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PREPARATION TO FUTURE LONG-TERM SPACE MISSIONS FOR EXOPLANETS HIGH CONTRAST DIRECT CHARACTERIZATION

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Abstract. A wide international community has clearly expressed the need to plan as a priority very deep and accurate space-based observations in order to characterize a sizeable sample of telluric temperate exoplanet atmospheres. Such a characterisation will necessitate complementary information in reflected light, from near UV to near IR (as proposed for the Habitable Worlds Observatory, the first priority flagship mission as identified in the US decadal survey) and in thermal emission (as identified as a priority in the ESA Voyage2050 prospective, and proposed in a mission such as LIFE). The considered timeline targets a mission in the 2040+ decade, after the current and upcoming continuous effort on further exploring the vast diversity and statistics of planetary systems, and the characterization of the easier (and mostly at shorter separations) exoplanets. This timeline is practically also needed in order to mature the technologies and the key instrumental concepts which are absolutely needed for such an ambitious observational goal. We intend to precise here such a need, together with the actual expertise and the role that should be taken within the French community on this topic. We conclude on the importance of a strong push and coordination on the specific R&D actions to be handled in a timely manner within the next 5 years.

Keywords: exoplanets, space missions, research and development, high-contrast

1 Space-based high contrast characterization capability: an identified community priority

Exoplanet research has been impressively active over the past decades, combining both observational and theoretical studies, using ground-based and space-based facilities. Our understanding of the subject and the focus of the main questions evolve correspondingly. After the detection of the first exoplanet around a solar-type star in 1995, large multi-technique surveys have revealed a wide diversity of planet types, and have informed us on the statistics and the structures of planetary systems. The planet formation scenarios are now discussed in the combined perspective of theoretical models and observational evidences such as the directly imaged young systems, including the interaction between disks and forming planets, or as the statistics, the physical and chemical properties of the resulting planets. The atmosphere characterization of exoplanets has also progressed a lot, starting with the most favorable cases, as for transiting planets at very shot separations or massive young (still warm) very distant giant planets.

All these studies need to be pursued and they will be with both major ground-based instruments such as ELT or space missions such as JWST, Roman Space Telescope, PLATO and ARIEL. This will be of highest importance to provide a more complete (and less biased) view of the planetary systems and of their dynamics, to identify the population of the probably best targets around nearby stars, and to enter the field of comparative exoplanetology, to probe and to understand the diversity of exoplanet atmospheres. This will definitely require a > decade-long work. However, it is already possible now to identify the following step in the 2040+ timescale. This is not only possible ; this is actually done within an international perspective, and we argue this is indeed mandatory for a practical technological preparation towards such a goal.

Both the American and European communities have explicitly identified the fine characterization of earth-like exoplanets as a programmatic priority. It will provide objective and significant information on the likelihood

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that ubiquitous conditions would be met for emerging life elsewhere. Quoting the US Astronomical decadal survey*: *"We are on a path to exploring worlds resembling Earth and answering the question: "Are we alone?" The task for the next decades will be finding the easiest of such planets to characterize, and then studying them in detail, searching for signatures of life."* The US community has defined as a priority flagship mission: *"A large space-based IR/O/UV telescope with high contrast imaging and spectroscopy capable of observing planets 10 billion times fainter than their host star"*, aka Habitable Worlds Observatory (HWO). The scientific goal is also clearly identified in the European community, as expressed in the Astronet perspective†, and more specifically for the space community, as a conclusion of the Voyage2050 prospective‡, for which: *"launching a Large mission enabling the characterisation of the atmosphere of temperate exoplanets in the mid-infrared should be a top priority for ESA within the Voyage 2050 timeframe."* A corresponding mission, LIFE, has been proposed and studied, both on the instrument basic concept aspects, the reasonable expected level of performance, and the corresponding science case (see Quanz et al. (2022b) and the following paper serie)

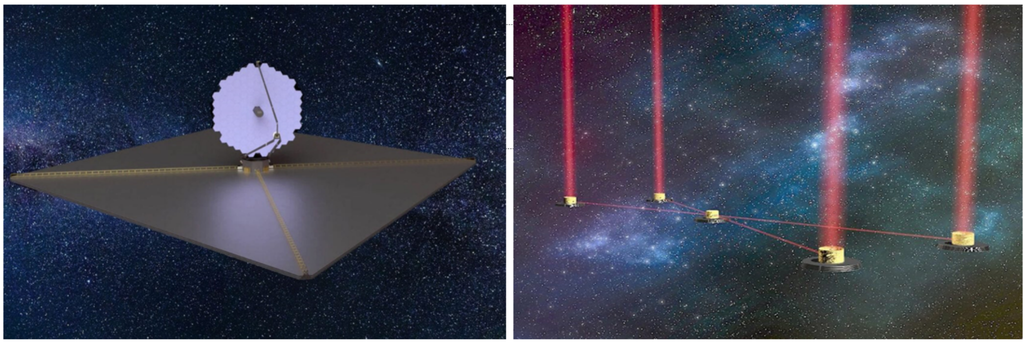

Fig. 1. Artist view of the future high contrast space missions. Left: Habitable World Observatory for UV/Vis/NIR high contrast imaging of exoplanets reflected light (NASA). Right: LIFE mission for IR interferometric high contrast detection of exoplanets thermal emission (proposed to ESA)

Such a goal for exo-earths characterization is very stimulating and ambitious. It also appears achievable, assuming the international community provides the appropriate effort in a timely and coordinated manner. This evaluation is made much stronger than it could have been a few decades ago, thanks to the impressive progress on both the scientific knowledge on exoplanetary systems. and on the instrumentation side. On the astronomical side, the game-changing information is the frequency of exoplanets. Now, we know that low-mass planets are very frequent, in a variety of stellar systems (single or binary, various stellar masses, planet multiplicity,...). It is possible to focus some very deep searches on the nearest stellar systems, with the most favorable angular separations and enough photons to be collected on large telescopes to envision high SNR spectral characterization. Concerning the instrumental aspects, we further detail hereafter the considered key domains which are involved.

2 Need for technological preparation coordinated in the international context

The actual definition of the 2040+ instrument architectures, and the formal development plans are not expected by now, but rather around 2030. The important point by then is to mature the relevant technologies and to provide some demonstrating proto-types for the key elements than may deeply impact the future design. It is also mandatory to properly evaluate the corresponding risk, the cost and the management organisation of the future missions. These are critical inputs at the stage of the mission decision. The envisioned future high contrast instruments are quite far some a direct extension or upgrade of already operating systems in space: it is clear that R&D must start very early-on. It must feed and inform rather than follow the formal programmatic decision.

Following such an analysis, NASA has explicitly defined a needed a "Great Observatory Maturation Program" (GOMAP) in order to identify and to carry on the critical R&D. This maturation shall bring all the critical

*https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

†https://www.astronet-eu.org

‡https://www.cosmos.esa.int/web/voyage-2050

aspects of the future concept to a safe readiness level (TRL 6) by 2029. A similar approach is perfectly relevant for a high-contrast IR interferometric mission such as LIFE.

This situation has been presented to ESA Science and Technological directorate members, by a small group of European representatives of the high contrast imaging community[§]. This dedicated meeting was also open through visioconference to international attendance. This actually offered the opportunity for the US partners (including the GOMAP Program Executive, within NASA HQ) to explicitly support the interest for known contacts and contributions in this R&D phase, from both individuals, institutes, and agencies. Within the need for coordination at international level, France has a leading role and a recognized expertise on a number of relevant topics for high contrast imaging or interferometry (see next section). This emphasizes the interest of a good preparation at this level.

A list of contacts covering a broad range of laboratories has been set up in order to exchange and coordinate such a preparation[¶]. This coordination initiative is supported by CNES-APR and INSU/AA, and a corresponding workshop is in preparation for Spring 2024. This group has also emphasized the need for an early technological preparation to future HWO-LIFE missions, as a contribution to CNES prospective.

At European scale, ground-based projects are in practice strongly stimulating some coordination across international teams. This happens for instance in the context of the developments of future instruments for the ELT (each first-light instrument includes a high-contrast mode), and for the VLTI (including enhanced adaptive optics correction and a nulling interferometric mode within the ASGARD instrumentation suite) ; longer term plans also motivate some coordinated R&D plans under construction for European INFRATECH calls, including the specific needs driven by an ELT instrument dedicated to high contrast (PCS). High contrast from space also gathers some strong communities as witnessed in the responses to the Voyage2050 calls (Quanz et al. 2022a; Snellen et al. 2022)[‖]. Some of the expertise is shared and offers strong synergies between the ground and space. The level of space-based performance also sets some specific requirements and challenges. Some of them will be addressed in the ESA-organized WITSO workshop[**] and, more specifically, a workshop dedicated to technological developments required for future exoplanet high contrast detection from space is foreseen for spring 2024.

3 Critical domains of instrumentation research and expertise in Europe and France

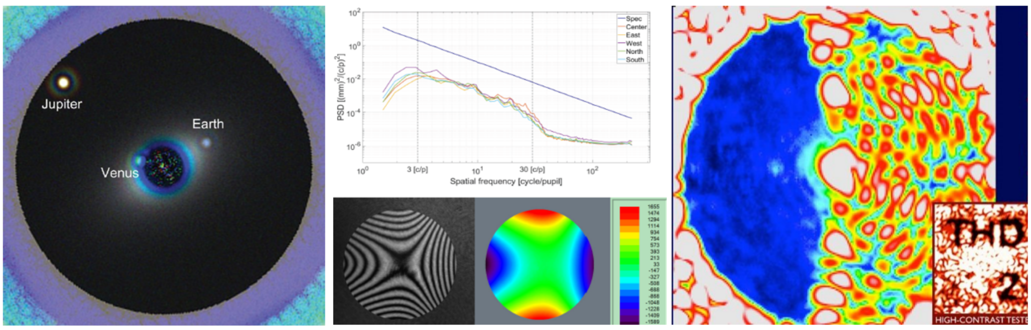

Fig. 2. Examples of advanced R&D for high contrast imaging. Left: Simulated performance of coronagraphic capability to rejected the stellar diffracted light down to imaging capability of a solar system twin from 10 pc away (N'Diaye et al. 2016). Middle: Super polishing of aspheric optics down to 5 nm rms, for Roman Space Telescope off-axis parabolae (courtesy M. Ferrari, LAM). Right: Wavefront sensing and control for dark-hole down to 10^{-8} level on the LESIA test bench (courtesy I. Laginja)

High contrast imaging or interferometry is very demanding for the exquisite goal performance, and they

[§]2023 May 30th. Slides: https://drive.google.com/file/d/1MTxuyb7fAitsAZe_fYykhNjG1KLRsxOv/view?usp=sharing
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[‖]see corresponding presentations at ESA Voyage2050 workshop on https://www.cosmos.esa.int/web/voyage-2050/workshop-programme
[**]https://atpi.eventsair.com/witso-2023/

require many different fields of expertise to be gathered for a successful development. The analysis of such requirements has been strongly supported by recent high contrast ground-based instruments, and also benefits from the inheritance of space-based missions, such as JWST (demonstrating the deployment, co-phasing and stability of its large segmented mirror up to a level of wavefront quality well above specifications) and in the near future Roman space telescope including very fine wavefront control for high contrast on a smaller mirror. In order to reach the future performance goals, we can at least mention the following aspects to be further matured and developed:

- system and trade-offs analysis at instrument level, based on large scale simulations and fundamental optical limitations, in order to include the many coupled sources of contrast degradation within a model. The general approach is known, but the considered level of performance has never been addressed
- experimental testbed capabilities, at a level of stability, calibration, and accuracy needed to address the required level of limitations.
- at component level: further key developments concerning integrated optics, coronographs, correcting optics, low-noise detectors in space environment, and/or very high wavefront quality on complex optics.
- operations and auto-calibration procedures: internal metrology, real-time wavefront sensing and control, and dark-hole procedures
- advanced signal processing for optimal real-time operation and a posteriori signal extraction, studied early on in a co-conception approach together with the instrument definition.

In each of these items, European (and in particular French) actors have demonstrated a very strong expertise with the potential of significant possible progress. In a context of limited time and resource, it will be definitely important to identify the most important items and to set some specific and quantified goals for corresponding R&D developments. The distribution of the effort should be discussed worldwide within typically 2 years for a consistent and efficient plan. The following 4 years should be devoted to the actual developments and demonstrations by the end of the decade. This will provide a clear and strong technological support to programmatic decisions on future missions, the instrument architecture definitions and the development plans.

4 Conclusion

The high-level scientific goal to characterize exo-earths and to evaluate the occurence of conditions favorable to the emergence of life is strongly expressed at international level both in US and in Europe. This very ambitious goal appears reachable within the 2040+ decade, but requires a strong and concerted R&D plan concerning high contrast capabilities to be organized now. France is in a recognized position to play a major role in this plan, based on very successful ground-based instruments in imaging and interferometry, and based on continuous R&D. The next 2 years will be important to identify the key technological items for be strongly matured, with a consistent and complementary workload distribution worldwide, in order to practically deploy such R&D actions up to 2029. Coordination work has been started in particular at the French level with a group and workshop foreseen in spring 2024 (INSU/AA and CNES), and another ESA workshop at European scale.

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