# Research Summary

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**About me -** My name is Eleonora Alei. I am a Post-Doctoral Fellow within the Exoplanets and Habitability group, led by Prof. Quanz, in the Institute of Particle Physics and Astrophysics at ETH Zurich.
My academic career has heavily leaned towards the topic of the habitability of terrestrial exoplanets. I believe it to be one of the most interesting yet challenging milestones to reach in the future.
During my Ph.D. at the University of Padua, Italy (in partnership with the INAF Observatory of Padua), I worked on atmospheric modeling of terrestrial exoplanets, developing various models and running hundreds of thousands of simulations. I also worked with biologists and engineers to build an experimental setup to simulate exotic atmospheres in the laboratory, studying how photosynthetic bacteria would adapt to alien conditions.
I am currently leading the atmospheric modeling team within the Exoplanet and Habitability Group at ETH Zurich. My main project is to develop an atmospheric retrieval framework, which will be used to determine the technical requirements of the *LIFE* mission. *LIFE* (Large Interferometer For Exoplanets) is a proposed mid-infrared space interferometer that will focus on detecting and characterizing habitable exoplanets through direct imaging. Performing atmospheric retrieval runs on simulated data is essential now more than ever, to make sure that the instrument is built in the best way possible, to correctly characterize exoplanets and potentially find signs of life in the universe.

## Context

The search for exoplanets (i.e. planets that orbit other stars in our Galaxy other than the Sun) has been growing as a bold branch of astrophysics for the past two decades, with more than 5000 confirmed exoplanets known to date. Surveys and missions reveal day by day new candidates and provide us insight concerning their orbital and bulk parameters, and the properties of their host stars. We are now aware of the fact that exoplanets differ from one another in many of these physical parameters. Soon, we should be able to fully understand the diversity of their chemical compositions, atmospheric processes, internal structures, and formation conditions [Madhusudhan et al., 2014]. One of the most interesting milestones for the study of exoplanets is to understand under which conditions life could appear and survive in other environments. We mean "life" in a terrestrial sense: to be able to bear any form of life, "environments must provide extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy resources to sustain metabolism" (NASA Astrobiology Roadmap, Goal 1).

To detect and characterize an exoplanet, we must rely on remote observations, based on both time-varying and spatially resolved signals [see e.g. Tinetti et al., 2013, for more details]. To the first category belong two of the most successful techniques: transit detection – measuring the periodic dimming of the stellar luminosity caused by the transit of a planet between the star and the observer, and the measurement of radial velocities – caused by the motion of the star around the center of mass of the star-exoplanet system. The latter category relies on directly measuring the emitted or reflected light from the planet, through high contrast imaging or interferometry. These techniques can be paired with spectroscopy to get atmospheric spectra of exoplanets, from which it is possible to gather information about the atmospheric composition and dynamics. In the context of habitability, we are particularly interested in a few atmospheric species (such as $O_2$ and its photochemical product $O_3$, $CH_4$, and $N_2O$) whose presence in the atmosphere could be justified by biological activity. These are commonly known as "biosignature" gases. Molecular oxygen could be a tracer of a potential biosphere since it is a direct product of life. Nevertheless, it can be also generated non-biologically in several ways such as the photodissociation of water vapor in the stratosphere: therefore, $O_2$ alone could not assure the presence of life on the observed planet. Simultaneous detection of $CH_4$ and $O_2$ (or $O_3$) in the atmosphere could provide instead a convincing indication of biological activity [see Lovelock, 1965, Lederberg, 1965].

## Past Work

My Ph.D. project was focused on Super Earths, rocky planets whose mass is within 1-10 Earth masses, and whose radius is within 0.8-2 Earth radii. During this time, I worked on both theoretical modeling and laboratory experiments.

I wrote `Exo-MerCat` [Alei et al., 2020], a Python script that collects and selects the most precise measurements for all interesting planetary and orbital parameters of all exoplanets included in the four major online databases:

NASA Exoplanet Archive[1], Exoplanet Orbit Database[2], Exoplanet Encyclopaedia[3], and Open Exoplanet Catalogue[4]. This software provides an additional source of all the available exoplanetary data in a uniform format that follows the IVOA (International Virtual Observatory Alliance) standard. For this reason, it is currently being used to define the input catalog of targets to be observed by the upcoming missions such as *PLATO* [Montalto et al., 2021]. It is accessible by the community either through the Virtual Observatory service, or a Graphical User Interface.

Furthermore, I was one of the main developers of a 1D radiative transfer structural model with convective adjustment, written in FORTRAN with an MPI parallelization. The model can calculate a self-consistent atmospheric profile at thermal equilibrium given an initial atmospheric composition. The advantage of 1D models compared to more complex ones is the speed of computation that allows to cover a wide parameter space in reasonable computing times. Among the thousands of simulations we ran, a subset of 6250 dry synthetic atmospheres at varying composition and irradiation were published and analyzed in Petralia et al. [2020].

My theoretical work was also useful for the "Atmosphere in a Test Tube" (ATM_ITT) project (see Claudi et al. [2021], Battistuzzi et al. [2020]), a collaboration among biologists, astronomers and engineers. The main goals of the ATM_ITT project were: (1) to build an environmental chamber and a stellar light simulator, (2) to reproduce potential atmospheres of warm Earths and Super Earths orbiting M stars, and (3) to expose cyanobacteria to the exotic environment to study their survivability. In this context, the results of my models defined how to alter the environment in the chamber. I was also responsible for the calibration of the stellar light simulator.

## Current Work

The identification of spectral features of terrestrial exoplanets is limited by the extremely low intensity of their signal, which requires higher sensitivity. Still, the characterization of these targets is one of the main goals of the major space agencies (see the ESA "Voyage 2050" process[5], as well as the US Astro 2020 Decadal survey [National Academies of Sciences, Engineering, and Medicine]). Space missions that aim at characterizing terrestrial exoplanets have been proposed, such as *HabEx* [Gaudi et al., 2020] and *LUVOIR* [Peterson et al., 2017]


**Figure 1:** *Artist impression of* LIFE. *Credits: https://www.life-space-mission.com*

focusing on the reflected (visible and near-infrared) portion of the planetary spectrum, as well as *LIFE* [Large Interferometer for Exoplanets, Quanz et al., 2021, i.e. *LIFE* Paper I], which will characterize terrestrial planets in the thermal (mid-infrared), emitted portion of the planetary spectrum. Using a formation of four aperture telescopes (diameter of 2-3.5 m each, see Figure 1) and a combiner telescope to perform nulling interferometry, *LIFE* will allow us to constrain the radius and effective temperature of (terrestrial) exoplanets, as well as provide unique information about their atmospheric structure and composition.

I am leading the subgroup for atmospheric modeling within the Exoplanets and Habitability Group[6] at ETH Zurich. In addition to supervising semester, Master's, and Ph.D. students in projects involving atmospheric modeling in the context of *LIFE*, my main task is to build and develop the atmospheric Bayesian framework to perform atmospheric retrievals for the *LIFE* mission. At this stage of the mission development, atmospheric modeling and retrieval studies are essential to determine the technical requirements for *LIFE*. These studies allow us to determine the resolution ($R=\frac{\Delta\lambda}{\lambda}$), the signal-to-noise ratio (S/N), and the wavelength range of interest for the instrument so that it can be built to achieve the ambitious goal of finding life in the universe.

Retrieval analyses have been widely used in the community to characterize exoplanetary atmospheres [see e.g. Mollière et al., 2017]. Bayesian retrieval frameworks are based on two main routines: (1) the "forward model", a theoretical spectral model that can produce synthetic spectra given a set of parameters; (2) the "parameter estimation module" which applies Bayesian inference to identify the best combination(s) of parameters that, if fed into the forward model, can reasonably reproduce

[1] https://exoplanetarchive.ipac.caltech.edu
[2] http://exoplanets.org
[3] http://exoplanet.eu
[4] http://www.openexoplanetcatalogue.com
[5] https://www.cosmos.esa.int/web/voyage-2050
[6] https://quanz-group.ethz.ch/

the observed spectrum. In our case, since there are no actual observed spectra of terrestrial exoplanets at our disposal, we calculate "mock observed spectra". Starting from synthetic spectra produced by various theoretical spectral models, we simulate a *LIFE*-like observation by using its simulator LIFEsim [Dannert et al., 2022, i.e. *LIFE* Paper II]. We then perform a retrieval on the observed spectra using the theoretical spectral model `petitRADTRANS` [Mollière et al., 2019] as forward model in the retrieval routine, and the Bayesian sampler model `pyMultiNest` [Buchner et al., 2014] as parameter estimation routine.

Since `petitRADTRANS` is a model built primarily for hot Jovian planets, it needed to be updated and adapted to correctly simulate the atmospheres of rocky temperate planets, much different in terms of bulk parameters, pressure-temperature regime, and atmospheric composition. Strongly collaborating with Dr. Paul Mollière, the head developer of `petitRADTRANS`, I updated the scattering and the collision-induced absorption treatments. I also added more molecules to the opacity database. These updates extended enormously the flexibility and the range of validity of the model.

The Bayesian framework was validated with an Earth twin by the former Master's student Björn Konrad, now a Ph.D. student in our group, whom I supervised. We considered a cloud-free Earth twin around a Sun-like star located at a distance of 10 pc from the observer. We performed retrievals for all combinations of R (20, 35, 50, 100), S/N (5, 10, 15, 20) and wavelength range (3 - 20 $\mu$m, 4 - 18.5 $\mu$m, 6 - 17 $\mu$m). We determined that a wavelength coverage of 4 - 18.5 $\mu$m, an R of 50, and an S/N of 10 are the minimum requirements for *LIFE* to detect the $CH_4$ in an atmosphere of an Earth twin planet. This work was recently accepted for publication in Astronomy & Astrophysics [Konrad et al., 2022, i.e. *LIFE* Paper III].

I then performed retrievals on the spectra of the Earth in time (Alei et al., i.e. *LIFE* Paper V, submitted to Astronomy & Astrophysics). I considered simulated spectra of the Earth at various stages of its evolution calculated by Rugheimer and Kaltenegger [2018]: a prebiotic Earth (at 3.9 billion years ago, or Ga), the Earth after the Great Oxygenation Event at 2.0 Ga, and after the Neoproterozoic Oxygenation Event at 0.8 Ga, and the modern Earth. These epochs represent the main changes in the composition of Earth's atmosphere, due to the appearance of life. This allowed me to study the robustness of the Bayesian framework when branching out of the modern Earth scenario while still in the realm of habitable (and inhabited) exoplanets. Assuming the minimum *LIFE* requirements found in *LIFE* Paper III (R=50, S/N=10, between 4 and 18.5 $\mu$m), I confirmed

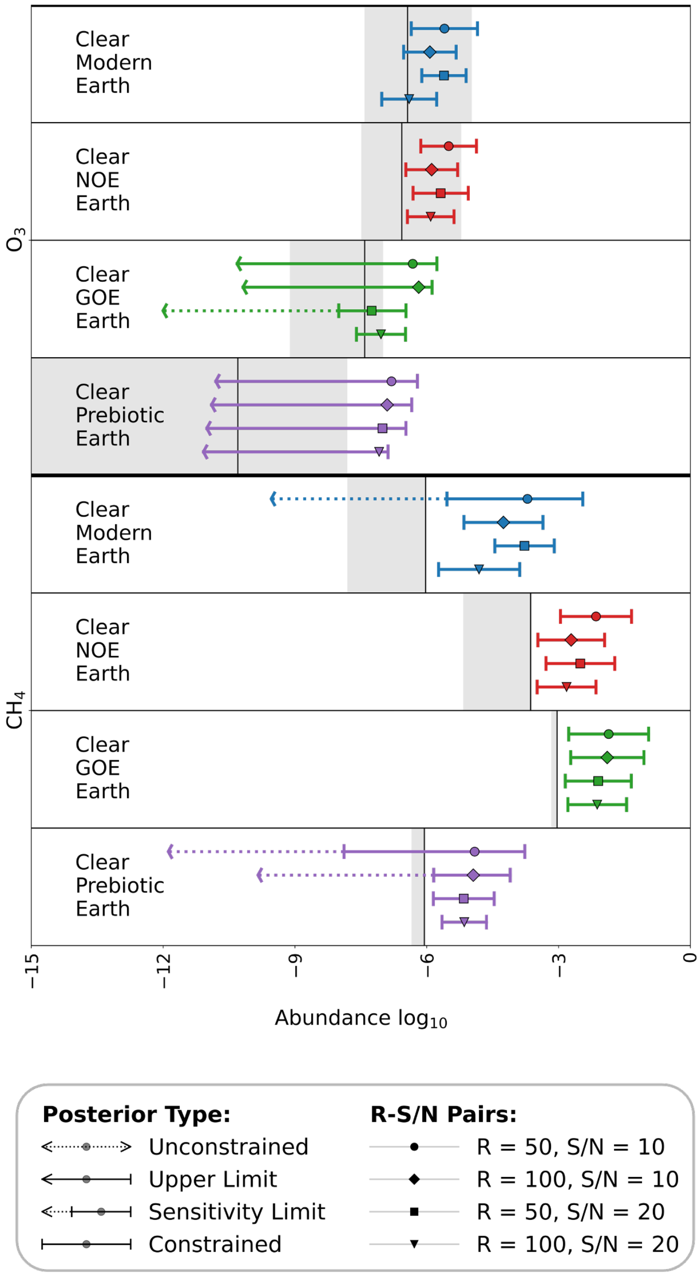


**Figure 2:** *Retrieved atmospheric abundances of $O_3$ and $CH_4$ assuming different combinations of R and S/N. The solid lines and gray areas indicate the expected values and their uncertainties for each species (Alei et al., LIFE Paper V, subm.).*

that these requirements allow the identification of the main spectral features of all the analyzed spectra. In particular (see Figure 2), *LIFE* could be able to detect $O_3$ in the atmosphere if $O_2$ represents at least 2% of the atmosphere (assuming a ground pressure of 1 bar). $CH_4$ could be constrained in terrestrial atmospheres if its abundance is around $\sim$0.1% of the atmosphere.

In other words, *LIFE* were to observe the Earth at various stages of its evolution orbiting the Sun at a 10 pc distance, it would be able to detect strong indicators of life starting from around 0.8 Ga (after the Neoproterozoic Oxygenation Event) in Earth's evolution. *LIFE* could gather tentative detections of potential biological activity even on earlier epochs (such as an Earth after the Great Oxygenation Event, at 2.0 Ga). Interestingly, this is in agreement with other studies based on a different wavelength range and other mission concepts [Kawashima and Rugheimer, 2019].

Increasing the sensitivity of the instrument, by doubling R and/or S/N, would allow for more precise results (see Figure 2). Doubling the S/N would be convenient, since it would allow us to observe the most promising targets for longer integration times, without altering the instrument architecture. Such results are extremely relevant in terms of the mission planning, and the detection of biosignatures in the atmospheres of habitable exoplanets.

The atmospheric modeling subgroup that I lead is the nexus of all the retrieval work that is currently being performed by the *LIFE* initiative. Other ongoing and future projects are:

1. The implementation of a cloud treatment in the retrieval framework and retrieval of *LIFE* simulated observations of Venus-twins (Konrad, Ph.D. thesis, supervised by Alei and Quanz);

2. Atmospheric retrievals of visible and infrared data, assuming to observe a target with both *HabEx*/*LUVOIR* and *LIFE* (Alei, in collaboration with Tyler Robinson @ NAU, Scott Gaudi @ OSU);

3. Atmospheric retrievals as a tool to detect ocean worlds (LIFE Initiative WG 2.1, "Habitability" sub-WG);

4. Inter-model comparison of various radiative transfer and retrieval models (Alei, within the NASA Nexus for Exoplanet System Science (NExSS) CUISINES WG);

5. Machine Learning techniques to improve the accuracy and computing speed of atmospheric retrievals (Gebhard, Ph.D. thesis, collaboration).

The search for other life forms is one of the most profound tasks of humankind. To be able to do this, experts from different fields (astronomy, biology, geology, chemistry, engineering) need to collaborate and find innovative ways of thinking. Given the vastness of this inquiry, I am excited to do my part in this worldwide effort. Hopefully, during my career, we will get to find an answer to the most fascinating question: is there life in the universe?

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