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UPDATE ON THE LARGE INTERFEROMETER FOR EXOPLANETS (LIFE)

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Abstract. The Large Interferometer for Exoplanets (LIFE) is a European-led international project with the goal of consolidating various efforts and defining a road map that leads to the launch of a space-based mid-infrared nulling interferometer (Quanz et al. 2018; Quanz 2019; Quanz et al. 2022). This mission will be designed with the capability to investigate the atmospheric properties of a large sample of (primarily) terrestrial exoplanets. LIFE directly addresses the scientific theme of detecting and characterizing temperate exoplanets in the MIR, which was recommended with "highest scientific priority" by ESA's Voyage 2050 Senior Committee report as a candidate topic for a future L-class mission in the ESA Science Programme.

In this presentation we will provide an update of the main preparatory activities of the different working groups both on the science side and technological side. It will be an opportunity for the French community to count its forces and express interests for future implications and instrumental developments.

Keywords: Interferometry

1 Introduction

Owing to both ground- and space-based observatories, the characterization of exoplanets has seen tremendous progress in the past decades, establishing a large diversity in detected systems. However, the reachable sample is still limited by the performance of our instruments to reach the highest contrasts and sensitivity. So far it has mostly included hot and giant exoplanets, which are very different from the examples in our solar system.

A crucial leap forward in exploring the exoplanet population will be the characterization of the atmospheres of rocky and temperate planets. While the coming generation of giant ground-based telescopes could offer the characterization of a few targets around nearby dwarf stars (Bowens et al. 2021), the full characterization of a statistically significant sample will require the deployment of large space observatories.

In the US, the Astro2020 Decadal survey (National Academies of Sciences, Engineering, and Medicine 2021) recommended the maturation of a near-infrared-optical-uv high-contrast observatory dubbed Habitable Worlds Observatory (HWO), which would be optimized for the characterization of temperate rocky exoplanets in reflected light. The elaboration of this ambitious facility has started in earnest.

In Europe, the ESA Voyage 2050 Senior Committee report (Linda J. Tacconi et al. 2021) is advocating the need for a space mission enabling the characterization of temperate exoplanets in the mid-infrared as a top priority, as the radius and atmospheric temperature are key to infer on the possibility of surface liquid water. The spectroscopic signature of water vapor, ozone, methane and other key molecules can inform us about the current state and history of the atmosphere.

2 Ambitions of the LIFE space mission

The LIFE initiative seeks to develop the scientific context, the technology, and a roadmap for an ambitious mid-infrared space mission that investigates the atmospheric properties of a large sample of terrestrial exoplanets - including 30-50 orbiting within the habitable zone of their host stars.

With this, the LIFE mission is set to:

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- Investigate the diversity of planetary bodies
- Assess the habitability of terrestrial exoplanets
- Search for potential biosignatures in exoplanet atmospheres.

Compared to a visible-light mission like HWO, the targeting of similar systems at wavelengths roughly 10 times larger prompt the use of aperture dimension 10 times larger than the planned 6-meter HWO telescope. Thanks to interferometry, a 60-meter aperture does not have to be a single mirror. Indeed, LIFE will rely on a space-based formation-flying array of collector spacecrafts and an extra beam-combiner spacecraft. It will operate over a spectral range of 4-18.5 μm with a spectral resolution of $R \approx 100$ (all numbers to be confirmed). This configuration would allow baselines from 10s to 100s of meters that would satisfy the angular resolution part of the problem. In the regime of around $10\,\mu m$, which represents the peak thermal emission of an Earth-like planet, the required contrast would be around 10^7, which is three orders of magnitudes below a reflected light situation.

Again, in comparison to reflected light observations, the mid-infrared would give a unique perspective on the investigated exoplanets. It should:

- … directly constrain the pressure-temperature structure of exoplanet atmospheres (Alei et al. 2024)
- … access (multiple) atmospheric absorption bands of major molecules such as H_2O, CO_2, and CO as well as collision induced absorption from N_2 and O_2
- … search for numerous atmospheric biosignatures in the context of terrestrial exoplanets and gas dominated Super-Earths (e.g., O_3 and CH_4, but also N_2O, PH_3, NH_3, and C_5H_8)
- … constrain directly the effective temperature of exoplanets and provide access to their radii
- … deliver a higher detection yield during search phase as it is less affected by the orbital phase function of the exoplanets' emission compared to reflected light missions
- … immediately start observing already known small, temperate exoplanets around nearby M-stars.

3 Legacy and support

Space-based interferometry for the detection of exoplanets is not a new concept, and LIFE has been able to leverage the legacy of extensive works carried out by projects like the Terrestrial Planet Finder - Interferometer (TPF-I) (Martin et al. 2007, 2008) and the DARWIN (Cockell et al. 2008; Mugnier et al. 2006a,b; Hanot 2006) mission concepts carried out by NASA and ESA, respectively, until the mid 2000s. The context that led to the canceling of these projects has changed significantly in the past twenty years. On the astrophysical scene the results of ground-breaking missions such as Kepler (Borucki & Koch 2011; Dressing & Charbonneau 2015; Bryson et al. 2020, 2021) or TESS (Polanski et al. 2024), have brought a solid understanding of the expected populations of exoplanets that can be sampled by a characterization mission, which can enable the robust estimates of scientific yields for such an interferometer (Quanz et al. 2022; Carrión-González et al. 2023). On the technological side, the study of formation flying satellites has progressed, with the huge success of missions like LISA pathfinder (Vetrugno 2017; Armano et al. 2024b,a). And the soon coming Proba 3 (Capobianco et al. 2021) and the LISA mission (Mueller 2024; Colpi et al. 2024) are already paving the way to lift some of the most prominent mission risks.

Furthermore, the scene of beam-combiner designs has seen the introduction of new innovative beam-combiner designs which have enriched our understanding of high-contrast interferometric observations (Guyon et al. 2013; Martinache & Ireland 2018; Laugier et al. 2020; Hansen et al. 2022, 2023). The efforts are also now supported by the results from a range of ground-based projects, (past, current and coming) such as:

- Keck Nuller (N band, double-Bracewell) (Colavita et al. 2009; Serabyn et al. 2012)
- LBTI Nuller (N band, single Bracewell) (Hoffmann et al. 2014; Defrère et al. 2016; Ertel et al. 2018, 2020)
- GRAVITY (K band Off-axis classical interferometry) (Lacour et al. 2019)
- Asgard/NOTT (L band VLTI nulling) (Defrère et al. 2018, 2022; Laugier et al. 2023)

One of the simplest schemes envisioned is the use of four collectors in a stretched rectangular array feeding a double-Bracewell beam-combiner (Dannert et al. 2022). By taking the difference of the two output intensity most of the error terms cancel out and the signal obtained is sensitive only to asymmetries in the intensity distribution of the scene, which is favorable for detecting exoplanets with reduced sensitivity to symmetrical features such as exozodi. The internal phase modulation would allow to further ward against stability problems on the infrared detector.

4 Selection of recent LIFE publications

The ongoing series of LIFE papers has explored some of the potential aspects of the LIFE mission, both on an astrophysical and instrumental perspective. It has featured studies on the yield, both for the discovery of exoplanets on synthetic populations (Quanz et al. 2022) and on known exoplanets (Carrión-González et al. 2023). It has investigated the capability to characterize the composition of atmospheres (Konrad et al. 2022), including the detection of known biosignatures (Meadows 2017; Schwieterman et al. 2018), and technosignatures (Seager et al. 2023; Schwieterman et al. 2024).

The exploration and validation of the instrument concept have also been investigated with the development of instrument simulators such as LIFEsim (Dannert et al. 2022), the examination of new kernel-nuller architectures (Hansen et al. 2022, 2023), and the improvement of data reduction methods (Matsuo et al. 2023).

The team aims to establish a roadmap to reach the technical requirements in all of the technical expects of LIFE, including the following:

- Wavefront correction and control
    - Space-compatible AO and DMs
    - Non-common path errors and tuning from the science detector
    - High dimensional stability
    - Laser metrology system
- Broadband high contrast
    - Achromatic starlight suppression / phase shifting
    - Polarization control
    - Broadband spatial filtering
    - Balanced beamsplitters
    - Photonics beam-combiner
- Stray light and thermal background mitigation
    - Beam transportation / pupil matching
- Sensor technology
    - Low noise MIR detectors
- Formation flying
    - Efficient array slewing
    - Efficient UV coverage

A laboratory bench called NICE (Nulling Interferometry Cryogenic Experiment) is under construction at ETH Zurich to demonstrate the capabilities of nulling interferometry under realistic conditions of cryogenic vacuum. the capabilities of the observing method to reach the sensitivity required for the characterization of Earth-like exoplanets. These efforts are currently funded by the Swiss Space Office via the ESA Prodex program and the Swiss National Science Foundation.

Despite the recommendation by the senior committee (Linda J. Tacconi et al. 2021) to launch a detailed study to assess the feasibility of a mission like LIFE, until now only a modest study (250 k€) was funded by ESA as a TDE (technology development element) to evaluate the capabilities of a single spacecraft interferometric mission. ESA has not yet selected the LIFE concept.

The French community has shown world-class expertise in infrared interferometry, wavefront control and high-contrast observations and had a leading role in several historical space nulling mission concepts. As such, it has a potential to bring a lot to the LIFE initiative.

5 Conclusions

The LIFE space mission may be seen as a mid-infrared counterpart to HWO, but offering unique scientific capabilities. As such, it is designed to detect and characterize a sample of 30 to 50 rocky temperate exoplanets, investigating their atmospheric chemistry, diversity, and habitability. In this spectral regime, it will provide answers about properties that are not (or less) directly available in reflected light, such as radius and effective temperature of the exoplanets, as well as the signature of important molecules such as H_2O, CO_2, O_3, CH_4.

The search of biosignatures and our capability to exclude abiotic origins to them on distant exoplanets is more than ever a topic of debate. Completing our spectral coverage in characterizing these foreign worlds into the mid-infrared will be paramount in order to make a compelling case on the detection of extraterrestrial signatures of life. Due to the physical limitations of diffraction, the use of a large nulling interferometer appears as the only alternative to sending sixty meter telescope into space.

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