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A possible future for space-based interferometry

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Abstract. We address the question of space interferometry following the recent outcome of the science themes selection by ESA for the L2/L3 missions slots. We review the current context of exoplanetary sciences and its impact for an interferometric mission. We argue that space interferometry will make a major step forward when the scientific communities interested in this technique will merge their efforts into a coherent technology development plan.

1. Introduction

In the late nineties and early 2000, the possibility of flying a large infrared interferometric space mission to search for Earth planets in the habitable zone of Solar-type stars and characterize them had materialized in the Darwin/TPF mission. In its most developed state the concept was based on a formation-flying four-telescope array operating as a nulling interferometer in the 6–20 μm wavelength range. The project was largely followed within the interferometric community and beyond, although there were never a full consensus – for many reasons, among which its cost – if that would be *the* mission concept on which to set programatic priorities. Both the European and US space agencies invested significant resources on these projects in order to improve the technological readiness of the mission. In 2007, the Darwin project was presented as a response to the ESA call for L1 missions (Léger et al. 2007). It was a 4×2-m telescope interferometer planned to do spectroscopy of ∼200 nearby Earth-size exoplanets over a 5-year mission lifetime. Unfortunately the proposal was not selected for further study, but the AWG and SSAC[1] committees recommended "to initiate the technology development for Darwin". Such a comment was surprising considering the technological development that had already taken place in the last ten years for Darwin/TPF. Obviously this was not enough for the mission to be selected, in particular considering the state of the art of the formation-flying technology needed for the mission.

After 2007 the context has significantly evolved in terms of scientific results in exoplanetology and mission concepts, and activities in nulling interferometry slowly faded. In 2013 a new call for science themes in the perspective of the L2/L3 missions was issued by ESA, to which the exoplanetology community responded in a cohesive way (Quirrenbach et al. 2013) by putting together a proposal to search for habitable distant worlds. The selection of the gravitational wave and X-ray astrophysics as core science themes for the L2/L3 missions further delayed the possibility of building a space-based interferometric observatory for infrared high-angular resolution astronomy. Here we review the case of space-based interferometry in the new context of exoplanetary sciences and beyond the original objectives of Darwin/TPF.

2. Space interferometry and the link to exoplanetary science

2.1 Overview of the current landscape

In the last 15 years, numerous RV and transit surveys have evidenced the strong diversity of planetary systems around main-sequence stars, which only partially reflects our long standing view inspired by our Solar System. This diversity is largely observed in terms of size, mass, composition, temperature and orbit. It is not the goal of this section to discuss in detail the physical and chemical properties of the different classes of planets, but rather giving a qualitative overview of these properties as this could determine the need – or not – for an interferometric facility.

– **mass/size:** The search for smaller and lighter planets is a natural continuation of the surveys that explored the population of Hot-Jupiters. High-precision radial velocity surveys with $\sim$1 m.s^{-1} resolution and high-precision photometry of transits with COROT and Kepler allowed exploration of the lower-end of the exoplanetary mass distribution, bringing a new light onto the nature and properties of the extrasolar planets population. New RV measurements have entered the domain of Neptunes ($\sim$10–50 $M_\oplus$), Super-Earths ($\sim$2–10 $M_\oplus$) and Earth-mass ($\sim$0.5–2 $M_\oplus$) planets (cf. Mayor et al. (2009), Dumusque et al. (2012)[2] with HARPS). Transits measurements have constrained the radii of exoplanets, starting from the first measured Super-Earth (Corot-7b, Léger et al. 2009) down to sub-Mercury size planets (Kepler-37b, Barclay et al. 2013). Earth-like similarities – in mass and radius – have therefore been discovered (cf. www.exoplanets.eu), however limited to the case of short-orbit planets which are the most effectively commonly objects with these techniques. The combination of mass and radius observations have permitted measurement of the mean density even for the small-

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[1] *Astronomy Working Group* and *Space Science Advisory Committee*

[2] The effective RV detection of Alpha-Centauri Bb has been questioned by Hatzes et al. (2013).

est planets, bringing first insight on their internal composition.

– **frequency:** Current statistics point out the probable high-occurrence rate of Earths and Super-Earths around FGKM stars, with ∼20 % occurrence rate around FGK stars (Howard et al. 2010; Fressin et al. 2013) and up to 50 % occurrence around M stars (Bonfils et al. 2013; Dressing et al. 2013). As mentioned earlier, these numbers must be taken with some precaution as they often correspond to extrapolations from the short-period planets effectively detected (i.e. P<50 days). The recent results obtained by HARPS, Corot and Kepler suggest that "small" planets, if detectable, are quite frequent. Theoretical modeling of the planetary Initial Mass Function (IMF) by the time the protoplanetary disk vanishes and under the core-accretion scenario seems to support this idea (Mordasini et al. 2009). In the context of a direct spectroscopy mission, this reservoir of planets would be have to be volume-limited to the closest objects (typically within ∼20 pc) because of SNR considerations. The plot of Fig. 1 shows the mass histogram of planets around F,G,K,(M) dwarfs within 20 pc and was built using data form the exoplanets.eu website. The case where M dwarfs are included is displayed separately (in blue) becasue of the observational and scientific challenge they represent. The graph indicates a bimodal distribution with a minimum at $\sim 30\,M_{\oplus}$, similarly to what is observed for the full population of planets around FGKM stars.

– **Earths, Super-Earths and HZ within 20 pc:** Although the spectroscopic characterization of Neptunes and Jupiters with H-He-rich atmospheres is intrinsically interesting for comparative planetology, the case of small rocky-core planets with potential habitable atmospheres (CO_2-N_2-H_2O-O_2) is central to address the question of habitability, provided we are able to detect them and take a spectrum of the exoplanet with adequate resolution. Hence we concentrate here on the case of Earths and Super-Earths (SE) by analyzing the population of

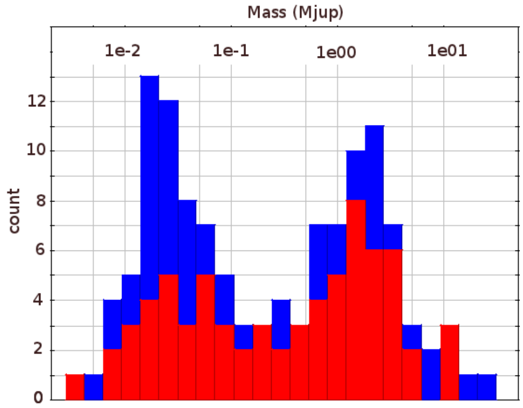

Figure 1.: *Mass histogram for planets orbiting main sequence stars within 20 pc built with data from exoplanet.eu. Red bars correspond to planets orbiting F,G,K stars, while blue bars include the M dwarfs.*

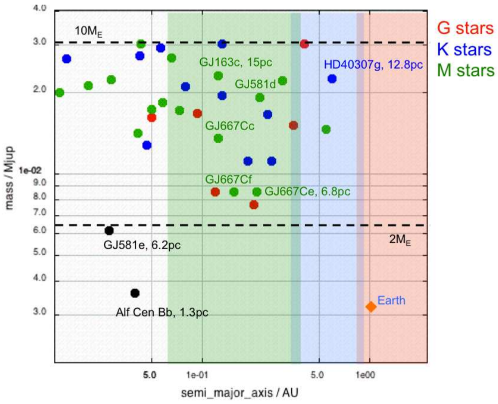

Figure 2.: *Separation in AU for all Earths and Super-Earths detected within 20 pc. The color code reports to G, K and M stars. The position of our Earth is shown for comparison.*

currently detected Earths and SE within 20 pc and its relevance to the Habitable Zone (HZ). Fig. 2 displays the minimum mass of a planet up to $10\,M_\oplus$ – taken as an upper limit for the mass of a Super-Earth – as a function of the separation from the host star in AU. It concerns all the Earths and Super-Earths detected within 20 pc which have been so far only detected only around G, K and M stars. Their position with respect to the HZ of their respective star – in green, blue and red – is shown as well. Without discussing the observational biases of the technique leading to this plot, we see that 1) SE constitute a considerable reservoir of targets for spectroscopic follow-up as they are more easily detected than their low-mass counterparts; 2) the M stars correspond to the sample with the larger number of detected planets lying in their HZ; 3) The number of detected nearby (Super)Earths per year shows a rising trend and we can reasonably expect that this sample will further increase (cf. Fig. 3).

Planets in the HZ of M-dwarfs has often been presented has a difficult case for habitability due to tidal locking and strong stellar flares/UV radiation field (e.g. Kasting 1993; France et al. 2013). Not surprisingly other studies suggest that such conditions do not exclude the possibility for a planet to be habitable (cf. Haberle et al. 1996; Pierrehumbert 2011; Segura et al. 2010). Considering that there are roughly ten times more nearby M dwarfs than G dwarfs (Chabrier 2003) and that $\eta_\oplus$ increases with later spectral type, it does not appear justified for a future mission to exclude M dwarfs from its list of targets (see Sect. 2.3 for the instrumental implications).

We also wish to stress here the fact that the overlap between the concepts of Habitable Zone – in its classical description – is a matter of debate within the exoplanet community. Should we focus on the HZ to characterize habitable planets, or not? That is the question! There is a long-standing ongoing debate on this point, which is difficult to solve because of the current lack of evidence for signs of habitability. New theories as “Superhabitable Worlds” have been pulled in

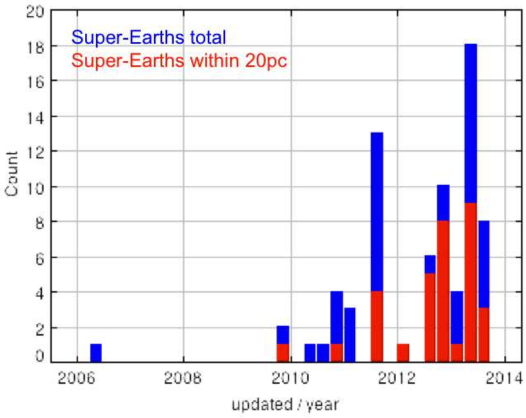

Figure 3.: *Time evolution histogram illustrating the detection rate of Super-Earths.*

the discussion (Heller & Armstrong 2014) and need to be followed, as they might have a significant impact on the future design of a spectroscopic mission.

2.2 Summarizing points

We summarize hereafter the pertinent points that will help us to make the case of infrared interferometry in the field of exoplanets.

- Both observational and theoretical studies suggest that the occurrence of small Earths and Super-Earths planets around F,G,K,M is higher than for more massive Neptunes and Jupiters. Provided suitable observatories are able to detect them, we will benefit of a large reservoir of candidates to address the question of habitability through spectroscopy. Because of the profound scientific importance of this question, it is meaningful to address the design of a future L-class spectroscopic mission with the prime objective of characterizing Earths and Super-Earths rather than Extrasolar Giant Planets (EGPs) atmospheres.
- How far should Earths and Super-Earths candidates to direct spectroscopy be picked up? The population of small planets discovered by Kepler are inaccessible to a spectroscopic mission because to distant and faint. It is generally assumed that for direct spectroscopy of Earths and Super-Earths by a 1 G€ mission it is necessary to choose targets within ∼20 pc in order to ensure a high enough signal-to-noise.
- Is there a preferential main sequence star spectral type that will be targeted by a future spectroscopic mission? A first level of answer is to consider that a future spectroscopy mission will be designed to characterize already detected Earths and Super-Earths around whatever spectral type, hoping that the sample of small planets within 20 pc will be large enough. Within a more selective approach, while G and K stars can be considered as natural targets, the case of M and F dwarfs deserves some more attention. As

mentioned earlier, the close environment of M dwarfs appears quite extreme for habitability, but this is still a matter of debate. On the positive side, the requirement on the planet/star contrast is relaxed compared to earlier spectral types, and despite the small angular size of their Habitable Zone, the latter remains accessible with an interferometer (cf. Section 2.3). Furthermore, the high number of nearby M dwarfs[3] coupled with an expected higher $\eta_\oplus$ ($\sim 50\%$) and to the increasing observing survey capabilities of small planets around them is a convincing fact for including M stars in the targets sample of a future mission. F stars are brighter and with a wider HZ, but rarer in the solar neighborhood. While intrinsically interesting as well – they are included in both the Darwin (Kaltenegger et al. 2010, K10) and in the NEAT (Malbet et al. 2012, M12) catalogs – only new data delivered by TESS and PLATO will reliably inform us on the frequency of small planets around F stars. Key information will also be delivered by the LBTI, which will contribute to quantify the level of exoplanetary dust potentially masking the faint signal of planets candidate to spectroscopy.

- What is the optimal spectral range where to operate? From a purely scientific point of view, this is an unsolvable question. While broad and deep molecular bands can be traced in the mid-infrared (e.g. CO_2, O_3), H_2O and O_2 features could be detected in the UV-Optical-NIR domains with R$\sim$100 with concepts like LUVOIR (Kouveliotou et al. 2013). From the mission concept point of view, it remains that if the mid-IR is the spectral range of interest, only the interferometric design will have the capability to resolve the HZ around the coolest main sequence stars.

2.3 Instrumental concepts to access the Habitable Zone

The spectroscopic characterization of exoplanets *in the HZ* of their host star is relevant for the question of habitability based on liquid water. In the recent years, comparative exoplanetology via transit spectroscopy such as proposed by the EChO mission has raised significant interest in the community. The goal is to achieve infrared low-resolution spectroscopy of a variety of short-period ($\sim$tens of days) and warm ($>$400 K) transiting Neptunes and Jupiters around solar-type stars. When constraining the case of small planets with thin atmospheres orbiting within the HZ of their host, the requirement for a sufficient SNR and a star/planet contrast smaller than 10^{-5} practically limit the observations to one or two M stars within 10 pc[4] (cf. EChO proposal). For the spectroscopy of longer-period planets, direct detection techniques are better adapted as they can offer immediate and unambiguous identification of spectroscopic features. Concretely this translates into either a coronographic or interferometric space mission as this has been developed in the proposal to the ESA call for an L3 mission. Fig. 4 shows for all the F,G,K,M stars of the Darwin catalog (Kaltenegger et al. 2010) the radius of the Habitable Zone in milliarcseconds as a function of the distance to the

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[3] We list, respectively, 351 Ms, 536 Ks, 235 Gs and 107 Fs within 30 pc (K10); 82 Ks, 65 Gs, and 53 Fs within 20 pc (M12); 248 Ms, 44 Ks, 20 Gs, 6 Fs within 10 pc (www.recons.org).

[4] Assuming a population of $\sim$250 Ms within 10 pc, a $\eta_\oplus$ $\sim$50% and a $\sim$1% transiting probability leads to 1.25 planet.

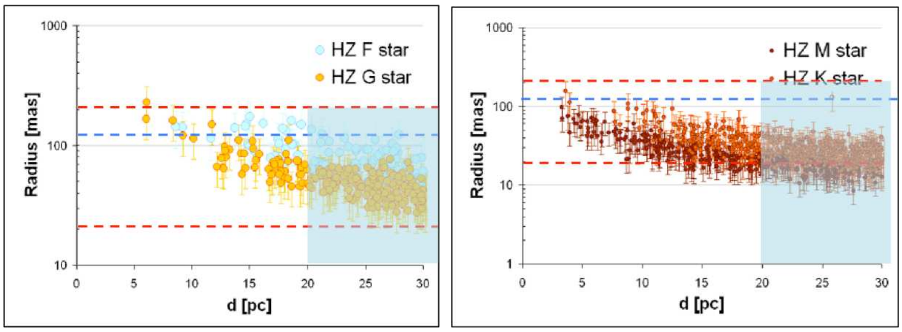

Figure 4.: *Overview of the accessible habitable zones as a function of distance and spectral types for an optical coronograph and an infrared interferometer, with respectively blue and red horizontal dashed line. (adapted from Kaltenegger et al. 2010)*

star up to 20 pc. The horizontal dashed lines define the upper and lower angular resolution limits for the habitable zones that can be spatially resolved in the two following cases: the blue dashed line sets the 2.5×λ/D IWA limit of a 2.5-m coronograph operating at λ=0.7 μm (although 4×λ/D would be more realistically feasible). Only the points above this line correspond to a directly accessible HZ. The red lines set the upper and lower resolution limit of an interferometer operating at 10 μm with a baseline tunable from 5 to 50 m.

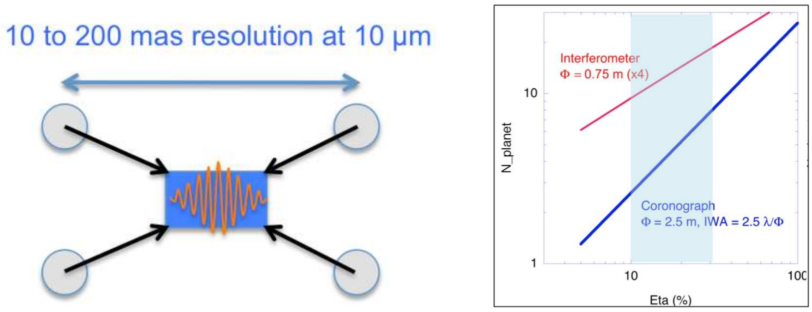

Figure 5.: *Left: schematic of the architecture of a descoped Emma-array configuration for an interferometer with 0.75-m diameter apertures. Right: number of habitable Earth/Super-Earth planets detected via optical coronogaphy and infrared interferometry as a function of $\eta_\oplus$ for FGK stars. This graph assumes prior detection, 5-year mission lifetime for spectroscopy, and R=20 at 10 μm (A. Léger, private comm.).*

From simple considerations on the achievable angular resolution, it appears that only the interferometric approach allows the observation of a large number of stars, *as long as the habitable zone is the main target of the mission.* In the case of K and M spectral types – which are of high scientific importance – the habitable zone is practically inaccessible with a coronographic mission. Furthermore, the *true* value of the $\eta_{\oplus}$ parameter will have a crucial impact on the number of Earths and Super-Earths that could be characterized with one or the other concept. Léger et al. (priv. comm.) have estimated the number of habitable planets that can be spectroscopically characterized by interferometry or coronography. The concepts adopted for the comparison are a coronograph as described above on one side and a four-telescope interferometer with 0.75 m apertures as depicted in Fig. 5 on the other side. The details of the assumptions made on the sources of noise for the two approaches are developed in a forthcoming paper. The plot of Fig. 5 underlines the different outcomes between the coronograph and the interferometer in terms of spectroscopy of nearby habitable Super-Earths by a factor 3 to 4, which is a significant factor in the low statistics case.

2.4 An exoplanet interferometer in the current context

A space-based interferometer dedicated to the characterization of habitable Earths will only focus on already detected nearby planets. Therefore what is the expected reservoir of Earth-like planet in the next decades? Several ground-based survey programs are already running or will be started in the coming years to detect habitable Earths and Super-Earths around M dwarfs with instruments such as ESPRESSO, CARMENES, or HARPS using precision RV techniques. This will potentially result in the detection of ~100 small habitable planets out of which ~1-2% will be transiting their host. These surveys will also monitor hotter F, G and K stars to detect any Super-Earth (essentially non-habitable) up to larger distances. From space where high-photometric accuracy can be achieved, CHEOPS will attempt to record the light dip of small Super-Earths orbiting bright stars and already detected by RV surveys, which will deliver new insights onto the density of these objects. Similarly to Kepler and COROT, the recently selected M3 mission PLATO will conduct blind searches of habitable Earths and Super-Earths even around bright and nearby stars, which was so far not observable with the two predecessors missions, and will build up on the heritage of GAIA in the field of exoplanets. A similar mission – TESS – is under development on the US side. Since the EChO mission was not selected for the M3 slot, a short term opportunity for transit spectroscopy of exoplanets resides in the NASA candidate mission FINESS, for which its main goal is comparative exoplanetology. More punctual but nevertheless important studies in the field of exoplanets characterization will be conducted with the 30-m + class ground-based telescopes, while JWST will spectroscopically characterize transiting planets around M dwarfs.

From the perspective of a direct spectroscopy mission for which nearby habitable Earth and Super-Earths would be the primary targets, a problem remains: all the stars that will be monitored via the aforementioned surveys are carefully chosen for their low stellar activity in order to leave the RV and photometric signals unaffected by stellar noise. This means that the sample of stars within 20 pc hosting a planet will be incomplete in terms of follow-up targets for direct spectroscopy. Circumventing this problem can be achieved by using high-precision astrometry of nearby stars, a technique that is almost unaffected by astrometric jitter noise at the level needed to detect a $1\,M_{\oplus}$ planet around a Solar-type star. This approach is chosen by the NEAT mission (Malbet et al. 2012), a candidate mission for a potential M4 slot and would be able to conduct a complete census of nearby Earths and Super-Earths within 20 pc.

In summary, despite a current context which for many reasons is unfavorable to space interferometry, it appears that unless of a major breakthrough in the development of both large and cheap space-based collectors, space interferometry in the 4–20 μm mid-infrared range remains the best concept for *the low-resolution spectroscopic search of biomarkers in the atmosphere of a significant number ($\gtrsim$10) of nearby Earths and Super-Earths in the HZ of their host stars.* The weak point of this approach still remains at a technological level.

3. Space interferometry beyond exoplanetary science

We can reasonably affirm without too many risks that the uniqueness of space interferometry for characterizing planets in the habitable zone of solar-type stars is, *as a principle*, uncontested within the Exoplanet community for the reasons presented above. However, following the Darwin/TPF decade, there is now little support to the idea that this route should be followed as a priority. The scientific achievements obtained with the RV and transits techniques, or with ground-based coronography on large telescopes has refrained part of the community to invest more resources for space-based nulling interferometry in regard to its complexity and cost. The outcome of the recent L2/L3 selection process has flagged positively the technical feasibility of a spectroscopy mission such as proposed by Quirrenbach et al. (2013), but stressed that the cost associated with the technological development was beyond the envelope of an L-class mission, leading to its non-selection. Even considering the topic of Formation Flying (FF) for which the PRISMA and PROBA-3 missions will provide a major boost, the maturity is not considered to be reached for a large FF array. Several reports have been written on the technological readiness for a mid-IR flagship mission (e.g. Lawson et al. 2009) and provide a good starting point to plan a future technology roadmap.
Interestingly, other key topics connected to galactic and extragalactic science may require the use of space-based interferometry (Sauvage et al. 2013). At longer wavelengths, the far-infrared community developed the case for an interferometric observatory to go beyond the resolution delivered by Herschel. Different technical solutions where proposed in September 2013, including a formation-flying interferometer based on the ESPRIT concept for heterodyne detection. Interferometric missions such as SPIRIT and SPECS were proposed in the US to operate in the same wavelength range. In the field of planetary sciences, a concept of heterodyne thermal infrared observatory named PSIO considers the option of an interferometric architecture (Fletcher et al. 2013).
In the light of these important elements, we suggest that in order for infrared space interferometry to become strongly supported as an L-class mission by the largest possible scientific community, the proposed science has to go beyond the theme of the Earth-analog characterization and must reflect the astrophysical interests of a wider community than the original Darwin/TPF project did. Clearly this would require a complete recasting of the science and technological roadmaps to explore overlaps and compatibility between the different proposed methods. For instance the capability of interferometric imaging would become at least as important as the nulling capabilities. But we argue this is the most plausible way to have space interferometry seriously considered in the current context. The re-

cently started Horizon-2020 program by the EC should offer an ideal stage for collaborations aiming at exploring possible convergence, boosting technology and support preparatory missions.

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