<sub>Earth</sub> in an 11-day orbit (meaning it receives about 70% of stellar energy compared to the Earth - see Fig. 2; [3]), and the seven Earth-size planets in the TRAPPIST-1 system [52] of which at least three have equilibrium temperatures that indicate they could have liquid water on their surfaces - see Fig. 2.

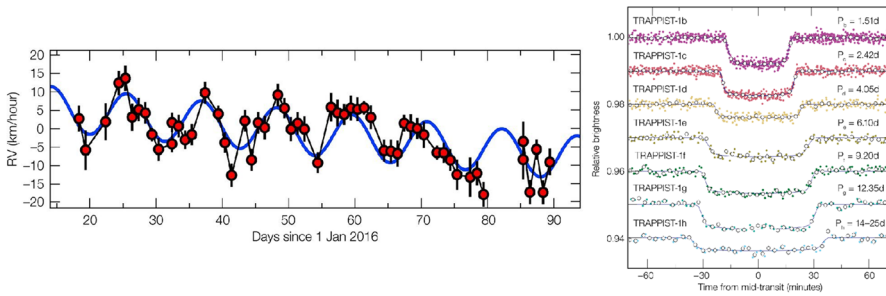
## 2.2 Planet demographics

A key finding of exoplanet research so far is that planets are very common and diverse - something that was completely unknown 25 years ago. Although the results of early RV and transit surveys were dominated by detections of hot Jupiters, this is largely caused by observational biases. These planets are actually relatively rare - occurring around typically 1% of FGK stars, dropping to even lower fractions around the lowest mass stars [98]. They are likely the product of extreme orbital migration, either due to early interactions with the protoplanetary disk and/or other objects in the system. The occurrence rate of gas giant planets out to a few AU is

<sup>3</sup> <https://www.cfa.harvard.edu/MEarth/Welcome.html>

<sup>4</sup> <https://www.eso.org/public/chile/teles-instr/paranal-observatory/speculoos/>

<sup>5</sup> <https://palereddot.org>



**Fig. 2** [Left] Discovery RV measurements from HARPS showing the signal from Proxima b. [Right] The transit signals of the seven Earth-size planets in the TRAPPIST-1 system. Credits: ESO/G. Anglada-Escudé & ESO/M. Gillon et al.

about 10–15%, with many of them in eccentric orbits. Such planets are found to be significantly more common around higher metallicity stars [126] – a correlation not found for lower mass planets.

Kepler has shown that Neptune size planets in close-in orbits ( $\ll 1$  AU) are common [61], and that about half of the stars have planets in size between the Earth and Neptune in orbits smaller than Mercury’s. The distribution in planet radius and orbital distance shows a valley of low number density separating gas-rich planets from possible rock-dominated planets, a separation which could be caused by processes of mass loss due to photo-evaporation [44, 147].

While the Kepler mission has just fallen short of an accurate determination of the occurrence rate of temperate Earth-size planets around FGK stars, it is clear that they are very abundant ( $>10\%$  - [17]). They may even be more ubiquitous around M-dwarfs, with estimates of one HZ planet with  $1\text{--}1.5 R_{\text{Earth}}$  for every four M-dwarfs [38].

The relatively few detections of young gas giant planets with direct imaging suggest that their occurrence rate at wide ( $>30$  AU) orbital separations is 0.01–1% (e.g. [14]), including significant uncertainties due to the steep age-luminosity and mass-luminosity relations for gas giant planets, and uncertainty in the initial entropy of formation. Current statistics from microlensing surveys are the most detailed for M-dwarf systems. They show that Jupiter and Neptune mass planets are less common than around solar-type stars, but there exists a significant population of cold super-Earths in relatively wide orbits (e.g. [27]).

### 2.3 Planet characterization – Bulk compositions and atmospheres

Radial velocity measurements of a transiting exoplanet system reveal the mass of the planet without inclination ambiguity, which in combination with the planet radius will provide an estimate of the planet’s mean density. Although this has so far been only possible for planets in relatively short orbits, it is clear that *bulk compositions* can vary wildly from planet to planet – even for planets with the same mass or radius. The density of Jupiter-like planets show a wide range of variation, probably because of differing rocky core fractions and due to various levels of inflation from

incident host star radiation. First indications are that the core masses of gas giants in wider orbits correlate with the metallicity of their host stars [146].

Lower mass planets are found to have increasingly higher densities, consisting of varying combinations of iron, rock, ice, and gas – which are not straightforward to solve due to degeneracies in internal structure models. It is expected that such degeneracies can at least be partly resolved by future atmospheric observations. Current statistics are highly biased towards planets in the shortest orbits. They imply that there is an overlap between terrestrial super-Earths and gas-rich mini-Neptunes with the same mass, but significantly different radii. Below a size of  $\sim 1.6 R_{\text{Earth}}$ , planets are mostly found to be rocky with compositions consistent with that of the Earth (e.g. [39]).

Most exoplanets are discovered without identifying a single photon from the planets themselves. For *atmospheric characterization*, planet light needs to be separated from that of the star. There are generally two families of techniques that can accomplish this. The first relies on temporal variations of the planet and starlight – these include transmission and secondary eclipse spectroscopy and planet phase curve observations. Since they mostly (but not exclusively) rely on transiting systems, and transit probabilities are lower for planets in increasingly wider orbits, such observations are performed on stars that are relatively distant and faint. The second family of techniques relies on angularly separating the planet light from that of the star, i.e. high contrast imaging – any direct image of a planet automatically contains information on the planet's atmospheric properties.

During a transit, starlight is blocked by the planet, but also a small fraction of starlight filters through the planet's atmosphere where it is partially absorbed and scattered by atoms, molecules, and/or cloud and haze particles. When the planet itself is eclipsed, comparison with observations just before and after the eclipse can reveal reflected light and direct thermal emission from the planet, which has also an imprint of possible atmospheric absorption and scattering processes. Observations during other parts of the orbit can reveal variations in emissions from the planet when different fractions of the dayside and nightside hemispheres of the planets come into view.

Gas giant planets in close-in orbits provide the most accessible signals for these time-differential techniques. Their high temperatures result in the most favorable planet/star contrasts for eclipse spectroscopy and, in combination with their  $\text{H}_2$  atmospheres, the largest transmission signals. Observations have mainly been performed with the Hubble and Spitzer Space Telescopes, but also from the ground – in particular using spectroscopy at very high resolving powers of  $R \sim 100,000$  which helps to remove stellar and telluric contamination (e.g. [130]). Observations of hot Jupiters have shown the presence of Rayleigh scattering from high altitude hazes [129], and atmospheric absorption from atomic gases such as sodium and iron, ionized iron and titanium (e.g. [60]), and molecules such as water, carbon monoxide, and titanium oxide [32, 109]. Some planets show significant atmospheric losses through their evaporating exosphere which contains atomic hydrogen and helium (e.g. [42, 139]). Eclipse and phase curve observations constrain the vertical and longitudinal temperature structure of these planets, including the presence of thermal inversions. Their day-to-nightside temperature variations provide clues on global



circulation processes and overall climate. High-altitude winds are also directly probed with high-dispersion spectroscopy. The extension of these techniques to smaller and cooler planets have revealed the presence of high altitude clouds that mask possible molecular absorption features [72]. This is a major concern, in particular for transmission spectroscopy, which may be mitigated by observing in the mid-infrared, e.g. with MIRI/JWST where the clouds are expected to become transparent.

For high contrast imaging, young gas giants (1–50 Myr) in wide orbits are best accessible due to their relatively large angular separation from their host stars and favorable contrast due to residual heat from their formation. As for eclipse observations, this constrains the temperature–pressure profiles of these planets and molecular content such as for water, carbon monoxide and methane (e.g. [25]). Planet spin rotation has been determined from line broadening [131] and the presence of a varying cloud cover has been established through planet flux variations.

More recently the first exciting exoplanet results have been presented using optical-NIR interferometry using the GRAVITY instrument of ESO's VLTI platform [73]. We like to note that mid-infrared space-based interferometry is the subject of a White Paper led by Sascha Quanz.

### 3 Outlook for the 2020–2035 period

#### 3.1 A census of the planet population in the milky way

As this White Paper advocates for the development of a large space telescope for high contrast imaging of nearby planetary systems, we will focus here on the question of what will be learned about the nearby planet population in the next 15 years. The NASA TESS mission<sup>6</sup> is currently conducting an almost complete all sky transit survey. It has finished its first Southern and Northern hemisphere surveys, and will likely continue to operate for several years—conducting an ecliptic survey, and/or revisiting the previous survey areas for one or multiple visits. With its larger telescope, the ESA CHEOPS mission<sup>7</sup> (launched in 2019) will perform crucial follow up studies of the most interesting systems, while the ESA PLATO mission<sup>8</sup> will combine unprecedented photometric precision with a very wide field of view to determine the percentage of solar type stars with temperate Earth-size planets. There will also still be an important role for ground-based transit surveys – such as SPECULOOS and ExTrA<sup>9</sup> (which also uses spectral information) – which will focus on planets transiting the smallest M-dwarf stars. Such stars are optically too faint and dispersed across the sky to be covered by the wide angle space-based surveys. With all these new and ongoing missions and

<sup>6</sup> <https://www.nasa.gov/tess-transiting-exoplanet-survey-satellite>

<sup>7</sup> <http://sci.esa.int/cosmic-vision/53541-cheops-definition-study-report-red-book/>

<sup>8</sup> <http://sci.esa.int/plato/59252-plato-definition-study-report-red-book/>

<sup>9</sup> <https://www.eso.org/public/teles-instr/lasilla/extra/>

surveys it is to be expected that nearly all nearby transiting systems will have been discovered by 2035. However, the closest Earth transiting a solar-type star will not be quite ‘nearby’. Since the transit probability is on the order of 0.5%, for every transiting Earth-twin there is expected to be a non-transiting counterpart about six times closer to us --- making it uncertain whether transiting Earth-twins will be preferable targets for high-contrast imaging.

Ground-based RV discoveries will further accelerate with the many existing and upcoming surveys, such as with HARPS+NIRPS, HARPS-North, ESPRESSO, Terra Hunting Experiment [145], and CARMENES (to name the main European-led projects) obtaining large fractions of their telescope time. Considering the high speed at which discoveries are made, it is to be expected that most planets around nearby M-dwarfs will have been found by 2035, with temperate planets already found around Proxima (1.4 pc; [3]), Barnard’s star (1.8 pc; [123]), Lalande 21,185 (2.5 pc; [34]), and Teegarden’s star (3.8 pc; [156]). While instrumental stability is expected to approach the level required to detect Earth twins around solar type stars (9 cm/s), astrophysical noise from granulation, pulsations, rotation modulated star spots, and magnetic cycles will make it difficult to reach this level in practice. Several avenues are being explored to separate out true planet-induced RV signals from stellar noise. Acquiring spectra at particularly high signal-to-noise can reveal subsets of spectral lines that react differently to stellar effects (e.g. [41]), and lines in the near infrared are expected to be less sensitive to activity. The Terra Hunting Experiment<sup>10</sup> will monitor fifty nearby solar type stars every night for ten years to optimize the observational window function – hoping to reach Earth twins in that way. However, such experiments will also select the quietest stars, and not necessarily the nearest. It is therefore not clear yet whether the Earth twins around the nearest Sun-like stars will be known by 2035. Measuring the masses of such planets through RV will be significantly easier afterwards, when the orbital periods are known through high-contrast imaging with the mission proposed here. A long-term high-precision RV monitoring campaign for the most nearby solar-type stars is therefore highly recommendable.

The full data release of the ESA Gaia mission will contain thousands of gas giant planets in relatively wide orbits around nearby stars. It will determine the architecture of the outer parts of the planetary systems around virtually all of our neighbors. NASA’s Nancy Grace Roman Space Telescope, or Roman (previously WFIRST) mission will conduct microlensing surveys that will provide the population statistics of outer planetary systems on a wider scale (and to a much lower mass) – generally from systems at hundreds to thousands of parsecs.

Assuming that the high contrast imaging mode of Roman will only be a technological demonstrator, high contrast imaging will, also in the 2020–2035 timeframe, be advanced from the ground only. The ELTs (2025–2030) will not only play an exciting role in characterization of the nearest exoplanet systems (see below), but also in discovering planets. At 10  $\mu\text{m}$ , the METIS instrument<sup>11</sup> on the European

<sup>10</sup> <http://www.terrahunting.org/index.html>

<sup>11</sup> <http://metis.strw.leidenuniv.nl>

ELT can detect an Earth twin in the Alpha Cen system within one night – a goal that is already being pursued using the VLT through the Breakthrough Initiative program [67].

Since the diameter of the European ELT is about five times larger than that of the VLT, the collecting area is 25 times larger, while its angular resolution (theoretically) is 5 times better, resulting in 25 times less background and stellar noise at the planet's location. This will make the ELT (in the extreme adaptive optics regime) at least a few hundred to a thousand times faster than the VLT, and also many new targets will become accessible at smaller angles only accessible by the ELT. While current young stellar system surveys are barely scratching the surface of unveiling the (proto-)planet population, this will be rapidly advanced with the ELTs – probing significantly lower masses and older systems. In combination with the revolutionary work by ALMA, it can be expected that the general paradigm of planet formation will be set in the 2035 timeframe. Of course, certain specific aspects will require significant more work, similar to today's understanding of stellar and galaxy evolution theory.

### 3.2 Exoplanet characterization

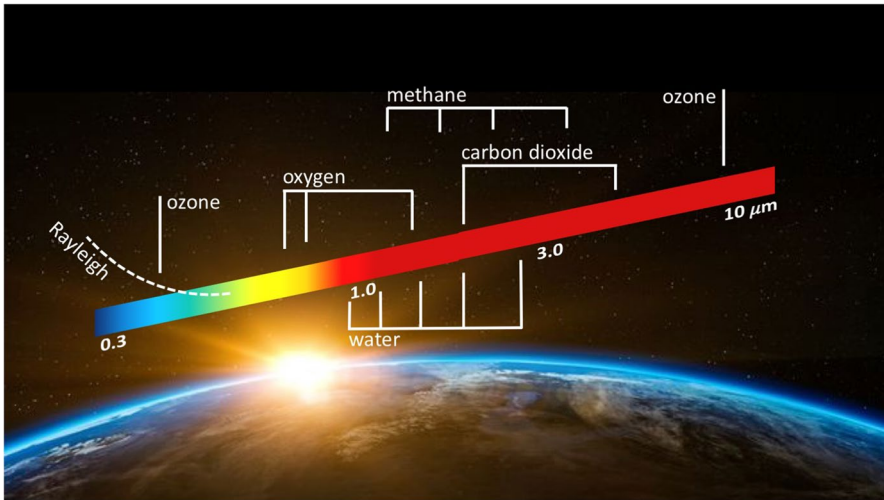
Exoplanet characterization from space will be dominated by the JWST (2021) and ESA's Ariel mission<sup>12</sup> (2028). Compared to the Hubble and Spitzer Space Telescopes, the JWST will be a giant leap forward in transmission and secondary eclipse spectroscopy, utilizing a collecting area that is respectively 6.3 and 44 times larger. For the first time a wide spectral range from red-optical to 20  $\mu\text{m}$  will be covered (e.g. [53]). Ariel will consist of a significantly smaller telescope, but it is one that will be fully dedicated to exoplanet characterization, concentrating on a large sample of hot and warm gas giants and smaller planets. It will form the basis of mapping atmospheric physics and chemistry for a wide range of planets in different environments and with different evolutionary histories.

How far the JWST can be pushed remains to be seen, but it is clear that great strides forward will be made. It is planned to measure the secondary eclipse depths of the TRAPPIST-1b planet (Guaranteed Time Observations) at 12 and 15  $\mu\text{m}$ , determining whether this planet has an atmosphere, and whether it contains carbon dioxide (e.g. [84]). Already these measurements will have an enormous impact, revealing to what extent rocky planets around late M-dwarfs can retain their atmosphere, and can be wet and habitable. There are three orders of magnitude of science between what we study now - mainly hot Jupiter atmospheres - and our goal of studying the habitats of temperate rocky planets. The JWST will cover a significant fraction of that ground, but will not be able to characterize Earth twins.

Three ELT projects are on track to see first light in the 2025–2030 time frame: the European ELT (39 m), the Giant Magellan Telescope (GMT; 25 m), and the Thirty Meter Telescope (TMT; 30 m). Concentrating on the European perspective, the ELT will host its first-generation instrument METIS, which is capable of detecting Proxima

---

<sup>12</sup> <http://sci.esa.int/ariel>



**Fig. 3** Schematic overview of important molecular features from the UV, optical, to the infrared

b by combining high-contrast imaging with high-dispersion spectroscopy (e.g. [81]) – focusing on spectral signatures of water, carbon dioxide, methane, and even heavy water – HDO [103]. Other very nearby temperate planets will also become accessible with HIRES – the optical-NIR high-dispersion spectrograph, expected as a second-generation ELT instrument – and capable of detecting molecular oxygen. The ELT will be pushed to its limits when such instruments are combined with extreme adaptive optics providing superb wavefront correction (e.g. PCS/EPICS). While this is clearly technically challenging, it would allow measurements of albedo, overall climate, and molecular absorption such as from water, carbon dioxide, methane, and oxygen (Fig. 3) for a handful of temperate rocky planets around the nearest M-dwarfs.

#### **4 Exoplanet & Astrobiology Science 2035–2050: the case for a large high-contrast-imaging space telescope**

As argued above, by 2035 we will have discovered most temperate planets around nearby (<5 pc) M-dwarfs. The nearest and most interesting transiting systems, both around M-dwarfs and solar-type stars, will also have been found. The nearest Earth twins (non-transiting around solar type stars) are only accessible with RV, and will remain a challenge. The large high-contrast-imaging space telescope, as advocated here, may have to determine their orbits first (which is not an issue, because they are very common), before (pre-existing) RV data can reveal their masses.

A handful of temperate, terrestrial planets that orbit the nearest M-dwarfs will have been characterized in detail with the ELTs. We will likely know their main atmospheric constituents, have constrained their climates and assessed their habitability. Veritable Earth-twins, those that orbit solar-type stars, will be out of reach of ground-based characterization due to their extreme planet/star contrasts. They form,

together with the many other planets in their systems, the hunting ground for a large high-contrast-imaging space telescope. Below we discuss the main science questions and topics that such a space telescope will address. We have finally reached a level of technical ability such that we can fulfill our long-standing desire to study Earth-twins and search for extraterrestrial life.

#### 4.1 Climate & habitability

As exoplanet science is an extreme form of remote sensing, a biosignature is defined as an effect of biological activity on its environment that is detectable at interstellar distances. This is expected to require a surface biosphere needing the support of a surface ocean (in contrast to e.g. a subsurface biosphere; [33, 128]). This drives the definition of the HZ as the region around a star where a planet with an Earth atmosphere can maintain liquid surface water [68, 71]. Supported by the fact that all life on Earth is carbon based, carbon is likely the only element in the periodic table that can form the basis of a sufficiently wide variety of complex molecules that can undergo complex chemistry, and thus can form living organisms. However, it is not clear exactly how life formed on Earth, nor can we yet produce life from inorganic material in the laboratory. We *do* know that life on Earth formed relatively quickly, implying that life will develop if the circumstances are right.

Several factors are expected to make a planet habitable, or at least impact its habitability, such as:

- A liquid ocean on its surface. This will depend on the balance between how much water is delivered to the planet during formation and its subsequent water loss.
- A secondary atmosphere, assuming that H<sub>2</sub>-dominated atmospheres are not habitable [116]
- Geological activity such as volcanism, to counteract atmospheric loss and protect against climate change [152].
- A global magnetic field, which depends on the composition and evolution of the planet (e.g. [40]).

The internal energy budget of the planet is likely to be important, which is dependent on its thermal history since formation and on possible tidal interactions with the host star and/or other planets in the system. It will be crucial to understand targets in the context of their host star and planetary system environments.

It is currently not clear whether M dwarfs, the targets of pre-2035 ground-based studies, can harbor habitable planets. Firstly, they have an up to 1-billion year pre-main-sequence phase during which the stars are significantly more luminous. This is expected to drive strong atmospheric and ocean loss. Secondly, M-dwarfs can exhibit strong chromospheric activity, producing flares that can briefly increase the stellar UV flux by 1–2 orders of magnitude or more, potentially accompanied by

charged particle ejecta. It is not clear how long-term exposure to such flares could affect a possible atmosphere and biosphere.

In addition, temperate planets around late M-dwarfs are expected to be tidally locked, significantly affecting their global circulation flows and climate. For example, it is not clear to what extent volatiles, like water, could be frozen out on an eternal nightside (e.g. [49, 83, 122, 125]). It is evident that true Earth-twins around solar-type stars will need to be studied to obtain a complete picture of the possible habitability and biological activity in the solar neighborhood. This can only be done with a space telescope, needed to reach the extreme star/planet contrasts required.

The prime focus of the large high-contrast-imaging space telescope is to:

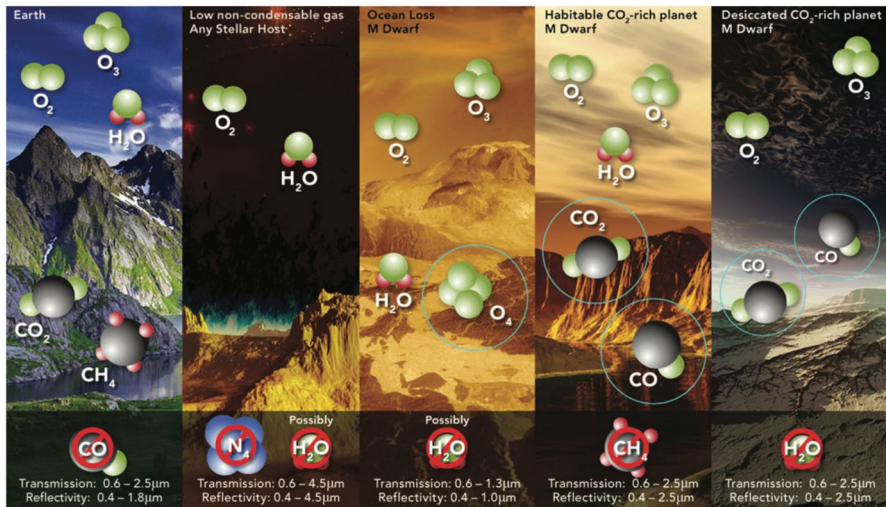
1. survey a sufficient number of stars to find ten(s) of exo-Earths ( $<1.5 R_{\text{Earth}}$ ) in the HZs of Sun-like stars in the solar neighborhood;
2. determine their planetary system architectures, understand the evolutionary history of the system, and current interplay between the planets;
3. determine and derive whether the planets have atmospheres, and if so their main atmospheric constituencies - for all accessible planets in the systems;
4. determine the overall climates of these planets, assess the diversity in planetary systems and understand their physical and chemical atmospheric processes, and possible geological influences;
5. find out whether the planets contain water, and therefore could be habitable.
6. Identify biomarker gases and determine whether they originate from biotic or abiotic processes.

## 4.2 Biomarker gases and the search for biological activity

It is clear that to unambiguously identify biomarker gases as signposts of biological activity, we need a deep understanding of both planet formation and evolutionary histories, and of the physical/chemical atmospheric and geological processes on the planet. This is why it is key to not only study potential habitable and biologically active planets in isolation, but to understand the system in context and compare their properties with those of inhabitable and inhabited planets.

Important recent work has evaluated molecular oxygen ( $\text{O}_2$ ) as a potential biosignature – originally identified as a promising pathway to find extraterrestrial life in exoplanet atmospheres by Lovelock [80]. It is currently the most detectable signal of life in the Earth's atmosphere (20% by volume), created as a waste product of oxygenic photosynthesis. Photochemistry of  $\text{O}_2$  also leads to the production of ozone.

New studies have identified different abiotic ways to form  $\text{O}_2$ , which can be recognized using their environmental context (e.g [101]; Fig. 4). Most of these abiotic scenarios involve very different surface conditions and evolutionary histories in comparison to Earth, such as photochemical processes for planets with high carbon dioxide concentrations, or planets with significant loss of water through photo-dissociation. The latter can even result in oxygen dominated atmospheres with multiple bars of  $\text{O}_2$ . These abiotic processes can all be distinguished in different ways. They either require a very dry planet such that measuring water features will be sufficient,



**Fig. 4** From Meadows [100]: Overview of possible false positive mechanisms for molecular oxygen. Detection of circled and forbidden molecules will separate out biotic and abiotic processes (credit; V. Meadows)

or by the detection of methane (which excludes an oxygen dominated atmosphere), or the absence of very deep and broad features of carbon dioxide which would disprove it as a dominant atmospheric gas. Inclusion of these environmental contexts has greatly strengthened the use of molecular oxygen as a reliable signature of biological activity. In addition, the first steps are being taken to identify and interpret other potential biomarker gases, such as methyl chloride and dimethyl sulfide, including those that permit detection of non-Earth-like metabolisms.

### 4.3 Science requirements for a > 2035 high-contrast-imaging space mission

*Direct imaging with a large space telescope is the only way to obtain spectra of the atmospheres of rocky planets in the HZs of solar type stars in a systematic way, because ground-based instrumentation is unable to reach the extreme contrasts required.*

Light emerging from the surface of the planet contains two components, that of intrinsic thermal emission and scattered (reflected) starlight. For temperate rocky planets, the thermal component significantly improves the planet/star contrast beyond 5 μm in wavelength, but since telescope angular resolution is inversely proportional to the wavelength, it would require an unfeasibly large telescope to directly image a sample of such planets in the mid-infrared. This can only be reached with a space-based nulling-interferometer, the subject of a different White Paper (led by Sascha Quanz). In this White Paper, we explore and advocate the only plausible alternative: to concentrate on starlight that is scattered by the planet's atmosphere, either through Rayleigh or Mie scattering, or reflection from its surface. This

starlight will be altered by atomic and molecular absorption on the way in and out of the planet's atmosphere, which therefore provides a measure of its constituents, physical and chemical (and possibly biological) processes, and climate.

A twin Earth around a solar-type star will have a contrast in reflected light (depending on its orbital phase and inclination) of at least a few billion, requiring a contrast of  $10^{-10}$ . To study a sizable sample of 10 to 20 Earth twins in the HZs of FGK stars requires a sample of 75–150 solar-type stars, corresponding to a maximum distance of 10 to 13 pc, which requires an inner working angle (IWA) of 100 to 80 milliarcseconds (mas). Of course, for any telescope this will depend on the observed wavelength (see below).

#### **4.3.1 Requirement 1: The instrument needs to reach a contrast of $10^{-10}$ at an IWA of 80–100 mas**

In the planet spectra, we will be most interested in scattering processes and molecular absorption features. Rayleigh scattering will be strongest in the UV and optical-blue. Several water vapor bands are present from 0.7  $\mu\text{m}$  onwards and are gradually stronger towards longer wavelengths (see Fig. 3). The strongest feature of molecular oxygen is at 0.76  $\mu\text{m}$ , with other bands at 0.69  $\mu\text{m}$  and 1.27  $\mu\text{m}$ , while ozone shows a cutoff at 0.33  $\mu\text{m}$  with a shallow feature at 0.55  $\mu\text{m}$ . Methane has the strongest features at 2.2  $\mu\text{m}$  and 3.2  $\mu\text{m}$ , with a weaker band at 1.6  $\mu\text{m}$ , while carbon dioxide has strong bands around 2.1, 2.8 and 4.3  $\mu\text{m}$ .

#### **4.3.2 Requirement 2: The wavelength range needs to cover the optical and near-infrared, with a goal to also include the UV and mid-infrared up to 5 $\mu\text{m}$**

The observed planet spectra will strongly depend on the reflective and scattering properties of the atmosphere as a function of altitude, and the volume mixing ratios of the spectroscopically active molecules. Since several features can overlap, it will be important to have a sufficiently high spectral resolution and sufficient wavelength range to identify multiple absorption bands of the same molecule.

#### **4.3.3 Requirement 3: The spectral resolution needs to be sufficient to uniquely identify molecular absorption**

The mission will need to be able to survey the planetary systems of 75 to 150 stars, and obtain their spectra at a sufficiently high signal-to-noise.

#### **4.3.4 Requirement 4: The light collecting power and mission lifetime of the space telescope should be such that spectra of 75–150 planetary systems can be obtained**

In the next section we will present and discuss the main characteristics of such a space mission. Currently, NASA is performing two concept studies of missions that could fulfill the requirements listed above. One is the Habitable Exoplanet



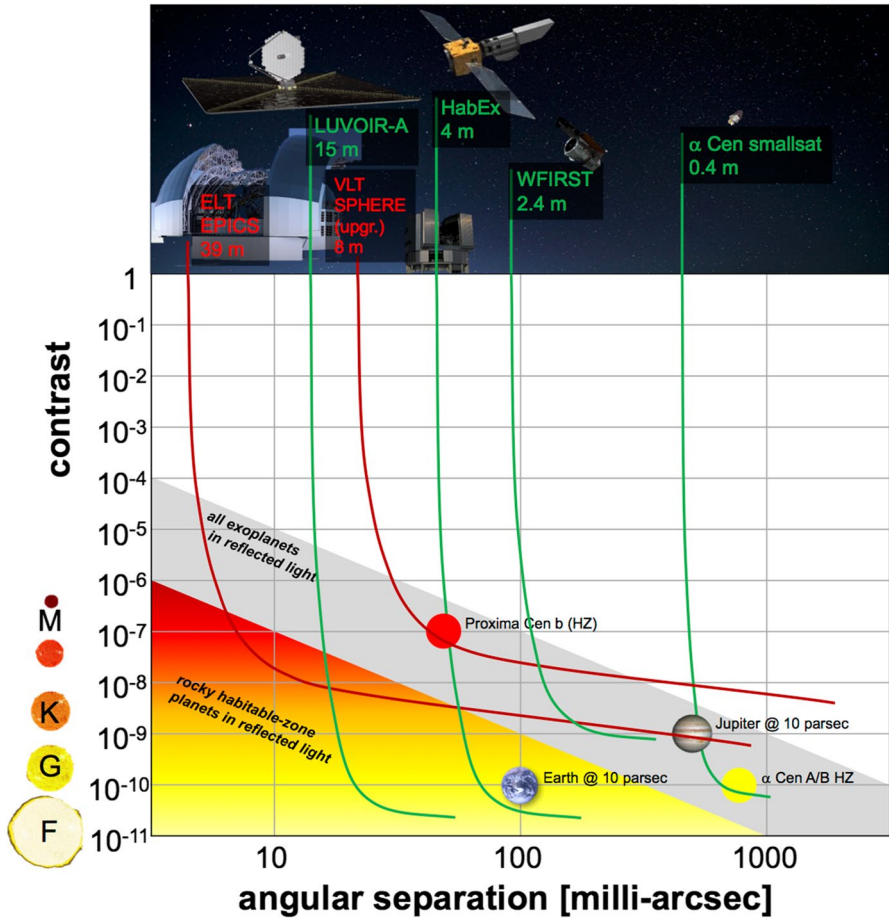


Fig. 5 Approximate projected reflected-light total contrast versus angular separation for future ground-based and space-based telescopes. HZ planets lie in the lower left hand corner, and this region is only accessible for M stars from the ground for ELTs and solar-type stars are reachable with smaller diameter telescopes in space. These curves are approximate and for illustration purposes only

Observatory (HabEx), a 4 m monolithic telescope operating between  $0.2\text{--}1.8 \mu\text{m}$  with an external starshade. The other is the Large UV/Optical/IR surveyor (LUVOIR), an 8-15 m general purpose telescope covering  $0.2\text{--}2.5 \mu\text{m}$ . These are both very exciting studies that investigate different ways of how the requirements above can be met, that will identify and map technical challenges, and will provide first cost estimates of different mission architectures.

Requirements 1, 2 and 4 on contrast, IWA, wavelength range, and sample size, are closely coupled to each other. The IWA governs to what distance a Earth-twin planet can still be separated from its parent star, and is set by the Rayleigh criterion ( $\lambda/D$ ) and/or the size and distance of the external occulter or starshade in the case of a HabEx-type design. At a distance of 10 (13) parsec this corresponds to a

maximum IWA of 100 (77) mas. Assuming that ultimately a space telescope plus internal coronagraph will reach its extreme contrast limits down to  $2.5\lambda/D$ , observations at a wavelength of 0.5, 1.0, and 2  $\mu\text{m}$  will require telescopes of at least 3 m (4 m), 6 m (8 m), and 12 m (16 m) in size respectively (see Fig. 5). External occulter have a different dependency, and the one currently under study for HabEx is envisaged to have an IWA of 40 mas and 100 mas at UV/Optical and infrared wavelengths respectively. This is the main reason why NASA is studying these different mission concepts of a 4 m (HabEx + starshade), 8 m (LUVOIR, architecture B) and 15 m (LUVOIR, architecture A).

In addition to spectroscopy, also the measurement of the polarization of the scattered/reflected light from an exoplanet enables the characterization of its atmosphere and surface, particularly in the combined method of spectropolarimetry. Such observations provide unique and unambiguous constraints on water clouds [65] and surface oceans, while they also enhance the contrast of biomarker molecule spectral lines [140]. Moreover, both spectroscopy and polarimetry allow us to distinguish the light from exoplanets from residual starlight and light from exozodiacal dust [112]. Finally, circular spectropolarimetry constitutes an ultimate probe of biological activity, as it is sensitive to the homochirality of biotic molecules [110], although it may require an even larger space telescope or a very favorable target to detect such signatures.

After the conclusion of the LUVOIR and HabEx mission design studies,<sup>13</sup> the process of the US decadal survey, and the successful launch of the JWST, it will be perfect timing for Europe to start to seriously contribute to the discussions of what type of mission design would be most effective and cost efficient in addressing the enigmatic and exciting questions about the place of Earth and humanity in the Universe, and to play an important and guiding role in realizing this exciting goal.

## 5 HabEx, LUVOIR, and potential areas for ESA contributions

### 5.1 Challenges of high-contrast-imaging in space

High Contrast Imaging (HCI) techniques aim to optimize the detection of the signal from scarce photons scattered or radiated by an exoplanet by removing the diffracted light halo of its parent star. To reach extreme levels of contrast, several complementary optical and data-reduction techniques need to work in very close harmony. See Ruane et al. [124], Jovanovic et al. [64], and [138] for recent reviews of HCI techniques.

HCI is becoming a mature technique on ground-based telescopes, with still rapidly expanding technological and scientific capabilities for dedicated instruments like VLT/SPHERE [10], Gemini/GPI (Macintosh et al. 2018), Subaru/SCEXAO [82], and Magellan/MagAO(-X) [88]. HCI from the ground is fundamentally

<sup>13</sup> <https://arxiv.org/abs/1912.06219>  
<https://arxiv.org/abs/2001.06683>

limited by the Earth's atmosphere, as even the most advanced Adaptive Optics (AO) systems are not fast enough to provide perfect correction of atmospheric turbulence for even the brightest stars (that also feed the wavefront sensor). The "raw" contrast is therefore limited to  $\sim 10^{-5}$  at small angular separations, as rapidly varying atmospheric speckles and slowly varying instrumental speckles still create a halo of starlight on the detector. On the ground, differential techniques that distinguish light from exoplanets from residual starlight (e.g. based on their different spatial, spectral, polarization, and coherent properties) are therefore vital to directly detect and characterize even the brightest exoplanets.

In space, the stable environment and long exposure times enable a raw contrast as deep as  $\sim 10^{-10}$  (Fig. 5). The level of control over the optics in a space-based HCI instrument is therefore of a completely different magnitude than for ground-based instruments, although the time-scales involved are slower. The necessary ingredients for a HCI space mission include:

- **A large, optimized telescope** to efficiently collect the sparse photons from the faint exoplanet targets, and to deliver a diffraction-limited performance with an angular resolving power of  $\sim \lambda/D$ . We adopt the visible band as the shortest wavelength range, as it contains essential biomarkers, and technology is mature for HCI (in contrast to the UV range), and therefore the telescope diameter  $D$  needs to be as large as possible to enable observations at the smallest possible angular separations.
- **Adaptive optics** with two deformable mirrors to actively control both the phase and the amplitude of the wavefront propagating through the instrument at extreme precision to ensure stability of the point-spread function (PSF) at a level of  $10^{-10}$ .
- **Coronagraphy** to selectively suppress the on-axis stellar PSF and its diffraction structure, whilst transmitting the exoplanet PSF for the smallest possible off-axis angular separation. A coronagraph is a trade-off between planet throughput, IWA and their tolerance to errors from telescope optics and their stability. Internal coronagraphs suppress starlight after it has entered the telescope, while an external occulter (starshade) at a large distance from the telescope can guarantee large contrast without stringent requirements on the optics.
- **Wavefront / electric field sensing techniques** to control the AO system (preferably with signals measured at the actual science focal plane) to dig "dark holes" in the residual stellar halo, in tandem with the coronagraph architecture.
- **Spectroscopy** to characterize the light captured for an exoplanet. Typically, extreme contrasts can only be attained in narrow spectral bandwidths ( $\sim 20\%$ ), so the spectroscopic implementation depends on the AO + coronagraph implementation. In addition, single-mode fibers can be used to both feed a spectrograph, and also contribute to the overall contrast [55, 118].
- **Polarization techniques** to mitigate the detrimental polarization-dependent aberrations of any optical system [15, 127], to enable the implementation of

broadband liquid-crystal-based coronagraphs [96, 134, 136], and to enable a measurement of exoplanet polarization to both enhance the contrast as well as provide complementary diagnostics to spectroscopy.

- **Sensitive detectors** to perform imaging/spectroscopy/polarimetry, without adding noise sources more severe than the photon noise. Specific detector architectures can also be used for focal-plane wavefront sensing: the Self-Coherent Camera (SCC; [7]), or the noise-less, wavelength resolving Microwave Kinetic Inductance detector (MKID; [16]).
- **Integrated system design approaches** to make sure that all listed subsystems actually perform better than just the sum of their parts, and that optimal solutions are chosen based on the overall technical/scientific performance.
- **Data-reduction techniques** to optimally extract the exoplanetary signals to determine their orbits, phase angles, size/albedo, spectral and polarization signals.
- **Mission planning/yield optimization** to observe the maximum number of targets given mission lifetime (and, e.g., starshade repointing), including the required revisits, and long exposures for characterization once a promising candidate has been pinned down.
- **Data-analysis methods** to interpret the acquired spectral and other data in terms of, e.g., atmospheric parameters and constituents.

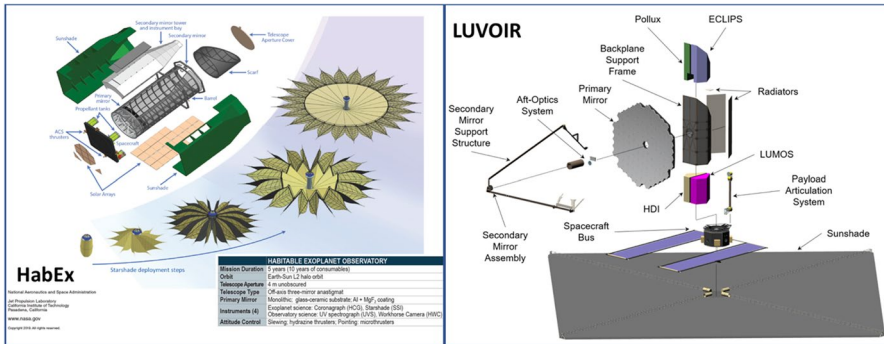
## 5.2 Mission architectures

This White Paper highlights the science and science requirements for a future HCI mission to detect biomarkers in the light from Earth-like exoplanets orbiting Sun-like stars. We advocate that ESA and the European exoplanet community take a leading role towards the realization of such a mission and all its aspects. It is to be expected that this endeavor that we will carry out on behalf of all of humanity will also be a truly global enterprise with several international partners. We do not state any hard preferences regarding technology or collaborative model. In this section, we present the final mission concepts of the NASA-led design studies HabEx and LUVOIR, that could fulfill our shared scientific goals, and are open to collaboration with external partners such as ESA (but are not guaranteed to fly, with a first decision pending the US Astro2020 Decadal process). But, most of all, the designs for HabEx and LUVOIR provide an excellent review of the state-of-the-art.

### 5.2.1 Current baseline design of the HabEx mission

The Habitable Exoplanet Observatory (HabEx<sup>14</sup>; [51]) is one of the mission concepts currently under study by NASA. Its baseline design consists of a monolithic, off-axis 4 m telescope in an L2 orbit, which is diffraction limited at 0.4  $\mu\text{m}$ . The

<sup>14</sup> <https://www.jpl.nasa.gov/habex/>



**Fig. 6** The HabEx (HabEx Final Report: [51]) and LUVOIR concept designs (LUVOIR Final Report: [85]). credit: A. Jones, NASA GSFC

preferred architecture has two ways to suppress starlight, with an internal coronagraph and with an external starshade. Both are envisioned to have dedicated instruments for imaging and spectroscopy. In the current study, a mission lifetime of five years is assumed (Fig. 6).

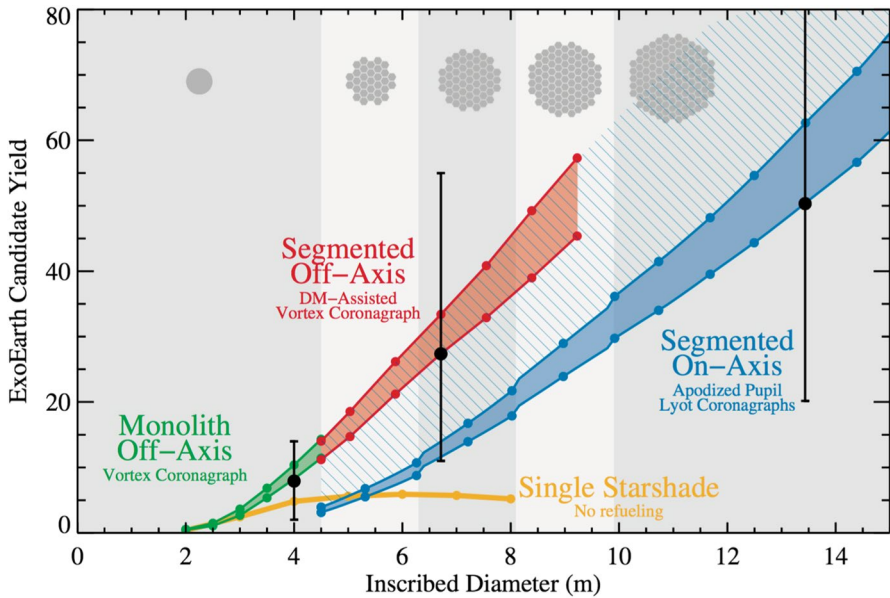
The off-axis monolithic mirror avoids the challenges encountered by centrally obscured or segmented mirrors to obtain coronagraphic performances sufficiently high close to the star, and with a sufficiently high throughput. HabEx has a vortex coronagraph in its baseline design, which works well in the presence of low-order wavefront (and polarization) aberrations, meaning less stringent requirements on thermal and mechanical stability of the telescope. It produces a raw contrast of  $10^{-10}$  at an IWA of 62 mas at  $0.5 \mu\text{m}$  with a 20% bandwidth. In the study, the coronagraph can be used with several cameras and an integral field spectrograph (IFS) covering  $0.45\text{--}0.67 \mu\text{m}$ ,  $0.67\text{--}1 \mu\text{m}$ , and an IR imaging spectrograph covering  $0.95\text{--}1.8 \mu\text{m}$ .

The baseline study also envisions a starshade of 52-m diameter that would fly in formation with the telescope at typically  $\sim 100,000$  km distance. The advantage of blocking the starlight before it enters the telescope are mainly a high throughput, small IWA and an outer working angle only set by the detector size. In this case, an IWA of 60 mas at  $1 \mu\text{m}$  is expected to be achieved. The distance between the starshade and the telescope can also be varied to optimize for observations at shorter or longer wavelengths. The starshade instrument is currently baselined as having three channels, covering  $0.2\text{--}0.45 \mu\text{m}$  with a grism,  $0.45\text{--}1 \mu\text{m}$  with an integral field spectrograph, and  $1\text{--}1.8 \mu\text{m}$  also with an IFS.

### 5.2.2 Current baseline design of the LUVOIR mission

The Large Ultraviolet / Optical / Infrared Surveyor, LUVOIR<sup>15</sup> [85] is another mission concept currently under study at NASA, with baseline architectures A

<sup>15</sup> <https://asd.gsfc.nasa.gov/luvoir/>



**Fig. 7** From [141]: Study of ExoEarth yield as a function of telescope aperture and off-axis or on-axis architectures. This is normalized for a mission of 2 years, and assuming  $\eta_{\text{Earth}} = 0.24$ . Note that the Earth-twin yield does not scale linearly with mission lifetime, because the best accessible systems get observed first (Credit: [141])

and B consisting of a 15-m on-axis and 8-m off-axis telescope respectively. They have segmented mirrors to fit in a single launch vehicle. It is envisioned to feature a coronagraph with imaging camera and integral field spectrograph covering 0.2–2  $\mu\text{m}$ . A serviceable design is an integral part of its architecture. Both the A and B architectures are designed to operate at L2 for a 5-year prime mission lifetime. LUVOIR leans on heritage from JWST, such as deployable telescopes and segmented wavefront control. The telescopes are diffraction limited at 0.5  $\mu\text{m}$ . An effort is underway to design a high-performance coronagraph coupled to a segmented, obscured telescope. In addition, technologies need to be developed for stabilization of the wavefront coming from the telescope involving low-order wavefront sensors and deformable mirrors. The highest contrast measured to date at testbeds at JPL is  $10^{-9}$ . Ultimately, contrasts of  $10^{-10}$  are envisioned at 3.5  $\lambda/D$  over a total passband of 0.2–2  $\mu\text{m}$ . Current baseline of the spectrograph has a resolving power of  $R = 140$  in the visual, and  $R = 70$  and 200 in the near-infrared.

### 5.3 Potential earth-twin yield of different mission designs

The HabEx and LUVOIR A and B architectures differ on key design aspects, such as on-axis versus off-axis, monolithic versus segmented mirrors, and differences in aperture size. Stark et al. [141] have carried out a preliminary study to assess the

impact of these design choices on the expected exo-Earth yields. They consider four telescope designs, one with an external occulter (a starshade) and three designs with internal coronagraphs. They conclude that, currently, an off-axis design significantly improves the final expected exo-Earth yield. The coronagraph design tradeoff with a secondary obscuration is sensitive to the IWA and planet flux throughput, which directly impacts the maximum distance of the stellar system that can be reached for a given telescope diameter  $D$ . For off-axis telescopes there seems to be little difference between monolithic or segmented mirrors.

The results from Stark et al. [141] are summarized in Fig. 7. The yield of 8 Earth-twins for the HabEx mission is for a two-year mission lifetime, assuming  $\eta_{\text{Earth}} = 0.24$ . Note that this does not scale linearly with survey time (which may be 5 or even 10 years) because it requires more distant and difficult targets to be imaged.

#### 5.4 A technological and scientific development path for Europe

The scientific goals of this White Paper are extremely ambitious, but address possibly the most exciting question humanity has been asking itself: Are we alone? To achieve the required performance and collaboration for a space mission as outlined above that will answer this question by 2050, ESA and the European scientific community need to embark as soon as possible on a “voyage” that has several intermediate destinations:

- **Start a European development program for technology validation and cost/risk reduction.** In Sect. 5.5 we identify an initial selection of specific European expertise to invest in.
- Establish a European strategy and collaborative model regarding **testbeds for technology demonstration** for HCI in space. Such laboratory experiments are crucial to validate new technologies, techniques and system level approaches, and drive their performance to the extremely challenging requirements introduced in Sect. 4.3.
- **Increase the Technology Readiness Level (TRL)** of specific technologies or subsystems with experiments on stratospheric balloons and smallsats. Such small missions could even resolve the habitable zone around our neighbor solar-type stars  $\alpha$  Cen A/B (see Fig. 5).
- Identify possible opportunities for **full science + technology demonstrator missions**, that perform important observations of gas giant or super-Earth-like exoplanets. Currently, the Coronagraphic Instrument (CGI) on Roman is the only space instrument which aims to detect and characterize planets in reflected light. The science yields of Roman-CGI [102] indicates that dozens of giant planets, known from RV detection, can be detected in photometry, while perhaps a single one can be observed in spectroscopy. The Earth-twin science case is far enough from the expected Roman yield to motivate an intermediate step with a compelling and unique science case, unfeasible from the ground before 2050. In the context of an M-class proposal to Cosmic Vision (in 2010), the scientific potential was investigated of a small (1.5 m) off-axis optimized telescope to study

**Table 1** Non-exhaustive list of current expertise in Europe

Large space telescopes	<ul style="list-style-type: none"> <li>• Euclid high precision optical telescope [151, 153]</li> <li>• ESA deployable mirror development (Marchi et al. 2017)</li> </ul>
Adaptive Optics	<ul style="list-style-type: none"> <li>• SPHERE extreme AO system: [10, 45, 115]</li> <li>• The très haute dynamique bench (THD; [9, 48])</li> <li>• Using 2 DMs for phase/amplitude control [99]</li> <li>• ESA active optics developments (Hallibert &amp; Marchi 2016; [76])</li> <li>• Deformable Mirror development [24]</li> </ul>
Coronagraphy	<ul style="list-style-type: none"> <li>• 4QPM coronagraph for JWST [8, 11]</li> <li>• APLC coronagraph [106, 107]</li> <li>• Coronagraph optimization [20]</li> <li>• AGPM/Vortex coronagraphs [31, 43]</li> <li>• Advanced liquid crystal coronagraphs ([134], [36]; [120]; [138])</li> </ul>
Wavefront / electric field sensing	<ul style="list-style-type: none"> <li>• SCC [7, 46]</li> <li>• ZELDA Zernike WFS [105, 108, 150]</li> <li>• vector-Zernike WFS [37]</li> <li>• Pyramid WFS [121]</li> <li>• Segmented space telescope phasing (JWST+LUVOIR; [77])</li> <li>• Speckle nulling [94]</li> <li>• COFFEE phase diversity [111]</li> <li>• Holographic Modal WFS [154], incl EFC [119]</li> <li>• Phase-Sorting Interferometry [30]</li> <li>• Asymmetric Pupil-WFS [93]</li> <li>• vAPP fpWFS [13]</li> <li>• QACITS algorithm [62]</li> </ul>
Spectroscopy	<ul style="list-style-type: none"> <li>• High-contrast imaging + High-resolution spectroscopy: Snellen et al. [131, 132], Vigan et al. [149]</li> <li>• SPHERE microlens-based IFS [28]</li> <li>• Slicer IFS: SINFONI [143], HARMONI [144]</li> <li>• SCAR coronagraph + single-mode fiber spectrograph ([55]; [118])</li> </ul>
Polarization techniques	<ul style="list-style-type: none"> <li>• Polarization-based 4QPM and VVC coronagraph [95]</li> <li>• Liquid-crystal coronagraphy + polarization filtering [136]</li> <li>• SPHERE-ZIMPOL [127]</li> <li>• Advanced polarimetric techniques: [133]; Snik et al. [135]</li> </ul>
Detectors	<ul style="list-style-type: none"> <li>• MKID detector development for visible light: Baselmans et al. [5], Bueno et al. [16]</li> </ul>
Astrophotonics	<ul style="list-style-type: none"> <li>• Photonic reformatting - NAIR [58]</li> <li>• 3D printed microlenses on single mode fibre IFUs ([35]; [56])</li> </ul>
System design	<ul style="list-style-type: none"> <li>• SPICES HCI space telescope concept [12]</li> </ul>
Data-reduction techniques	<ul style="list-style-type: none"> <li>• Spectral Differential Imaging [29, 148]</li> <li>• Principal Component Analysis [2]</li> <li>• ANDROMEDA [19]</li> <li>• ALICE [26]</li> </ul>

giant planet atmospheres (SPICES, [12, 87]). A similar mission with a larger size telescope will definitely make a compelling science case as an intermediate step towards the large HCI space telescope as described in this White Paper. Furthermore, a dedicated starshade mission in combination with existing telescopes (ground or space-based) would enable direct observations of exoplanets at extremely high contrast [63].



- Perform **benchmark observations of the Earth as an exoplanet**, e.g. by a dedicated small instrument on/around the Moon [66], or from a cubesat or the International Space Station, can further inform design decisions for a large HCI instrument to observe Earth-twins, and guide the development of data-analysis techniques and improve models of the Earth's atmosphere and surface, which are essential for detecting life on an exo-Earth, and for understanding the effects of our life on Earth (e.g. climate change, biodiversity loss, etc.).
- To achieve a high-confidence detection of life on an exoplanet, we need to **form an interdisciplinary community** of astronomers, geophysicists, technical physicists (optics, detectors, etc. specialists), biologists, ecologists, climate scientists, etc. to be able to fully interpret the observations in all their aspects. Moreover, we need to collaborate with researchers in the fields of the humanities, philosophers, artists, and of course society at large to give meaning to such a detection of life elsewhere in the Universe.

## 5.5 Identification of areas for Europe to participate

The table below indicates the current expertise from European researchers. This is meant to be indicative and not an exhaustive list of technology areas we recommend ESA to further invest in (Table 1).

**Acknowledgments** I.S. acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program under grant agreement No 694513. A.L.M. acknowledges the financial support of the F.R.S.-FNRS through a postdoctoral researcher grant. MB acknowledges support from the UK Science and Technology Facilities Council (STFC) research grant ST/S000631/1. I.R. acknowledges support from the Spanish Ministry of Science and Innovation and the European Regional Development Fund through grant PGC2018-098153-B-C33, as well as the support of the Generalitat de Catalunya/CERCA programme. E.P. acknowledges support from the Spanish Ministry of Science through grant PGC2018-098153-B-C31. J.M.D. acknowledges funding from the European Research Council (ERC) under the European Unions Horizon 2020 research and innovation programme (grant agreement no. 679633; Exo-Atmos) Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We acknowledge financial support from the ASI-INAF agreement n.2018-16-HH.0 We acknowledge financial support from Spanish MCIU SEV-2017-0709 and PID2019-110689RB-I00 awards. We acknowledge financial support from the ASI-INAF agreement n.2018-16-HH.0 AV acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 757561). KH acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 771620). NJM acknowledges funding from the Leverhulme Trust, and a Science and Technology Facilities Council Consolidated Grant (ST/R000395/1). PdV acknowledges funding from the Netherlands Organisation for Scientific Research NWO (Veni Grant No. 639.041.750). IP acknowledges financial support from the ASI-INAF agreements 2019-29-HH.06-HH.0 and 2015-019-R.1-2018. FS acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement no. 678194; FALCONER). MJ acknowledges support from the Knut and Alice Wallenberg foundation (KAW). JLB acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program under grant agreement No 805445. T.H. acknowledges support from the European Research Council under the Horizon 2020 Framework Program via the ERC Advanced Grant Origins 83 24 28. JLG acknowledges ISSI Team 464 for useful discussion.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

1. Alonso, R., Brown, T.M., Torres, G., Latham, D.W., Sozzetti, A., Mandushev, G., Belmonte, J.A., Charbonneau, D., Deeg, H.J., Dunham, E.W., O'Donovan, F.T., Stefanik, R.P.: TrES-1: the transiting planet of a bright K0 V star. *Astrophys. J.* **613**, L153–L156 (2004)
2. Amara, A., Quanz, S.P.: PYNPOINT: an image processing package for finding exoplanets. *Mon. Not. R. Astron. Soc.* **427**, 948–955 (2012)
3. Anglada-Escudé, G., Amado, P.J., Barnes, J., Berdiñas, Z.M., Butler, R.P., Coleman, G.A.L., de La Cueva, I., Dreizler, S., Endl, M., Giesers, B., Jeffers, S.V., Jenkins, J.S., Jones, H.R.A., Kiraga, M., Kürster, M., López-González, M.J., Marvin, C.J., Morales, N., Morin, J., et al.: A terrestrial planet candidate in a temperate orbit around Proxima Centauri. *Nature*. **536**, 437–440 (2016)
4. Bakos, G.Á., Lázár, J., Papp, I., Sári, P., Green, E.M.: System description and first light curves of the Hungarian automated telescope, an autonomous observatory for variability search. *Publ. Astron. Soc. Pac.* **114**, 974–987 (2002)
5. Baselmans, J.J.A., Bueno, J., Yates, S.J.C., Yurduseven, O., Llombart, N., Karatsu, K., Baryshev, A.M., Ferrari, L., Endo, A., Thoen, D.J., de Visser, P.J., Janssen, R.M.J., Murugesan, V., Driessen, E.F.C., Coiffard, G., Martín-Pintado, J., Hargrave, P., Griffin, M.: A kilo-pixel imaging system for future space based far-infrared observatories using microwave kinetic inductance detectors. *Astron. Astrophys.* **601**, (2017)
6. Batalha, N.M., Borucki, W.J., Bryson, S.T., Buchhave, L.A., Caldwell, D.A., Christensen-Dalsgaard, J., Ciardi, D., Dunham, E.W., Fressin, F., Gautier, T.N., Gilliland, R.L., Haas, M.R., Howell, S.B., Jenkins, J.M., Kjeldsen, H., Koch, D.G., Latham, D.W., Lissauer, J.J., Marcy, G.W., et al.: Kepler's First Rocky Planet: Kepler-10b. *Astrophys. J.* **729**, (2011)
7. Baudoz, P., Boccaletti, A., Baudrand, J., & Rouan, D.: The Self-Coherent Camera: a new tool for planet detection. *IAU Colloq. 200: Direct Imaging of Exoplanets: Science & Techniques*. 553–558 (2006a)
8. Baudoz, P., Boccaletti, A., Riaud, P., Cavarroc, C., Baudrand, J., Reess, J.M., Rouan, D.: Feasibility of the four-quadrant phase mask in the mid-infrared on the James Webb space telescope. *Publ. Astron. Soc. Pac.* **118**, 765–773 (2006b)
9. Baudoz, P., Galicher, R., Potier, A., Dupuis, O., Thijs, S., Patru, F.: Optimization and performance of multi-deformable mirror correction on the THD2 bench. *Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III*. **10706**, (2018)
10. Beuzit, J.-L., Vigan, A., Mouillet, D., Dohlen, K., Gratton, R., Boccaletti, A., Sauvage, J.-F., Schmid, H.M., Langlois, M., Petit, C., Baruffolo, A., Feldt, M., Milli, J., Wahhaj, Z., Abe, L., Anselmi, U., Antichi, J., Barette, R., Baudrand, J., et al.: SPHERE: the exoplanet imager for the Very Large Telescope. *Astronomy and Astrophysics*. **631**, (2019)
11. Boccaletti, A., Riaud, P., Baudoz, P., Baudrand, J., Reess, J. M., & Rouan, D.: JWST: a mid-IR coronagraph for imaging extrasolar planets. *5th International Conference on Space Optics*. 554, 273–279 (2004)
12. Boccaletti, A., Schneider, J., Traub, W., Lagage, P.-O., Stam, D., Gratton, R., Trauger, J., Cahoy, K., Snik, F., Baudoz, P., Galicher, R., Reess, J.-M., Mawet, D., Augereau, J.-C., Patience, J., Kuchner, M., Wyatt, M., Pantin, E., Maire, A.-L., et al.: SPICES: spectro-polarimetric imaging and characterization of exoplanetary systems. From planetary disks to nearby Super Earths. *Exp Astron.* **34**, 355–384 (2012)

13. Bos, S.P., Doelman, D.S., Miller, K.L., Snik, F.: New concepts in vector-apodizing phase plate coronagraphy. *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*. **11448**, (2020)
14. Bowler, B.P.: Imaging extrasolar Giant planets. *Publ. Astron. Soc. Pac.* **128**(102001), (2016)
15. Breckinridge, J.B., Lam, W.S.T., Chipman, R.A.: Polarization aberrations in astronomical telescopes: the point spread function. *Publ. Astron. Soc. Pac.* **127**(445), (2015)
16. Bueno, J., Murugesan, V., Karatsu, K., Thoen, D., Baselmans, J.J.A.: Ultrasensitive kilo-pixel imaging Array of photon noise-limited kinetic inductance detectors over an octave of bandwidth for THz astronomy. *J. Low Temp. Phys.* **193**, 96–102 (2018)
17. Burke, C.J., Christiansen, J.L., Mullally, F., Seader, S., Huber, D., Rowe, J.F., Coughlin, J.L., Thompson, S.E., Catanzarite, J., Clarke, B.D., Morton, T.D., Caldwell, D.A., Bryson, S.T., Haas, M.R., Batalha, N.M., Jenkins, J.M., Tenenbaum, P., Twicken, J.D., Li, J., et al.: Terrestrial planet occurrence rates for the Kepler GK dwarf sample. *Astrophys. J.* **809**, (2015)
18. Butler, R.P., Vogt, S.S., Marcy, G.W., Fischer, D.A., Wright, J.T., Henry, G.W., Laughlin, G., Lissauer, J.J.: A Neptune-mass planet orbiting the nearby M dwarf GJ 436. *Astrophys. J.* **617**, 580–588 (2004)
19. Cantalloube, F., Mouillet, D., Mugnier, L.M., Milli, J., Absil, O., Gomez Gonzalez, C.A., Chauvin, G., Beuzit, J.-L., Cornia, A.: Direct exoplanet detection and characterization using the ANDROMEDA method: performance on VLT/NaCo data. *Astron. Astrophys.* **582**, (2015)
20. Carlotti, A., N'Diaye, M., Pueyo, L., Mawet, D.: Three possible types of coronagraphs for the E-ELT PCS instrument. *Ground-based and Airborne Instrumentation for Astronomy V*. **9147**, (2014)
21. Charbonneau, D., Brown, T.M., Latham, D.W., Mayor, M.: Detection of planetary transits across a Sun-like star. *Astrophys. J.* **529**, L45–L48 (2000)
22. Charbonneau, D., Brown, T.M., Noyes, R.W., Gilliland, R.L.: Detection of an extrasolar planet atmosphere. *Astrophys. J.* **568**, 377–384 (2002)
23. Charbonneau, D., Allen, L.E., Megeath, S.T., Torres, G., Alonso, R., Brown, T.M., Gilliland, R.L., Latham, D.W., Mandushev, G., O'Donovan, F.T., Sozzetti, A.: Detection of thermal emission from an extrasolar planet. *Astrophys. J.* **626**, 523–529 (2005)
24. Charton, J., Bitenc, U., Curis, J.-F., Camet, S., Di Chiaro, R., Bougeard, R.: Recent improvements of high density magnetic deformable mirrors: faster, larger and stronger. *Adaptive Optics Systems IV*. **9148**, (2014)
25. Chilcote, J., Pueyo, L., De Rosa, R. J., Vargas, J., Macintosh, B., Bailey, V. P., Barman, T., Bauman, B., Bruzzone, S., Bulger, J., Burrows, A. S., Cardwell, A., Chen, C. H., Cotten, T., Dillon, D., Doyon, R., Draper, Z. H., Duchêne, G., Dunn, J., Erikson, D., Fitzgerald, M. P., Follette, K. B., Gavel, D., Goodsell, S. J., Graham, J. R., Greenbaum, A. Z., Hartung, M., Hibon, P., Hung, L.-W., Ingraham, P., Kalas, P., Konopacky, Q., Larkin, J. E., Maire, J., Marchis, F., Marley, M. S., Marois, C., Metchev, S., Millar-Blanchaer, M. A., Morzinski, K. M., Nielsen, E. L., Norton, A., Oppenheimer, R., Palmer, D., Patience, J., Perrin, M., Poyneer, L., Rajan, A., Rameau, J., Rantakyro, F. T., Sadakuni, N., Saddlemyer, L., Savransky, D., Schneider, A. C., Serio, A., Sivaramakrishnan, A., Song, I., Soummer, R., Thomas, S., Wallace, J. K., Wang, J. J., Ward-Duong, K., Wiktorowicz, S., & Wolff, S.: 1–2.4  $\mu\text{m}$  Near-IR Spectrum of the Giant Planet  $\beta$  Pictoris b Obtained with the Gemini Planet Imager. *Astron J.* **153**, (2017)
26. Choquet, É., Pueyo, L., Hagan, J. B., Gofas-Salas, E., Rajan, A., Chen, C., Perrin, M. D., Debes, J., Golimowski, D., Hines, D. C., N'Diaye, M., Schneider, G., Mawet, D., Marois, C., & Soummer, R.: Archival legacy investigations of circumstellar environments: overview and first results. *Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave*. **9143**, (2014)
27. Clanton, C., Gaudi, B.S.: Synthesizing exoplanet demographics: a single population of long-period planetary companions to M dwarfs consistent with microlensing, radial velocity, and direct imaging surveys. *Astrophys. J.* **819**, (2016)
28. Claudi, R.U., Turatto, M., Antichi, J., Gratton, R., Scuderì, S., Cascone, E., Mesa, D., Desidera, S., Baruffolo, A., Berton, A., Bagnara, P., Giro, E., Bruno, P., Fantinel, D., Beuzit, J.-L., Puget, P., Dohlen, K.: The integral field spectrograph of SPHERE: the planet finder for VLT. *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*. **6269**, (2006)
29. Claudi, R.U., Turatto, M., Gratton, R.G., Antichi, J., Bonavita, M., Bruno, P., Cascone, E., De Caprio, V., Desidera, S., Giro, E., Mesa, D., Scuderì, S., Dohlen, K., Beuzit, J.L., Puget, P.: SPHERE IFS: the spectro differential imager of the VLT for exoplanets search. *Ground-based and Airborne Instrumentation for Astronomy II*. **7014**, (2008)

30. Codona, J.L., Kenworthy, M.: Focal plane Wavefront sensing using residual adaptive optics speckles. *Astrophys. J.* **767**, (2013)
31. Delacroix, C., Absil, O., Forsberg, P., Mawet, D., Christiaens, V., Karlsson, M., Boccaletti, A., Baudoz, P., Kuitinen, M., Vartiainen, I., Surdej, J., Habraken, S.: Laboratory demonstration of a mid-infrared AGPM vector vortex coronagraph. *Astron. Astrophys.* **553**, (2013)
32. Deming, D., Wilkins, A., McCullough, P., Burrows, A., Fortney, J.J., Agol, E., Dobbs-Dixon, I., Deming, D., Seager, S., Richardson, L.J., Harrington, J.: Infrared radiation from an extrasolar planet. *Nature*. **434**, 740–743 (2005)
33. Des Marais, D.J., Harwit, M.O., Jucks, K.W., Kasting, J.F., Lin, D.N.C., Lunine, J.I., Schneider, J., Seager, S., Traub, W.A., Woolf, N.J.: Remote sensing of planetary properties and biosignatures on extrasolar terrestrial planets. *Astrobiology*. **2**, 153–181 (2002)
34. Díaz, R. F., Delfosse, X., Hobson, M. J., Boisse, I., Astudillo-Defru, N., Bonfils, X., Henry, G. W., Arnold, L., Bouchy, F., Bourrier, V., Brugger, B., Dalal, S., Deleuil, M., Demangeon, O., Dolon, F., Dumusque, X., Forveille, T., Hara, N., Hébrard, G., Kiefer, F., Lopez, T., Mignon, L., Moreau, F., Mousis, O., Moutou, C., Pepe, F., Perruchot, S., Richaud, Y., Santerne, A., Santos, N. C., Sotile, R., Stalport, M., Ségransan, D., Udry, S., Unger, N., & Wilson, P. A.: The SOPHIE search for northern extrasolar planets. XIV. A temperate ( $T_{\text{SUB}} < 300 \text{ K}$ ) super-earth around the nearby star Gliese 411. *Astronomy and Astrophysics*. **625**, (2019)
35. Dietrich, P.-I., Harris, R.J., Blaicher, M., Corrigan, M.K., Morris, T.J., Freude, W., Quirrenbach, A., Koos, C.: Printed freeform lens arrays on multi-core fibers for highly efficient coupling in astrophotonic systems. *Opt. Express*. **25**, 18288–18295 (2017)
36. Doelman, D.S., Snik, F., Warriner, N.Z., Escuti, M.J.: Patterned liquid-crystal optics for broadband coronagraphy and wavefront sensing. Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. **10400**, (2017)
37. Doelman, D.S., Fagginger Auer, F., Escuti, M.J., Snik, F.: Simultaneous phase and amplitude aberration sensing with a liquid-crystal vector-Zernike phase mask. *Opt. Lett.* **44**, 17 (2019)
38. Dressing, C.D., Charbonneau, D.: The occurrence of potentially habitable planets orbiting M dwarfs estimated from the full Kepler dataset and an empirical measurement of the detection sensitivity. *Astrophys. J.* **807**, (2015)
39. Dressing, C. D., Charbonneau, D., Dumusque, X., Gettel, S., Pepe, F., Collier Cameron, A., Latham, D. W., Molinari, E., Udry, S., Affer, L., Bonomo, A. S., Buchhave, L. A., Cosentino, R., Figueira, P., Fiorenzano, A. F. M., Harutyunyan, A., Haywood, R. D., Johnson, J. A., Lopez-Morales, M., Lovis, C., Malavolta, L., Mayor, M., Micela, G., Motalebi, F., Nascimbeni, V., Phillips, D. F., Piotto, G., Pollacco, D., Queloz, D., Rice, K., Sasselov, D., Ségransan, D., Sozzetti, A., Szentgyorgyi, A., & Watson, C.: The Mass of Kepler-93b and The Composition of Terrestrial Planets. *The Astrophysical Journal*. **800**, (2015)
40. Driscoll, P., Bercovici, D.: Divergent evolution of earth and Venus: influence of degassing, tectonics, and magnetic fields. *Icarus*. **226**, 1447–1464 (2013)
41. Dumusque, X.: Measuring precise radial velocities on individual spectral lines. I. Validation of the method and application to mitigate stellar activity. *Astronomy and Astrophysics*. **620**, (2018)
42. Ehrenreich, D., Bourrier, V., Wheatley, P. J., Lecavelier des Etangs, A., Hébrard, G., Udry, S., Bonfils, X., Delfosse, X., Désert, J.-M., Sing, D. K., & Vidal-Madjar, A.: A giant comet-like cloud of hydrogen escaping the warm Neptune-mass exoplanet GJ 436b. *Nature*. **522**, 459–461 (2015)
43. Forsberg, P., Karlsson, M.: High aspect ratio optical gratings in diamond. *Diam. Relat. Mater.* **34**, 19 (2019)
44. Fulton, B.J., Petigura, E.A., Howard, A.W., Isaacson, H., Marcy, G.W., Cargile, P.A., Hebb, L., Weiss, L.M., Johnson, J.A., Morton, T.D., Sinukoff, E., Crossfield, I.J.M., Hirsch, L.A.: The California-Kepler survey. III. A Gap in the Radius Distribution of Small Planets. *The Astronomical Journal*. **154**, (2017)
45. Fusco, T., Petit, C., Rousset, G., Sauvage, J.-F., Dohlen, K., Mouillet, D., Charton, J., Baudoz, P., Kasper, M., Fedrigo, E., Rabou, P., Feautrier, P., Downing, M., Gigan, P., Conan, J.-M., Beuzit, J.-L., Hubin, N., Wildi, F., Puget, P.: Design of the extreme AO system for SPHERE, the planet finder instrument of the VLT. Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. **6272**, (2006)
46. Galicher, R., Baudoz, P., Rousset, G.: Wavefront error correction and earth-like planet detection by a self-coherent camera in space. *Astron. Astrophys.* **488**, L9–L12 (2008)
47. Galicher, R., Baudoz, P., Rousset, G., Totems, J., Mas, M.: Self-coherent camera as a focal plane wavefront sensor: simulations. *Astron. Astrophys.* **509**, (2010)

48. Galicher, R., Baudoz, P., Delorme, J. R., Mazoyer, J., Rousset, G., Firminy, J., Boussaha, F., N'Diaye, M., Dohlen, K., & Caillat, A.: High contrast imaging on the THD bench: progress and upgrades. *Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave*. 9143, (2014)
49. Garcia-Sage, K., Glocer, A., Drake, J.J., Gronoff, G., Cohen, O.: On the magnetic protection of the atmosphere of Proxima Centauri b. *Astrophys. J.* **844**, (2017)
50. Gaudi, B. S., Stassun, K. G., Collins, K. A., Beatty, T. G., Zhou, G., Latham, D. W., Bieryla, A., Eastman, J. D., Siverd, R. J., Crepp, J. R., Gonzales, E. J., Stevens, D. J., Buchhave, L. A., Pepper, J., Johnson, M. C., Colon, K. D., Jensen, E. L. N., Rodriguez, J. E., Bozza, V., Novati, S. C., D'Ago, G., Dumont, M. T., Ellis, T., Gaillard, C., Jang-Condell, H., Kasper, D. H., Fukui, A., Gregorio, J., Ito, A., Kielkopf, J. F., Manner, M., Matt, K., Narita, N., Oberst, T. E., Reed, P. A., Scarpetta, G., Stephens, D. C., Yeigh, R. R., Zambelli, R., Fulton, B. J., Howard, A. W., James, D. J., Penny, M., Bayliss, D., Curtis, I. A., Depoy, D. L., Esquerdo, G. A., Gould, A., Joner, M. D., Kuhn, R. B., Labadie-Bartz, J., Lund, M. B., Marshall, J. L., McLeod, K. K., Pogge, R. W., Relles, H., Stockdale, C., Tan, T. G., Trueblood, M., & Trueblood, P.: A giant planet undergoing extreme-ultraviolet irradiation by its hot massive-star host. *Nature*. 546, 514–518 (2017)
51. Gaudi, B. S., Seager, S., Mennesson, B., Kiessling, A., Warfield, K., Cahoy, K., Clarke, J. T., Domagal-Goldman, S., Feinberg, L., Guyon, O., Kasdin, J., Mawet, D., Plavchan, P., Robinson, T., Rogers, L., Scowen, P., Somerville, R., Stapelfeldt, K., Stark, C., Stern, D., Turnbull, M., Amini, R., Kuan, G., Martin, S., Morgan, R., Redding, D., Stahl, H. P., Webb, R., Alvarez-Salazar, O., Arnold, W. L., Arya, M., Balasubramanian, B., Baysinger, M., Bell, R., Below, C., Benson, J., Blais, L., Booth, J., Bourgeois, R., Bradford, C., Brewer, A., Brooks, T., Cady, E., Caldwell, M., Calvet, R., Carr, S., Chan, D., Cormarkovic, V., Coste, K., Cox, C., Danner, R., Davis, J., Dewell, L., Dorsett, L., Dunn, D., East, M., Effinger, M., Eng, R., Freebury, G., Garcia, J., Gaskin, J., Greene, S., Hennessy, J., Hilgemann, E., Hood, B., Holota, W., Howe, S., Huang, P., Hull, T., Hunt, R., Hurd, K., Johnson, S., Kissil, A., Knight, B., Kolenz, D., Kraus, O., Krist, J., Li, M., Lisman, D., Mandic, M., Mann, J., Marchen, L., Marrese-Reading, C., McCreedy, J., McGown, J., Missun, J., Miyaguchi, A., Moore, B., Nemat, B., Nikzad, S., Nissen, J., Novicki, M., Perrine, T., Pineda, C., Polanco, O., Putnam, D., Qureshi, A., Richards, M., Eldorado Riggs, A. J., Rodgers, M., Rud, M., Saini, N., Scalisi, D., Scharf, D., Schulz, K., Serabyn, G., Sigrist, N., Sikkia, G., Singleton, A., Shaklan, S., Smith, S., Southerd, B., Stahl, M., Steeves, J., Sturges, B., Sullivan, C., Tang, H., Taras, N., Tesch, J., Therrell, M., Tseng, H., Valente, M., Van Buren, D., Villalvazo, J., Warwick, S., Webb, D., Westerhoff, T., Wofford, R., Wu, G., Woo, J., Wood, M., Ziemer, J., Arney, G., Anderson, J., Maíz-Apellániz, J., Bartlett, J., Belikov, R., Bendek, E., Cenko, B., Douglas, E., Dulz, S., Evans, C., Faramaz, V., Feng, Y. K., Ferguson, H., Follette, K., Ford, S., García, M., Geha, M., Gelino, D., Götberg, Y., Hildebrandt, S., Hu, R., Jahnke, K., Kennedy, G., Kreidberg, L., Isella, A., Lopez, E., Marchis, F., Macri, L., Marley, M., Matzko, W., Mazoyer, J., McCandliss, S., Meshkat, T., Mordasini, C., Morris, P., Nielsen, E., Newman, P., Petigura, E., Postman, M., Reines, A., Roberge, A., Roederer, I., Ruane, G., Schwieterman, E., Sirbu, D., Spalding, C., Teplitz, H., Tumulson, J., Turner, N., Werk, J., Wofford, A., Wyatt, M., Young, A., & Zellem, R.: The Habitable Exoplanet Observatory (HabEx) Mission Concept Study Final Report. arXiv e-prints. (2020)
52. Gillon, M., Triaud, A. H. M. J., Demory, B.-O., Jehin, E., Agol, E., Deck, K. M., Lederer, S. M., de Wit, J., Burdanov, A., Ingalls, J. G., Bolmont, E., Lecote, J., Raymond, S. N., Selsis, F., Turbet, M., Barkaoui, K., Burgasser, A., Burleigh, M. R., Carey, S. J., Chaushev, A., Copperwheat, C. M., Delrez, L., Fernandes, C. S., Holdsworth, D. L., Kotze, E. J., Van Grootel, V., Almléay, Y., Benkhaldoun, Z., Magain, P., & Queloz, D.: Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1. *Nature*. 542, 456–460 (2017)
53. Greene, T.P., Line, M.R., Montero, C., Fortney, J.J., Lustig-Yaeger, J., Luther, K.: Characterizing transiting exoplanet atmospheres with JWST. *Astrophys. J.* **817**, (2016)
54. Haffert, S.Y., Bohn, A.J., de Boer, J., Snellen, I.A.G., Brinchmann, J., Girard, J.H., Keller, C.U., Bacon, R.: Two accreting protoplanets around the young star PDS 70. *Nature Astronomy*. **3**, 749–754 (2019)
55. Haffert, S. Y., Por, E. H., Keller, C. U., Kenworthy, M. A., Doelman, D. S., Snik, F., & Escuti, M. J.: The Single-mode Complex Amplitude Refinement (SCAR) coronagraph. II. Lab verification, and toward the characterization of Proxima b. *Astronomy and Astrophysics*. 635, (2020a)
56. Haffert, S. Y., Harris, R. J., Zanutta, A., Pike, F. A., Bianco, A., Redaelli, E., Benoît, A., MacLachlan, D. G., Ross, C. A., Gris-Sánchez, I., Trappen, M. D., Xu, Y., Blaicher, M., Maier, P., Riva, G., Sinquin, B., Kulcsár, C., Bharmal, N. A., Gendron, E., Staykov, L., Morris, T. J., Barboza,

- S., Muench, N., Bardour, L., Prengère, L., Raynaud, H.-F., Hottinger, P., Anagnos, T., Osborn, J., Koos, C., Thompson, R. R., Birks, T. A., Snellen, I. A. G., Keller, C. U., Close, L., & Males, J. R.: Multi-core fibre-fed integral-field unit (MCIFU): overview and first-light. Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. 11448, (2020b)
57. Hallibert, P., Zuccaro Marchi, A.: Developments in active optics for space instruments: an ESA perspective. *Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II*. **9912**, (2016)
  58. Harris, R.J., Tepper, J., Davenport, J.J., Pedretti, E., Haynes, D.M., Hottinger, P., Anagnos, T., Shankar Nayak, A., Herrero Alonso, Y., Deka, P.J., Minardi, S., Quirrenbach, A., Labadie, L., Haynes, R.: NAIR: novel astronomical instrumentation through photonic reformatting. *Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III*. **10706**, (2018)
  59. Henry, G.W., Marcy, G.W., Butler, R.P., Vogt, S.S.: A Transiting “51 Peg-like” Planet. *Astrophys. J.* **529**, L41–L44 (2000)
  60. Hoeijmakers, H.J., Ehrenreich, D., Heng, K., Kitzmann, D., Grimm, S.L., Allart, R., Deitrick, R., Wytenbach, A., Oreshenko, M., Pino, L., Rimmer, P.B., Molinari, E., Di Fabrizio, L.: Atomic iron and titanium in the atmosphere of the exoplanet KELT-9b. *Nature*. **560**, 453–455 (2018)
  61. Howard, A. W., Marcy, G. W., Bryson, S. T., Jenkins, J. M., Rowe, J. F., Batalha, N. M., Borucki, W. J., Koch, D. G., Dunham, E. W., Gautier, T. N., Van Cleve, J., Cochran, W. D., Latham, D. W., Lissauer, J. J., Torres, G., Brown, T. M., Gilliland, R. L., Buchhave, L. A., Caldwell, D. A., Christensen-Dalsgaard, J., Ciardi, D., Fressin, F., Haas, M. R., Howell, S. B., Kjeldsen, H., Seager, S., Rogers, L., Sasselov, D. D., Steffen, J. H., Basri, G. S., Charbonneau, D., Christiansen, J., Clarke, B., Dupree, A., Fabrycky, D. C., Fischer, D. A., Ford, E. B., Fortney, J. J., Tarter, J., Girouard, F. R., Holman, M. J., Johnson, J. A., Klaus, T. C., Machalek, P., Moorhead, A. V., Morehead, R. C., Ragozzine, D., Tenenbaum, P., Twicken, J. D., Quinn, S. N., Isaacson, H., Shporer, A., Lucas, P. W., Walkowicz, L. M., Welsh, W. F., Boss, A., Devore, E., Gould, A., Smith, J. C., Morris, R. L., Prsa, A., Morton, T. D., Still, M., Thompson, S. E., Mullally, F., Endl, M., & MacQueen, P. J.: Planet Occurrence within 0.25 AU of Solar-type Stars from Kepler. *The Astrophysical Journal Supplement Series*. 201 (2012)
  62. Huby, E., Baudoz, P., Mawet, D., Absil, O.: Post-coronagraphic tip-tilt sensing for vortex phase masks: the QACITS technique. *Astron. Astrophys.* **584**, (2015)
  63. Janson, M.: Celestial exoplanet survey Occulter: a concept for direct imaging of extrasolar earth-like planets from the ground. *Publ. Astron. Soc. Pac.* **119**, 214–227 (2007)
  64. Jovanovic, N., Absil, O., Baudoz, P., Beaulieu, M., Bottom, M., Cady, E., Carlomagno, B., Carlotti, A., Doelman, D., Fogarty, K., Galicher, R., Guyon, O., Haffert, S., Huby, E., Jewell, J., Keller, C., Kenworthy, M. A., Knight, J., Kühn, J., Miller, K., Mazoyer, J., N’Diaye, M., Por, E., Pueyo, L., Riggs, A. J. E., Ruane, G., Sirbu, D., Snik, F., Wallace, J. K., Wilby, M., & Ygouf, M.: Review of high-contrast imaging systems for current and future ground-based and space-based telescopes: Part II. Common path wavefront sensing/control and coherent differential imaging. *Adaptive Optics Systems VI*. 10703 (2018)
  65. Karalidi, T., Stam, D.M., Hovenier, J.W.: Looking for the rainbow on exoplanets covered by liquid and icy water clouds. *Astron. Astrophys.* **548**, (2012a)
  66. Karalidi, T., Stam, D.M., Snik, F., Bagnulo, S., Sparks, W.B., Keller, C.U.: Observing the earth as an exoplanet with LOUPE, the lunar observatory for unresolved polarimetry of earth. *Planetary and Space Science*. **74**, 202–207 (2012b)
  67. Kasper, M., Arsenault, R., Käuff, H.-U., Jakob, G., Fuenteseca, E., Riquelme, M., Siebenmorgen, R., Sterzik, M., Zins, G., Ageorges, N., Gutruf, S., Reutlinger, A., Kampf, D., Absil, O., Carlomagno, B., Guyon, O., Klupar, P., Mawet, D., Ruane, G., et al.: NEAR: low-mass planets in  $\alpha$  Cen with VISIR. *The Messenger*. **169**, 16–20 (2017)
  68. Kasting, J.F., Whitmire, D.P., Reynolds, R.T.: Habitable zones around Main sequence stars. *Icarus*. **101**, 108–128 (1993)
  69. Keppler, M., Benisty, M., Müller, A., Henning, T., van Boekel, R., Cantalloube, F., Ginski, C., van Holstein, R. G., Maire, A.-L., Pohl, A., Samland, M., Avenhaus, H., Baudino, J.-L., Boccaletti, A., de Boer, J., Bonnefoy, M., Chauvin, G., Desidera, S., Langlois, M., Lazzoni, C., Marleau, G.-D., Mordasini, C., Pawellek, N., Stolker, T., Vigan, A., Zurlo, A., Birnstiel, T., Brandner, W., Feldt, M., Flock, M., Girard, J., Gratton, R., Hagelberg, J., Isella, A., Janson, M., Juhasz, A., Kemmer, J., Kral, Q., Lagrange, A.-M., Launhardt, R., Matter, A., Ménard, F., Milli, J., Mollière, P., Olofsson, J., Pérez, L., Pinilla, P., Pinte, C., Quanz, S. P., Schmidt, T., Udry, S., Wahhaj, Z., Williams, J. P., Buenzli, E., Cudel, M., Dominik, C., Galicher, R., Kasper, M., Lannier, J., Mesa, D., Mouillet, D.,

- Peretti, S., Perrot, C., Salter, G., Sissa, E., Wildi, F., Abe, L., Antichi, J., Augereau, J.-C., Baruffolo, A., Baudoz, P., Bazzon, A., Beuzit, J.-L., Blanchard, P., Brems, S. S., Buey, T., De Caprio, V., Carillet, M., Carle, M., Cascone, E., Cheetham, A., Claudi, R., Costille, A., Delboulbé, A., Dohlen, K., Fantinel, D., Feautrier, P., Fusco, T., Giro, E., Gluck, L., Gry, C., Hubin, N., Hugot, E., Jaquet, M., Le Mignant, D., Llored, M., Madec, F., Magnard, Y., Martinez, P., Maurel, D., Meyer, M., Möller-Nilsson, O., Moulin, T., Mugnier, L., Origné, A., Pavlov, A., Perret, D., Petit, C., Pragt, J., Puget, P., Rabou, P., Ramos, J., Rigal, F., Rochat, S., Roelfsema, R., Rousset, G., Roux, A., Salasnich, B., Sauvage, J.-F., Sevin, A., Soenke, C., Stadler, E., Suarez, M., Turatto, M., & Weber, L.: Discovery of a planetary-mass companion within the gap of the transition disk around PDS 70. *Astronomy and Astrophysics*. 617 (2018)
70. Knutson, H.A., Charbonneau, D., Allen, L.E., Fortney, J.J., Agol, E., Cowan, N.B., Showman, A.P., Cooper, C.S., Megeath, S.T.: A map of the day-night contrast of the extrasolar planet HD 189733b. *Nature*. **447**, 183–186 (2007)
71. Kopparapu, R.K.: The habitable zone: the climatic limits of habitability. *Handbook of Exoplanets*. (2018)
72. Kreidberg, L., Bean, J.L., Désert, J.-M., Benneke, B., Deming, D., Stevenson, K.B., Seager, S., Berta-Thompson, Z., Seifahrt, A., Homeier, D.: Clouds in the atmosphere of the super-earth exoplanet GJ1214b. *Nature*. **505**, 69–72 (2014)
73. Lacour, S., Nowak, M., Wang, J., Pfuhl, O., Eisenhauer, F., Abuter, R., Amorim, A., Anugu, N., Benisty, M., Berger, J. P., Beust, H., Blind, N., Bonnefoy, M., Bonnet, H., Bourget, P., Brandner, W., Buron, A., Collin, C., Charnay, B., Chapron, F., Clénet, Y., Coudé Du Foresto, V., de Zeeuw, P. T., Deen, C., Dembet, R., Dexter, J., Duvert, G., Eckart, A., Förster Schreiber, N. M., Fédou, P., Garcia, P., Garcia Lopez, R., Gao, F., Gendron, E., Genzel, R., Gillessen, S., Gordo, P., Greenbaum, A., Habibi, M., Haubois, X., Haußmann, F., Henning, T., Hippler, S., Horrobin, M., Hubert, Z., Jimenez Rosales, A., Jocou, L., Kendrew, S., Kervella, P., Kolb, J., Lagrange, A.-M., Lapeyrière, V., Le Bouquin, J.-B., Léna, P., Lippa, M., Lenzen, R., Maire, A.-L., Mollière, P., Ott, T., Paumard, T., Perraut, K., Perrin, G., Pueyo, L., Rabien, S., Ramírez, A., Rau, C., Rodríguez-Coira, G., Rousset, G., Sanchez-Bermudez, J., Scheithauer, S., Schuhler, N., Straub, O., Straubmeier, C., Sturm, E., Tacconi, L. J., Vincent, F., van Dishoeck, E. F., von Fellenberg, S., Wank, I., Waisberg, I., Widmann, F., Wieprecht, E., Wiest, M., Wiezorrek, E., Woillez, J., Yazici, S., Ziegler, D., & Zins, G.: First direct detection of an exoplanet by optical interferometry. *Astrometry and K-band spectroscopy of HR 8799 e*. *Astronomy and Astrophysics*. 623 (2019)
74. Lagrange, A.-M., Gratadour, D., Chauvin, G., Fusco, T., Ehrenreich, D., Mouillet, D., Rousset, G., Rouan, D., Allard, F., Gendron, É., Charton, J., Mugnier, L., Rabou, P., Montri, J., Lacombe, F.: A probable giant planet imaged in the  $\beta$  Pictoris disk. *VLT/NaCo deep L'-band imaging*. *Astronomy and Astrophysics*. **493**, L21–L25 (2009)
75. Lagrange, A.-M., Meunier, N., Rubini, P., Keppler, M., Galland, F., Chapellier, E., Michel, E., Balona, L., Beust, H., Guillot, T., Grandjean, A., Borgniet, S., Mékarnia, D., Wilson, P.A., Kiefer, F., Bonnefoy, M., Lillo-Box, J., Pantoja, B., Jones, M., et al.: Evidence for an additional planet in the  $\beta$  Pictoris system. *Nature Astronomy*. **3**, 1135–1142 (2019)
76. Laslandes, M., Ferrari, M., Hugot, E., Lemaitre, G.: Space active optics: in flight aberrations correction for the next generation of large space telescopes. *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*. **10565**, (2017)
77. Leboulleux, L., Sauvage, J.-F., Pueyo, L. A., Fusco, T., Soummer, R., Mazoyer, J., Sivaramakrishnan, A., N'Diaye, M., & Fauvarque, O.: Pair-based Analytical model for Segmented Telescopes Imaging from Space for sensitivity analysis. *Journal of Astronomical Telescopes, Instruments, and Systems*. **4**, (2018)
78. Léger, A., Rouan, D., Schneider, J., Barge, P., Fridlund, M., Samuel, B., Ollivier, M., Guenther, E., Deleuil, M., Deeg, H. J., Auvergne, M., Alonso, R., Aigrain, S., Alapini, A., Almenara, J. M., Baglin, A., Barbieri, M., Bruntt, H., Bordé, P., Bouchy, F., Cabrera, J., Catala, C., Carone, L., Carpano, S., Csizmadia, S., Dvorak, R., Erikson, A., Ferraz-Mello, S., Foing, B., Fressin, F., Gandolfi, D., Gillon, M., Gondoin, P., Grasset, O., Guillot, T., Hatzes, A., Hébrard, G., Jorda, L., Lammer, H., Llebaria, A., Loeillet, B., Mayor, M., Mazeh, T., Moutou, C., Pätzold, M., Pont, F., Queloz, D., Rauer, H., Renner, S., Samadi, R., Shporer, A., Sotin, C., Tingley, B., Wuchterl, G., Adda, M., Agogu, P., Appourchaux, T., Ballans, H., Baron, P., Beaufort, T., Bellenger, R., Berlin, R., Bernardi, P., Blouin, D., Baudin, F., Bodin, P., Boissard, L., Boit, L., Bonneau, F., Borzeix, S., Briet, R., Buey, J.-T., Butler, B., Cailleau, D., Cautain, R., Chabaud, P.-Y., Chaintreuil, S., Chiavassa, F., Costes, V., Cuna Parrho, V., de Oliveira Fialho, F., Decaudin, M., Defise, J.-M., Djalal,

- S., Epstein, G., Exil, G.-E., Fauré, C., Fenouillet, T., Gaboriaud, A., Gallic, A., Gamet, P., Gavalda, P., Grolleau, E., Gruneisen, R., Gueguen, L., Guis, V., Guivarc'h, V., Guterman, P., Hallouard, D., Hasiba, J., Heuripeau, F., Huntzinger, G., Hustaix, H., Imad, C., Imbert, C., Johlander, B., Jouret, M., Journoud, P., Karioty, F., Kerjean, L., Lafaille, V., Lafond, L., Lam-Trong, T., Landiech, P., Lapeyriere, V., Larqué, T., Laudet, P., Lautier, N., Lecann, H., Lefevre, L., Leruyet, B., Levacher, P., Magnan, A., Mazy, E., Mertens, F., Mesnager, J.-M., Meunier, J.-C., Michel, J.-P., Monjoin, W., Naudet, D., Nguyen-Kim, K., Orcesi, J.-L., Ottacher, H., Perez, R., Peter, G., Plasson, P., Plessier, J.-Y., Pontet, B., Pradines, A., Quentin, C., Reynaud, J.-L., Rolland, G., Rollenhagen, F., Romagnan, R., Russ, N., Schmidt, R., Schwartz, N., Sebbag, I., Sedes, G., Smit, H., Steller, M. B., Sunter, W., Surace, C., Tello, M., Tiphène, D., Toulouse, P., Ulmer, B., Vandermarcq, O., Vergnault, E., Vuillemin, A., & Zanatta, P.: Transiting exoplanets from the CoRoT space mission. VIII. CoRoT-7b: the first super-Earth with measured radius. *Astronomy and Astrophysics*. 506, 287–302 (2009)
79. Lopez-Morales, M., Currie, T., Teske, J., Gaidos, E., Kempton, E., Males, J., Lewis, N., Rackham, B. V., Ben-Ami, S., Birkby, J., Charbonneau, D., Close, L., Crane, J., Dressing, C., Froning, C., Hasegawa, Y., Konopacky, Q., Kopparapu, R. K., Mawet, D., Mennesson, B., Ramirez, R., Stelzer, D., Szentgyorgyi, A., Wang, J., Alam, M., Collins, K., Dupree, A., Karovska, M., Kirk, J., Levi, A., McGruder, C., Packman, C., Rugheimer, S., & Rukdee, S.: Detecting Earth-like Biosignatures on Rocky Exoplanets around Nearby Stars with Ground-based Extremely Large Telescopes. *Bulletin of the American Astronomical Society*. 51, (2019)
80. Lovelock, J.E.: A physical basis for life detection experiments. *Nature*. **207**, 568–570 (1965)
81. Lovis, C., Snellen, I., Mouillet, D., Pepe, F., Wildi, F., Astudillo-Defru, N., Beuzit, J.-L., Bonfils, X., Cheetham, A., Conod, U., Delfosse, X., Ehrenreich, D., Figueira, P., Forveille, T., Martins, J.H.C., Quanz, S.P., Santos, N.C., Schmid, H.-M., Ségransan, D., Udry, S.: Atmospheric characterization of Proxima b by coupling the SPHERE high-contrast imager to the ESPRESSO spectrograph. *Astron. Astrophys.* **599**, (2017)
82. Lozi, J., Guyon, O., Jovanovic, N., Goebel, S., Pathak, P., Skaf, N., Sahoo, A., Norris, B., Martinache, F., N'Diaye, M., Mazin, B., Walter, A. B., Tuthill, P., Kudo, T., Kawahara, H., Kotani, T., Ireland, M., Cvetojevic, N., Huby, E., Lacour, S., Vievard, S., Groff, T. D., Chilcote, J. K., Kasdin, J., Knight, J., Snik, F., Doelman, D., Minowa, Y., Clergeon, C., Takato, N., Tamura, M., Currie, T., Takami, H., & Hayashi, M.: SCEXAO, an instrument with a dual purpose: perform cutting-edge science and develop new technologies. *Adaptive Optics Systems VI*. 10703 (2018)
83. Luger, R., Barnes, R.: Extreme water loss and abiotic O<sub>2</sub> buildup on planets throughout the habitable zones of M dwarfs. *Astrobiology*. **15**, 119–143 (2015)
84. Lustig-Yaeger, J., Meadows, V.S., Lincowski, A.P.: The detectability and characterization of the TRAPPIST-1 exoplanet atmospheres with JWST. *Astron. J.* **158**, (2019)
85. LUVUOIR Team: The LUVUOIR Mission Concept Study Final Report. arXiv e-prints. (2019)
86. Madhusudhan, N., Crouzet, N., Desert, J.-M., Gilliland, R.L., Haynes, K., Knutson, H.A., Line, M., Magic, Z., Mandell, A.M., Ranjan, S., Charbonneau, D., Clampin, M., Seager, S., Showman, A.P.: Infrared transmission spectroscopy of the exoplanets HD 209458b and XO-1b using the wide field Camera-3 on the Hubble space telescope. *Astrophys. J.* **774**, (2013)
87. Maire, A.-L., Galicher, R., Boccaletti, A., Baudoz, P., Schneider, J., Cahoy, K., Stam, D., & Traub, W.: Atmospheric characterization of cold exoplanets with a 1.5-m space coronagraph. *Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave*. 8442 (2012)
88. Males, J. R., Close, L. M., Miller, K., Schatz, L., Doelman, D., Lumbres, J., Snik, F., Rodack, A., Knight, J., Van Gorkom, K., Long, J. D., Hedglen, A., Kautz, M., Jovanovic, N., Morzinski, K., Guyon, O., Douglas, E., Follette, K. B., Lozi, J., Bohlman, C., Durney, O., Gasho, V., Hinz, P., Ireland, M., Jean, M., Keller, C., Kenworthy, M., Mazin, B., Noenickx, J., Alfred, D., Perez, K., Sanchez, A., Sauve, C., Weinberger, A., & Conrad, A.: MagAO-X: project status and first laboratory results. *Adaptive Optics Systems VI*. 10703 (2018)
89. Marley, M., Lewis, N., Arney, G., Bailey, V., Batalha, N., Beichman, C., Benneke, B., Blečić, J., Cahoy, K., Chilcote, J., Domagal-Goldman, S., Dressing, C., Fitzgerald, M., Fortney, J., Freedman, R., Gelino, D., Gizis, J., Guyon, O., Greene, T., Hammel, H., Hasegawa, Y., Jovanovic, N., Konopacky, Q., Kopparapu, R., Liu, M., Lopez, E., Lunine, J., Lupu, R., Macintosh, B., Mandt, K., Marois, C., Mawet, D., Mayorga, L., Morley, C., Nielsen, E., Roberge, A., Serabyn, E., Skemer, A., Stapelfeldt, K., Vischer, C., & Wang, J.: Imaging Cool Giant Planets in Reflected Light: Science Investigations and Synergy with Habitable Planets. *Bulletin of the American Astronomical Society*. 51 (2019)



90. Marois, C., Macintosh, B., Barman, T., Zuckerman, B., Song, I., Patience, J., Lafrenière, D., Doyon, R.: Direct imaging of multiple planets orbiting the star HR 8799. *Science*. **322**, 1348 (2008)
91. Marois, C., Zuckerman, B., Konopacky, Q.M., Macintosh, B., Barman, T.: Images of a fourth planet orbiting HR 8799. *Nature*. **468**, 1080–1083 (2010)
92. Marois, C., Correia, C., Galicher, R., Ingraham, P., Macintosh, B., Currie, T., De Rosa, R.: GPI PSF subtraction with TLOCI: the next evolution in exoplanet/disk high-contrast imaging. *Adaptive Optics Systems IV*. **9148**, (2014)
93. Martinache, F.: The asymmetric pupil Fourier Wavefront sensor. *Publ. Astron. Soc. Pac.* **125**(422), (2013)
94. Martinache, F., Guyon, O., Jovanovic, N., Clergeon, C., Singh, G., Kudo, T., Currie, T., Thalmann, C., McElwain, M., Tamura, M.: On-sky speckle nulling demonstration at small angular separation with SCExAO. *Publ. Astron. Soc. Pac.* **126**(565), (2014)
95. Mawet, D., Riaud, P., Baudrand, J., Baudoz, P., Boccaletti, A., Dupuis, O., Rouan, D.: The four-quadrant phase-mask coronagraph: white light laboratory results with an achromatic device. *Astron. Astrophys.* **448**, 801–808 (2006)
96. Mawet, D., Pueyo, L., Moody, D., Krist, J., Serabyn, E.: The vector Vortex coronagraph: sensitivity to central obscuration, low-order aberrations, chromaticism, and polarization. *Modern Technologies in Space- and Ground-based Telescopes and Instrumentation*. **7739**, (2010)
97. Mayor, M., Queloz, D.: A Jupiter-mass companion to a solar-type star. *Nature*. **378**, 355–359 (1995)
98. Mayor, M., Pepe, F., Queloz, D., Bouchy, F., Rupprecht, G., Lo Curto, G., Avila, G., Benz, W., Bertaux, J.-L., Bonfils, X., Dall, T., Dekker, H., Delabre, B., Eckert, W., Fleury, M., Gilliotte, A., Gojak, D., Guzman, J.C., Kohler, D., et al.: Setting new standards with HARPS. *The Messenger*. **114**, 20–24 (2003)
99. Mazoyer, J., Pueyo, L.: Fundamental limits to high-contrast wavefront control. *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*. **10400**, (2017)
100. Meadows, V.S.: Reflections on O<SUB>2</SUB> as a biosignature in exoplanetary atmospheres. *Astrobiology*. **17**, 1022–1052 (2017)
101. Meadows, V.S., Reinhard, C.T., Arney, G.N., Parenteau, M.N., Schwieterman, E.W., Domagal-Goldman, S.D., Lincowski, A.P., Stapelfeldt, K.R., Rauer, H., DasSarma, S., Hegde, S., Narita, N., Deitrick, R., Lustig-Yaeger, J., Lyons, T.W., Siegler, N., Grenfell, J.L.: Exoplanet biosignatures: understanding oxygen as a biosignature in the context of its environment. *Astrobiology*. **18**, 630–662 (2018)
102. Mennesson, B., Debes, J., Douglas, E., Nemati, B., Stark, C., Kasdin, J., Macintosh, B., Turnbull, M., Rizzo, M., Roberge, A., Zimmerman, N., Cahoy, K., Krist, J., Bailey, V., Trauger, J., Rhodes, J., Moustakas, L., Frerking, M., Zhao, F., Poberezhskiy, I., & Demers, R.: The WFIRST coronagraph instrument: a major step in the exploration of sun-like planetary systems via direct imaging. *Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave*. 10698, (2018)
103. Mollière, P., Snellen, I.A.G.: Detecting isotopologues in exoplanet atmospheres using ground-based high-dispersion spectroscopy. *Astron. Astrophys.* **622**, (2019)
104. Müller, A., Keppler, M., Henning, T., Samland, M., Chauvin, G., Beust, H., Maire, A.-L., Molaverdikhani, K., van Boekel, R., Benisty, M., Boccaletti, A., Bonnefoy, M., Cantalloube, F., Charnay, B., Baudino, J.-L., Gennaro, M., Long, Z. C., Cheetham, A., Desidera, S., Feldt, M., Fusco, T., Girard, J., Gratton, R., Hagelberg, J., Janson, M., Lagrange, A.-M., Langlois, M., Lazzoni, C., Ligi, R., Ménard, F., Mesa, D., Meyer, M., Mollière, P., Mordasini, C., Moulin, T., Pavlov, A., Pawellek, N., Quanz, S. P., Ramos, J., Rouan, D., Sissa, E., Stadler, E., Vigan, A., Wahhaj, Z., Weber, L., & Zurlo, A.: Orbital and atmospheric characterization of the planet within the gap of the PDS 70 transition disk. *Astronomy and Astrophysics*. 617, (2018)
105. N'Diaye, M., Dohlen, K., Fusco, T., Paul, B.: Calibration of quasi-static aberrations in exoplanet direct-imaging instruments with a Zernike phase-mask sensor. *Astron. Astrophys.* **555**, (2013)
106. N'Diaye, M., Pueyo, L., Soummer, R.: Apodized pupil Lyot coronagraphs for arbitrary apertures. IV. Reduced Inner Working Angle and Increased Robustness to Low-order Aberrations. *The Astrophysical Journal*. **799**, (2015)

107. N'Diaye, M., Soummer, R., Pueyo, L., Carlotti, A., Stark, C.C., Perrin, M.D.: Apodized pupil Lyot coronagraphs for arbitrary apertures. V. Hybrid Shaped Pupil Designs for Imaging Earth-like planets with Future Space Observatories. *The Astrophysical Journal*. **818**, (2016a)
108. N'Diaye, M., Vigan, A., Dohlen, K., Sauvage, J.-F., Caillat, A., Costille, A., Girard, J.H.V., Beuzit, J.-L., Fusco, T., Blanchard, P., Le Merrer, J., Le Mignant, D., Madec, F., Moreaux, G., Mouillet, D., Puget, P., Zins, G.: Calibration of quasi-static aberrations in exoplanet direct-imaging instruments with a Zernike phase-mask sensor. II. Concept validation with ZELDA on VLT/SPHERE. *Astronomy and Astrophysics*. **592**, (2016b)
109. Nugroho, S.K., Kawahara, H., Masuda, K., Hirano, T., Kotani, T., Tajitsu, A.: High-resolution spectroscopic detection of TiO and a stratosphere in the day-side of WASP-33b. *Astron. J.* **154**, (2017)
110. Patty, C. H. L., Loes ten Kate, I., Buma, W. J., van Spanning, R. J. M., Steinbach, G., Ariese, F., & Snik, F.: Circular Spectropolarimetric Sensing of Vegetation in the Field: Possibilities for the Remote Detection of Extraterrestrial Life. *Astrobiology*. **19**, 1221–1229 (2019)
111. Paul, B., Sauvage, J.-F., Mugnier, L.M., Dohlen, K., Petit, C., Fusco, T., Mouillet, D., Beuzit, J.-L., Ferrari, M.: Compensation of high-order quasi-static aberrations on SPHERE with the coronagraphic phase diversity (COFFEE). *Astron. Astrophys.* **572**, (2014)
112. Perrin, M. D., Hines, D. C., Wisniewski, J. P., & Schneider, G.: Imaging of protoplanetary and debris disks. *Polarimetry of Stars and Planetary Systems*. 244 (2015)
113. Perryman, M., Hartman, J., Bakos, G.Á., Lindegren, L.: Astrometric exoplanet detection with Gaia. *Astrophys. J.* **797**, (2014)
114. Petigura, E.A., Howard, A.W., Marcy, G.W.: Prevalence of earth-size planets orbiting Sun-like stars. *Proc. Natl. Acad. Sci.* **110**, 19273–19278 (2013)
115. Petit, C., Sauvage, J.-F., Fusco, T., Sevin, A., Suarez, M., Costille, A., Vigan, A., Soenke, C., Perret, D., Rochat, S., Barufolo, A., Salasnich, B., Beuzit, J.-L., Dohlen, K., Mouillet, D., Puget, P., Wildi, F., Kasper, M., Conan, J.-M., et al.: SPHERE eXtreme AO control scheme: final performance assessment and on sky validation of the first auto-tuned LQG based operational system. *Adaptive Optics Systems IV*. **9148**, (2014)
116. Pierrehumbert, R., Gaidos, E.: Hydrogen greenhouse planets beyond the habitable zone. *Astrophys. J.* **734**, (2011)
117. Por, E.H.: Optimal design of apodizing phase plate coronagraphs. *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*. **10400**, (2017)
118. Por, E. H., & Haffert, S. Y.: The Single-mode Complex Amplitude Refinement (SCAR) coronagraph. I. Concept, theory, and design. *Astronomy and Astrophysics*. 635, (2020)
119. Por, E.H., Keller, C.U.: Focal-plane electric field sensing with pupil-plane holograms. *Adaptive Optics Systems V*. **9909**, (2016)
120. Por, E.H., Haffert, S.Y., Radhakrishnan, V.M., Doelman, D.S., van Kooten, M., Bos, S.P.: High contrast imaging for Python (HCIPy): an open-source adaptive optics and coronagraph simulator. *Adaptive Optics Systems VI*. **10703**, (2018)
121. Ragazzoni, R., Vassallo, D., Dima, M., Portaluri, E., Bergomi, M., Greggio, D., Viotto, V., Gullieuszik, M., Biondi, F., Carolo, E., Chinellato, S., Farinato, J., Magrin, D., Marafatto, L.: Multiple spatial frequencies pyramid WaveFront sensing. *Publ. Astron. Soc. Pac.* **129**(115001), (2017)
122. Ribas, I., Bolmont, E., Selsis, F., Reiners, A., Leconte, J., Raymond, S. N., Engle, S. G., Guinan, E. F., Morin, J., Turbet, M., Forget, F., & Anglada-Escudé, G.: The habitability of Proxima Centauri b. I. Irradiation, rotation and volatile inventory from formation to the present. *Astronomy and Astrophysics*. 596, (2016)
123. Ribas, I., Tuomi, M., Reiners, A., Butler, R. P., Morales, J. C., Perger, M., Dreizler, S., Rodríguez-López, C., González Hernández, J. I., Rosich, A., Feng, F., Trifonov, T., Vogt, S. S., Caballero, J. A., Hatzes, A., Herrero, E., Jeffers, S. V., Lafarga, M., Murgas, F., Nelson, R. P., Rodríguez, E., Strachan, J. B. P., Tal-Or, L., Teske, J., Toledo-Padrón, B., Zechmeister, M., Quirrenbach, A., Amado, P. J., Azzaro, M., Béjar, V. J. S., Barnes, J. R., Berdiñas, Z. M., Burt, J., Coleman, G., Cortés-Contreras, M., Crane, J., Engle, S. G., Guinan, E. F., Haswell, C. A., Henning, T., Holden, B., Jenkins, J., Jones, H. R. A., Kaminski, A., Kiraga, M., Kürster, M., Lee, M. H., López-González, M. J., Montes, D., Morin, J., Ofir, A., Pallé, E., Rebolo, R., Reffert, S., Schweitzer, A., Seifert, W., Shtetman, S. A., Staab, D., Street, R. A., Suárez Mascareño, A., Tsapras, Y., Wang, S. X., & Anglada-Escudé, G.: A candidate super-Earth planet orbiting near the snow line of Barnard's star. *Nature*. 563, 365–368 (2018)


124. Ruane, G., Riggs, A., Mazoyer, J., Por, E. H., N'Diaye, M., Huby, E., Baudoz, P., Galicher, R., Douglas, E., Knight, J., Carlomagno, B., Fogarty, K., Pueyo, L., Zimmerman, N., Absil, O., Beaulieu, M., Cady, E., Carlotti, A., Doelman, D., Guyon, O., Haffert, S., Jewell, J., Jovanovic, N., Keller, C., Kenworthy, M. A., Kuhn, J., Miller, K., Sirbu, D., Snik, F., Wallace, J. K., Wilby, M., & Ygouf, M.: Review of high-contrast imaging systems for current and future ground- and space-based telescopes I: coronagraph design methods and optical performance metrics. *Space Telescopes and Instrumentation 2018: Optical, infrared, and millimeter wave*. 10698, (2018)
125. Rugheimer, S., Kaltenecker, L., Segura, A., Linsky, J., Mohanty, S.: Effect of UV radiation on the spectral fingerprints of earth-like planets orbiting M stars. *Astrophys. J.* **809**, (2015)
126. Santos, N.C., Israelian, G., Mayor, M.: Spectroscopic [Fe/H] for 98 extra-solar planet-host stars. Exploring the probability of planet formation. *Astronomy and Astrophysics*. **415**, 1153–1166 (2004)
127. Schmid, H. M., Bazzon, A., Roelfsema, R., Mouillet, D., Milli, J., Menard, F., Gisler, D., Hunziker, S., Pragt, J., Dominik, C., Boccaletti, A., Ginski, C., Abe, L., Antonucci, S., Avenhaus, H., Baruffolo, A., Baudoz, P., Beuzit, J. L., Carillet, M., Chauvin, G., Claudi, R., Costille, A., Daban, J.-B., de Haan, M., Desidera, S., Dohlen, K., Downing, M., Elswijk, E., Engler, N., Feldt, M., Fusco, T., Girard, J. H., Gratton, R., Hanenburg, H., Henning, T., Hubin, N., Joos, F., Kasper, M., Keller, C. U., Langlois, M., Lagadec, E., Martinez, P., Mulder, E., Pavlov, A., Podio, L., Puget, P., Quanz, S. P., Rigal, F., Salasnich, B., Sauvage, J.-F., Schuil, M., Siebenmorgen, R., Sissa, E., Snik, F., Suarez, M., Thalmann, C., Turatto, M., Udry, S., van Duin, A., van Holstein, R. G., Vigan, A., & Wildi, F.: SPHERE/ZIMPOL high resolution polarimetric imager. I. System overview, PSF parameters, coronagraphy, and polarimetry. *Astronomy and Astrophysics*. 619 (2018)
128. Schwieterman, E.W., Kiang, N.Y., Parenteau, M.N., Harman, C.E., DasSarma, S., Fisher, T.M., Arney, G.N., Hartnett, H.E., Reinhard, C.T., Olson, S.L., Meadows, V.S., Cockell, C.S., Walker, S.I., Grenfell, J.L., Hegde, S., Rugheimer, S., Hu, R., Lyons, T.W.: Exoplanet biosignatures: a review of remotely detectable signs of life. *Astrobiology*. **18**, 663–708 (2018)
129. Sing, D. K., Fortney, J. J., Nikolov, N., Wakeford, H. R., Kataria, T., Evans, T. M., Aigrain, S., Ballester, G. E., Burrows, A. S., Deming, D., Désert, J.-M., Gibson, N. P., Henry, G. W., Huitson, C. M., Knutson, H. A., Lecavelier Des Etangs, A., Pont, F., Showman, A. P., Vidal-Madjar, A., Williamson, M. H., & Wilson, P. A.: A continuum from clear to cloudy hot-Jupiter exoplanets without primordial water depletion. *Nature*. 529, 59–62 (2016)
130. Snellen, I.A.G., de Kok, R.J., de Mooij, E.J.W., Albrecht, S.: The orbital motion, absolute mass and high-altitude winds of exoplanet HD209458b. *Nature*. **465**, 1049–1051 (2010)
131. Snellen, I.A.G., Brandl, B.R., de Kok, R.J., Brogi, M., Birkby, J., Schwarz, H.: Fast spin of the young extrasolar planet  $\beta$  Pictoris b. *Nature*. **509**, 63–65 (2014)
132. Snellen, I., de Kok, R., Birkby, J.L., Brandl, B., Brogi, M., Keller, C., Kenworthy, M., Schwarz, H., Stuik, R.: Combining high-dispersion spectroscopy with high contrast imaging: probing rocky planets around our nearest neighbors. *Astron. Astrophys.* **576**, (2015)
133. Snik, F., & Keller, C. U.: *Astronomical Polarimetry: Polarized Views of Stars and Planets. Planets, Stars and Stellar Systems. Volume 2: Astronomical Techniques, Software and Data*. 175 (2013)
134. Snik, F., Otten, G., Kenworthy, M., Miskiewicz, M., Escuti, M., Packham, C., Codona, J.: The vector-APP: a broadband apodizing phase plate that yields complementary PSFs. *Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II*. **8450**, (2012)
135. Snik, F., Craven-Jones, J., Escuti, M., Fineschi, S., Harrington, D., De Martino, A., Mawet, D., Riedi, J., Tyo, J.S.: An overview of polarimetric sensing techniques and technology with applications to different research fields. *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*. **90990B**, (2014a)
136. Snik, F., Otten, G., Kenworthy, M., Mawet, D., Escuti, M.: Combining vector-phase coronagraphy with dual-beam polarimetry. *Ground-based and Airborne Instrumentation for Astronomy V*. **9147**, (2014b)
137. Snik, F., van Harten, G., Alenin, A.S., Vaughn, I.J., Tyo, J.S.: A multi-domain full-stokes polarization modulator that is efficient for 300-2500nm spectropolarimetry. *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*. **96130G**, (2015)
138. Snik, F., Absil, O., Baudoz, P., Beaulieu, M., Bendek, E., Cady, E., Carlomagno, B., Carlotti, A., Cvetojevic, N., Doelman, D., Fogarty, K., Galicher, R., Guyon, O., Haffert, S., Huby, E., Jewell, J., Jovanovic, N., Keller, C., Kenworthy, M. A., Knight, J., Kuhn, J., Mazoyer, J., Miller, K., N'Diaye, M., Norris, B., Por, E., Pueyo, L., Riggs, A. J. E., Ruane, G., Sirbu, D., Wallace, J. K., Wilby, M., & Ygouf, M.: Review of high-contrast imaging systems for current and future ground-based

- and space-based telescopes III: technology opportunities and pathways. *Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III*. 10706 (2018)
139. Spake, J.J., Sing, D.K., Evans, T.M., Oklopčić, A., Bourrier, V., Kreidberg, L., Rackham, B.V., Irwin, J., Ehrenreich, D., Wyttenbach, A., Wakeford, H.R., Zhou, Y., Chubb, K.L., Nikolov, N., Goyal, J.M., Henry, G.W., Williamson, M.H., Blumenthal, S., Anderson, D.R., et al.: Helium in the eroding atmosphere of an exoplanet. *Nature*. **557**, 68–70 (2018)
  140. Stam, D.M.: Spectropolarimetric signatures of earth-like extrasolar planets. *Astron. Astrophys.* **482**, 989–1007 (2008)
  141. Stark, C. C., Belikov, R., Bolcar, M. R., Cady, E., Crill, B. P., Ertel, S., Groff, T., Hildebrandt, S., Krist, J., Lisman, P. D., Mazoyer, J., Mennesson, B., Nemati, B., Pueyo, L., Rauscher, B. J., Riggs, A. J., Ruane, G., Shaklan, S. B., Sirbu, D., Soummer, R., Laurent, K. S., & Zimmerman, N.: ExoEarth yield landscape for future direct imaging space telescopes. *Journal of Astronomical Telescopes, Instruments, and Systems*. **5**, (2019)
  142. Street, R.A., Pollaco, D.L., Fitzsimmons, A., Keenan, F.P., Horne, K., Kane, S., Collier Cameron, A., Lister, T.A., Haswell, C., Norton, A.J., Jones, B.W., Skillen, I., Hodgkin, S., Wheatley, P., West, R., Brett, D.: SuperWASP: wide angle search for planets. *Scientific Frontiers in Research on Extrasolar Planets*. **294**, 405–408 (2003)
  143. Thatte, N.A., Tecza, M., Eisenhauer, F., Mengel, S., Krabbe, A., Pak, S., Genzel, R., Bonaccini, D., Emsellem, E., Rigaut, F.J., Delabre, B., Monnet, G.: SINFONI: a near-infrared AO-assisted integral field spectrometer for the VLT. *Adaptive Optical System Technologies*. **3353**, 704–715 (1998)
  144. Thatte, N. A., Clarke, F., Bryson, I., Schnetler, H., Tecza, M., Bacon, R. M., Remillieux, A., Mediavilla, E., Herreros Linares, J. M., Arribas, S., Evans, C. J., Lunney, D. W., Fusco, T., O'Brien, K., Tosh, I. A., Ives, D. J., Finger, G., Houghton, R., Davies, R. L., Lynn, J. D., Allen, J. R., Zieloniewski, S. D., Kendrew, S., Ferraro-Wood, V., Pécontal-Rousset, A., Kosmalski, J., Richard, J., Jarno, A., Gallie, A. M., Montgomery, D. M., Henry, D., Zins, G., Freeman, D., García-Lorenzo, B., Rodríguez-Ramos, L. F., Revuelta, J. S. C., Hernandez Suarez, E., Bueno-Bueno, A., Gigante-Ripoll, J. V., Garcia, A., Dohlen, K., & Neichel, B.: HARMONI: the first light integral field spectrograph for the E-ELT. *Ground-based and Airborne Instrumentation for Astronomy V*. 9147 (2014)
  145. Thompson, S.J., Queloz, D., Baraffe, I., Brake, M., Dolgopopov, A., Fisher, M., Fleury, M., Geelhoed, J., Hall, R., González Hernández, J.I., ter Horst, R., Kragt, J., Navarro, R., Naylor, T., Pepe, F., Piskunov, N., Rebolo, R., Sander, L., Ségransan, D., et al.: HARPS3 for a roboticized Isaac Newton telescope. *Ground-based and Airborne Instrumentation for Astronomy VI*. **9908**, (2016)
  146. Thorngren, D.P., Fortney, J.J., Murray-Clay, R.A., Lopez, E.D.: The mass-metallicity relation for Giant planets. *Astrophys. J* **831**, (2016)
  147. Van Eylen, V., Agentoft, C., Lundkvist, M.S., Kjeldsen, H., Owen, J.E., Fulton, B.J., Petigura, E., Snellen, I.: An asteroseismic view of the radius valley: stripped cores, not born rocky. *Mon. Not. R. Astron. Soc.* **479**, 4786–4795 (2018)
  148. Vigan, A., Moutou, C., Langlois, M., Allard, F., Boccaletti, A., Carbillet, M., Mouillet, D., Smith, I.: Photometric characterization of exoplanets using angular and spectral differential imaging. *Mon. Not. R. Astron. Soc.* **407**, 71–82 (2010)
  149. Vigan, A., Otten, G.P.P.L., Muslimov, E., Dohlen, K., Philipps, M.W., Seemann, U., Beuzit, J.-L., Dorn, R., Kasper, M., Mouillet, D., Baraffe, I., Reiners, A.: Bringing high-spectral resolution to VLT/SPHERE with a fiber coupling to VLT/CRIRES+. *Ground-based and Airborne Instrumentation for Astronomy VII*. **10702**, (2018)
  150. Vigan, A., N'Diaye, M., Dohlen, K., Sauvage, J.-F., Milli, J., Zins, G., Petit, C., Wahhaj, Z., Cantalloube, F., Caillat, A., Costille, A., Le Merrer, J., Carlotti, A., Beuzit, J.-L., Mouillet, D.: Calibration of quasi-static aberrations in exoplanet direct-imaging instruments with a Zernike phase-mask sensor. III. On-sky validation in VLT/SPHERE. *Astronomy and Astrophysics*. **629**, (2019)
  151. Wachter, S., & Markovic, K.: The Euclid Mission. 42nd COSPAR Scientific Assembly. 42 (2018)
  152. Walker, J.K., Koehler, J.A., Creutzberg, F., McNamara, A.G., Vallance Jones, A., Whalen, B.A.: Post substorm convection and auroral arc currents determined from multiple ionospheric, magnetic, and electric field observations. *J. Geophys. Res.* **86**, 9975–9988 (1981)
  153. Wallner, O., Ergenzinger, K., Flatscher, R., Johann, U.: DARWIN system concepts. *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*. **10567**, (2017)
  154. Wilby, M.J., Keller, C.U., Snik, F., Korkiakoski, V., Pietrow, A.G.M.: The coronagraphic modal Wavefront sensor: a hybrid focal-plane sensor for the high-contrast imaging of circumstellar environments. *Astron. Astrophys.* **597**, (2017)

155. Wolszczan, A., Frail, D.A.: A planetary system around the millisecond pulsar PSR1257 + 12. *Nature*. **355**, 145–147 (1992)
156. Zechmeister, M., Dreizler, S., Ribas, I., Reiners, A., Caballero, J. A., Bauer, F. F., Béjar, V. J. S., González-Cuesta, L., Herrero, E., Lalitha, S., López-González, M. J., Luque, R., Morales, J. C., Pallé, E., Rodríguez, E., Rodríguez López, C., Tal-Or, L., Anglada-Escudé, G., Quirrenbach, A., Amado, P. J., Abril, M., Aceituno, F. J., Aceituno, J., Alonso-Floriano, F. J., Ammler-von Eiff, M., Antona Jiménez, R., Anwand-Heerwart, H., Arroyo-Torres, B., Azzaro, M., Baroch, D., Barrado, D., Becerril, S., Benítez, D., Berdiñas, Z. M., Bergond, G., Bluhm, P., Brinkmüller, M., del Burgo, C., Calvo Ortega, R., Cano, J., Cardona Guillén, C., Carro, J., Cárdenas Vázquez, M. C., Casal, E., Casasayas-Barris, N., Casanova, V., Chaturvedi, P., Cifuentes, C., Claret, A., Colomé, J., Cortés-Contreras, M., Czesla, S., Díez-Alonso, E., Dorda, R., Fernández, M., Fernández-Martín, A., Fuhrmeister, B., Fukui, A., Galadí-Enríquez, D., Gallardo Cava, I., García de la Fuente, J., García-Piquer, A., García Vargas, M. L., Gesa, L., Góngora Rueda, J., González-Álvarez, E., González Hernández, J. I., González-Peinado, R., Grözing, U., Guàrdia, J., Guizarro, A., de Guindos, E., Hatzes, A. P., Hauschildt, P. H., Hedrosa, R. P., Helmling, J., Henning, T., Hermelo, I., Hernández Arabi, R., Hernández Castaño, L., Hernández Otero, F., Hintz, D., Huke, P., Huber, A., Jeffers, S. V., Johnson, E. N., de Juan, E., Kaminski, A., Kemmer, J., Kim, M., Klahr, H., Klein, R., Klüter, J., Klutsch, A., Kossakowski, D., Kürster, M., Labarga, F., Lafarga, M., Llamas, M., Lampón, M., Lara, L. M., Launhardt, R., Lázaro, F. J., Lodieu, N., López del Fresno, M., López-Puertas, M., López Salas, J. F., López-Santiago, J., Magán Madinabeitia, H., Mall, U., Mancini, L., Mandel, H., Marfil, E., Marín Molina, J. A., Maroto Fernández, D., Martín, E. L., Martín-Fernández, P., Martín-Ruiz, S., Marvin, C. J., Mirabet, E., Montañés-Rodríguez, P., Montes, D., Moreno-Raya, M. E., Nagel, E., Naranjo, V., Narita, N., Nortmann, L., Nowak, G., Ofir, A., Oshagh, M., Panduro, J., Parviainen, H., Pascual, J., Passegger, V. M., Pavlov, A., Pedraz, S., Pérez-Calpena, A., Pérez Medialdea, D., Perger, M., Perryman, M. A. C., Rabaza, O., Ramón Ballesta, A., Rebolo, R., Redondo, P., Reffert, S., Reinhardt, S., Rhode, P., Rix, H.-W., Rodler, F., Rodríguez Trinidad, A., Rosich, A., Sadegi, S., Sánchez-Blanco, E., Sánchez Carrasco, M. A., Sánchez-López, A., Sanz-Forcada, J., Sarkis, P., Sarmiento, L. F., Schäfer, S., Schmitt, J. H. M. M., Schöfer, P., Schweitzer, A., Seifert, W., Shulyak, D., Solano, E., Sota, A., Stahl, O., Stock, S., Strachan, J. B. P., Stuber, T., Stürmer, J., Suárez, J. C., Taberner, H. M., Tala Pinto, M., Trifonov, T., Veredas, G., Vico Linares, J. I., Vilardell, F., Wagner, K., Wolthoff, V., Xu, W., Yan, F., & Zapatero Osorio, M. R.: The CARMENES search for exoplanets around M dwarfs. Two temperate Earth-mass planet candidates around Teegarden's Star. *Astronomy and Astrophysics*. **627**. (2019)

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

## Affiliations

Ignas A. G. Snellen<sup>1</sup>  · F. Snik<sup>1</sup> · M. Kenworthy<sup>1</sup> · S. Albrecht<sup>2</sup> · G. Anglada-Escudé<sup>3,4</sup> · I. Baraffe<sup>5</sup> · P. Baudoz<sup>6</sup> · W. Benz<sup>7</sup> · J.-L. Beuzit<sup>8</sup> · B. Biller<sup>9,10</sup> · J. L. Birkby<sup>11</sup> · A. Boccaletti<sup>6</sup> · R. van Boekel<sup>12</sup> · J. de Boer<sup>1</sup> · Matteo Brogi<sup>13,14,15</sup> · L. Buchhave<sup>16</sup> · L. Carone<sup>12</sup> · M. Claire<sup>17</sup> · R. Claudi<sup>18</sup> · B.-O. Demory<sup>19</sup> · J.-M. Désert<sup>20</sup> · S. Desidera<sup>18</sup> · B. S. Gaudi<sup>21</sup> · R. Gratton<sup>18</sup> · M. Gillon<sup>22</sup> · J. L. Grenfell<sup>23</sup> · O. Guyon<sup>24,25,26</sup> · T. Henning<sup>12</sup> · S. Hinkley<sup>5</sup> · E. Huby<sup>27</sup> · M. Janson<sup>28</sup> · C. Hellings<sup>29</sup> · K. Heng<sup>13,20</sup> · M. Kasper<sup>30</sup> · C. U. Keller<sup>1</sup> · O. Krause<sup>12</sup> · L. Kreidberg<sup>12</sup> · N. Madhusudhan<sup>31</sup> · A.-M. Lagrange<sup>6,27,32</sup> · R. Launhardt<sup>12</sup> · T. M. Lenton<sup>33</sup> · M. Lopez-Puertas<sup>34</sup> · A.-L. Maire<sup>35</sup> · N. Mayne<sup>5</sup> · V. Meadows<sup>36</sup> · B. Mennesson<sup>37</sup> · G. Micela<sup>38</sup> · Y. Miguel<sup>1,39</sup> · J. Milli<sup>32</sup> · M. Min<sup>39</sup> · E. de Mooij<sup>40</sup> · D. Mouillet<sup>32</sup> · M. N'Diaye<sup>41</sup> · V. D'Orazi<sup>18</sup> · E. Palte<sup>42</sup> · I. Pagano<sup>43</sup> · G. Piotto<sup>44</sup> · D. Queloz<sup>45</sup> · H. Rauer<sup>46</sup> · I. Ribas<sup>3,4</sup> · G. Ruane<sup>37</sup> · F. Selsis<sup>47</sup>

**A. Sozzetti<sup>14</sup> · D. Stam<sup>48</sup> · C.C. Stark<sup>49</sup> · A. Vigan<sup>8</sup> · Pieter de Visser<sup>39</sup>**

- <sup>1</sup> Leiden Observatory, Leiden University, Postbus 9513, 2300 RA Leiden, The Netherlands
- <sup>2</sup> Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, 8000 Aarhus C, Denmark
- <sup>3</sup> Institut de Ciències de l'Espai (ICE, CSIC) Campus UAB, Can Magrans s/n, E-08193 Bellaterra, Spain
- <sup>4</sup> Institut d'Estudis Espacials de Catalunya (IEEC) Gran Capità, 2-4, E-08034 Barcelona, Spain
- <sup>5</sup> University of Exeter, Physics Building, Stocker Road, Exeter EX4 4QL, UK
- <sup>6</sup> LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 place Jules Janssen, 92195 Meudon, France
- <sup>7</sup> Physics Institute of University of Bern, Gesellschaftsstrasse 6, CH-3012 Bern, Switzerland
- <sup>8</sup> Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France
- <sup>9</sup> SUPA, Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK
- <sup>10</sup> Centre for Exoplanet Science, University of Edinburgh, Edinburgh, UK
- <sup>11</sup> University of Oxford Department of Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK
- <sup>12</sup> Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany
- <sup>13</sup> Department of Physics, University of Warwick, Coventry CV4 7AL, UK
- <sup>14</sup> INAF - Osservatorio Astrofisico di Torino, Via Osservatorio 20, I-10025 Pino Torinese, Italy
- <sup>15</sup> Centre for Exoplanets and Habitability, University of Warwick Gibbet Hill, Coventry CV4 7AL, UK
- <sup>16</sup> DTU Space, National Space Institute, Technical University of Denmark, Elektrovej 328, DK-2800 Kgs. Lyngby, Denmark
- <sup>17</sup> Centre for Exoplanet Science, University of St Andrews, St Andrews, UK
- <sup>18</sup> INAF - Osservatorio Astronomico di Padova Vicolo dell'Osservatorio, 2, I-35122 Padova, Italy
- <sup>19</sup> Center for Space and Habitability, University of Bern, Gesellschaftsstrasse 6, CH-3012 Bern, Switzerland
- <sup>20</sup> Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
- <sup>21</sup> Department of Astronomy, The Ohio State University, 140 W. 18th Avenue, Columbus, OH 43210, USA
- <sup>22</sup> Astrobiology Research Unit, University of Liège, Allée du 6 Août, 19, 4000 Liège (Sart-Tilman), Belgium
- <sup>23</sup> Department of Extrasolar Planets and Atmospheres, Institute for Planetary Research, German Aerospace Centre, Berlin, Rutherfordstr. 2, 12489 Berlin, Adlershof, Germany
- <sup>24</sup> Subaru Telescope, NAOJ, 650 North A'ohoku Place, Hilo, HI 96720, USA
- <sup>25</sup> Steward Observatory, University of Arizona, Tucson, AZ 85721, USA
- <sup>26</sup> Astrobiology Center of NINS, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
- <sup>27</sup> IMCCE - Observatoire de Paris, 77 Avenue Denfert-Rochereau, F-75014 Paris, France
- <sup>28</sup> Department of Astronomy, Stockholm University, AlbaNova University Center, SE-106 91 Stockholm, Sweden

- 
- <sup>29</sup> Centre for Exoplanet Science, University of St Andrews, North Haugh, St Andrews KY169SS, UK
- <sup>30</sup> European Southern Observatory, Karl Schwarzschild St. 2, 85748 Garching, Germany
- <sup>31</sup> Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
- <sup>32</sup> IPAG, Univ. Grenoble Alpes, CNRS, F-38000 Grenoble, France
- <sup>33</sup> Global Systems Institute, University of Exeter, North Park Road, Exeter EX4 4QE, UK
- <sup>34</sup> Instituto de Astrofísica de Andalucía, CSIC, Glorieta de la Astronomía, s/n, 18008 Granada, Spain
- <sup>35</sup> STAR Institute, University of Liège, Allée du Six Août 19c, 4000 Liège, Belgium
- <sup>36</sup> Department of Astronomy and Astrobiology Program, University of Washington, Box 351580, Seattle, Washington 98195, USA
- <sup>37</sup> Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
- <sup>38</sup> INAF - Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy
- <sup>39</sup> SRON, Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
- <sup>40</sup> School of Mathematics and Physics, Queen's University Belfast, University Road, Belfast BT7 1NN, UK
- <sup>41</sup> Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France
- <sup>42</sup> Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain
- <sup>43</sup> INAF- Osservatorio Astrofisico di Catania, via Santa Sofia 78, p.le M. Rodonò, 95123 Catania, Italy
- <sup>44</sup> Dipartimento di Fisica e Astronomia, Università di Padova, Vicolo dell'Osservatorio, 3, I-35122 Padova, Italy
- <sup>45</sup> Cavendish Laboratory, J J Thomson Avenue, Cambridge CB3 0HE, UK
- <sup>46</sup> Institut für Planetenforschung, Deutsches Zentrum für Luft- und Raumfahrt, 12489 Berlin, Germany
- <sup>47</sup> Laboratoire d'astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, 33615 Pessac, France
- <sup>48</sup> Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, the Netherlands
- <sup>49</sup> Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA