The LIFE Initiative
Scientific Prospects and Challenges

Characterization of exoplanet atmospheres in the mid-infrared - diversity, habitability, biosignatures

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The vision of the LIFE initiative
Understanding our place in the cosmos in the context of exoplanet and planetary science

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.

The LIFE mission will

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

Quanz et al. 2021 (Experimental Astronomy; 30, 1007/110686-021-09791-g)
Detecting and characterizing rocky exoplanets from space

Scientific synergies between different missions and ground-based instruments

- Reflected light (UV-NIR)
- Thermal emission (MIR)

Solar-type stars

M stars

Image credit: NASA, LIFE Initiative, ESO, TMT, GMT
The LIFE mission

- ...is a space-based formation-flying mid-infrared (nulling) interferometer
- ...consists of 4 collector spacecraft (tbc) separated by tens to hundreds of meters and a beam combiner
- ...covers the mid-infrared wavelength range between ~4-18.5 μm with a spectral resolution of R ~50 (tbc)

Artist impression of LIFE concept (credit: LIFE initiative)
The LIFE mission

- The wavelength range is chosen to cover the peak of the thermal emission of temperate terrestrial planets.
- This wavelength range features absorption bands of major molecular constituents including biosignatures such as ozone (O₃), methane (CH₄) and nitrous oxide (N₂O).

MIR spectra of terrestrial planets in our Solar System

Kaltenegger2017
Exoplanet characterization: the mid-infrared advantage

A mission like LIFE can...

- directly constrain the **pressure-temperature structure** of exoplanet atmospheres
- access (multiple) atmospheric absorption bands of **major molecules** such as H$_2$O, 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$_2$O, PH$_3$, NH$_3$, and C$_5$H$_8$)
- constrain directly the **effective temperature** of exoplanets and provide access to their radii
- secure 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 and include those in the final target list

cf. Line, Quanz et al. (2019; decadal White Paper)
LIFE: Exoplanet Detection Yield Estimates

- Expected detection yields are similar to large future NASA flagship concepts
- Monte Carlo simulations based on Kepler statistics (SAG13) and stars within ~20 pc
- Assuming
  - 2.5 years total search phase
  - 4 x 2m apertures
  - 5% total instrument throughput
  - 10 h slew between targets
  - 20% general overhead

Quanz et al. 2022 (arXiv210107500Q)
LIFE discovery space vs. JWST
LIFE discovery space vs. JWST
LIFE discovery space vs. known exoplanets within 10 pc

New LIFE paper by Oscar Carrion-Gonzalez in preparation
LARGE INTERFEROMETER FOR EXOPLANETS

Circumstellar Disks

AGNs

Star Formation & Stellar Clusters

Evolved Stars

...probing the terrestrial planet formation region

...resolving the dusty torus

...probing the innermost regions of dense clouds and cores

...revealing dust properties and distribution within their shells
The science of LIFE: challenges ahead

- LIFE’s impact on non-exoplanet science not quantified yet
- Different beam combination and/or signal modulation schemes are being looked at, but quantifying the impact on growing number of science cases remains to be done
- Implementation of instrumental noise terms and their impact on detection yield and other science cases is ongoing
- Quantitative science cases leveraging larger subsets of the population of detectable planets still missing
- Uncertainties in exoplanet statistics (Bryson et al. 2021) leads to large uncertainties in expected detection yield and hence science return
- How do we manage to find more (all?) good targets prior to launch?
Thank you
Detection yield of rocky planets around Sun-like stars

Revising the detection yield of the search phase based on Bryson et al. 2021

Assumption: 5% throughput

Assumption: 2-m aperture size
Comprehensive Habitability Studies

LIFE will enable comparative studies of potentially habitable environments.

Sample size needs to be large enough for null result to be significant and scientifically interesting.

Quanz et al. 2021 (Experimental Astronomy; 10.1007/s10686-021-09791-z)
The LIFE initiative in an international context

ESA Voyage 2050 Senior Committee report emphasizes importance of LIFE science case in the context of ESA Science Program:

“Therefore, 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.”

“This would give ESA and the European community the opportunity to solidify its leadership in the field of exoplanets, […]”

“Being the first to measure a spectrum of the direct thermal emission of a temperate exoplanet in the mid infrared would be an outstanding breakthrough that could lead to yet again another paradigm-shifting discovery.”

ESA Senior Committee Report (https://www.cosmos.esa.int/web/voyage-2050)
Fundamental planet parameter from single epoch

- Investigating rocky, HZ planets detected during search phase
- Signal is extracted from noisy time series and data is fitted with black-body
- Average error on
  - Temperature: $\sim 10\%$
  - Radius: $\sim 20\%$
  - Separation: $\sim 12\%$
LIFE: a unique opportunity for rocky exoplanet science

ESA Voyage 2050 European roadmap for future space exploration

- Calls are already closed
- No exoplanet mission candidate

- No call for proposals anytime soon
- We already had 3 F/M-class missions

F3–mission (~2037-2039)
F4–mission (~2040-2043)
M8–mission (~2045-2048)

F2–mission (~2030-2031)
M7–mission (~2037)

CHEOPS (2019)
Plato (2026)
JWST (2021)
Ariel (2029)

LIFE L5 (2043?)
The LIFE paper series is a growing success
Recent progress and ongoing efforts increase technological readiness

Major technological challenges for mid-infrared space-based interferometry are being tackled by various groups.

**Cryogenic nulling**

New mid-infrared testbench under construction at ETH Zurich to demonstrate interferometric nulling under realistic conditions.

**Photonics**

Major breakthroughs in astrophotonics for interferometric nulling at near-infrared wavelengths motivate mid-infrared applications as next step.

**Low-noise detectors**

MKIDs (Microwave Kinetic Inductance Detectors) show excellent performance at sub-mm and near-infrared wavelengths and close in on mid-infrared regime.

**Autonomous formation flying**

Various space missions aim to demonstrate high precision formation flying performance in the coming years including ESA’s Proba3.

Credit: Pieter de Visser / SRON
Credit: Covelojevic et al. 2022
Credit: ETH Zurich
Credit: ESA