Atmospheric Retrieval of Terrestrial Solar System Planets for LIFE

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LIFE can detect the potential biosignature CH_4 in an Earth-twin atmosphere.

LIFE can accurately measure the albedo, radius, and CO_2 abundance of a Venus-twin.

Earth-Twin Retrievals for LIFE

Konrad et al. [1]

Link to Paper

We run Bayesian atmospheric retrievals for mock observations with LIFE of the mid-infrared (MIR) thermal emission spectrum of a cloud-free Earth-twin exoplanet at 10 pc. The mock observations are generated with LIFEsim [2], which accounts for all major astrophysical noise sources. We investigate how well we can constrain the atmospheric properties of an Earth-twin in retrievals of spectra of different quality.

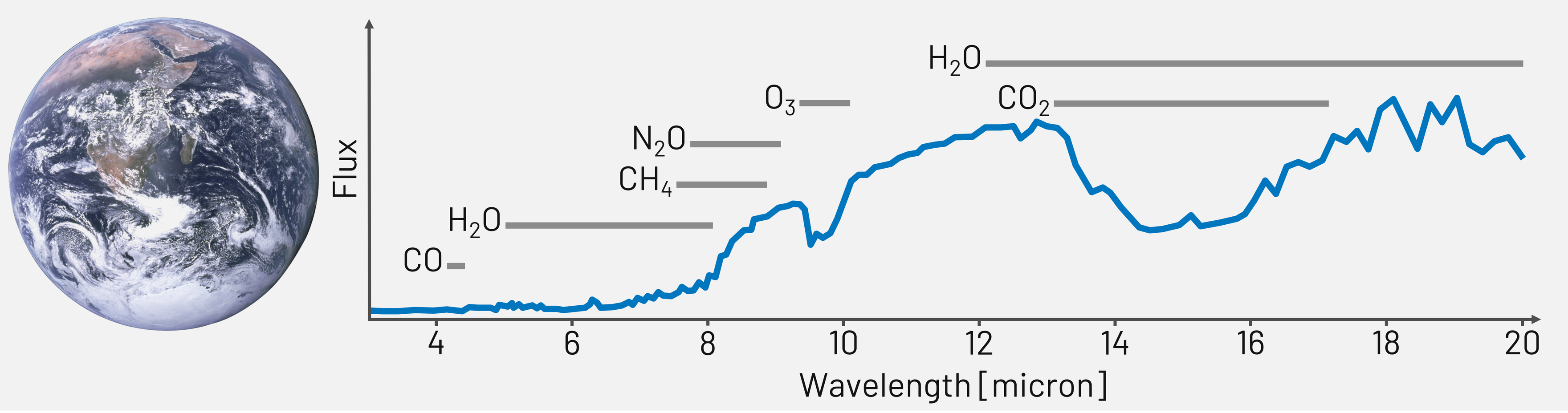
The quality of a spectrum depends on three factors:

- Spectral resolution (R),
- LIFEsim noise level (S/N),
- Wavelength coverage.

Our Earth-twin spectra account for:

- Line features from gases (see Figure 1),
- Collision induced absorption (N_2-N_2, N_2-O_2, O_2-O_2).

Figure 1: Simulated MIR Earth spectrum. We indicate the most relevant absorption bands of all considered atmospheric gases.



Venus-Twin Retrievals for LIFE

Konrad et al. (in prep.)

Similar to the Earth-twin, we run retrievals for mock observations of a Venus-twin with LIFE. To accurately model Venus' MIR spectrum, the sulfuric acid (H_2SO_4) clouds must be taken into account. We use LIFEsim to generate the mock observations of a Venus-twin at 10 pc.

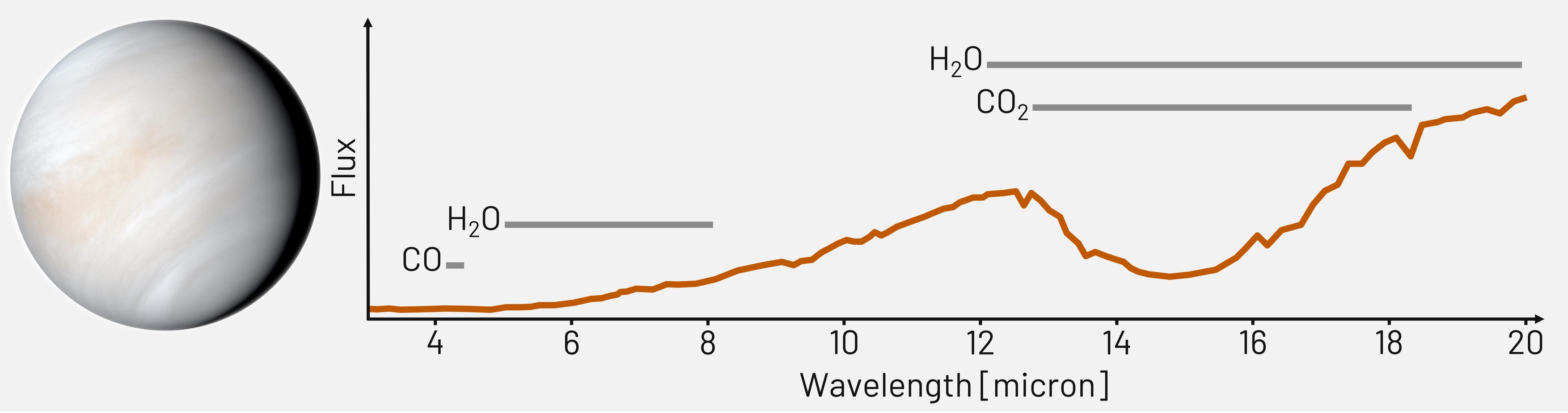
By running retrievals assuming a cloud-free or cloudy atmosphere, we investigate how the quality of a spectrum and clouds impact retrieval results. We investigate:

- if clouds are detectable in the MIR,
- how clouds impact the retrieval,
- if the R and S/N found for the Earth-twin are sufficient for the Venus-twin.

Our Venus-twin spectra account for:

- Line features from gases (see Figure 2),
- Collision induced absorption (CO_2-CO_2),
- Opaque H_2SO_4 clouds.

Figure 2: Simulated MIR Venus spectrum. We indicate the most relevant absorption bands of all considered atmospheric gases.



Earth-Twin Results

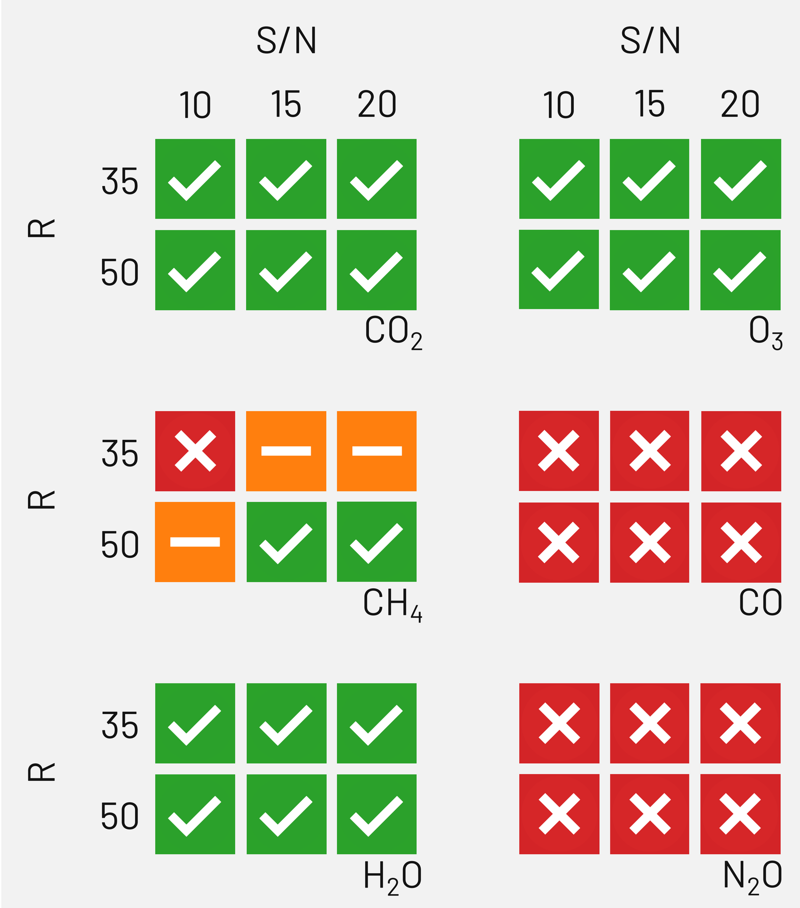
Independent of the spectral quality, most of the fundamental planet parameters are constrainable via MIR LIFE observations:

- ✅ Planet radius (uncertainty $< \pm 0.1 R_\oplus$)
- ✅ Surface temperature (uncertainty $< \pm 20$ K)
- ✅ Surface pressure (uncertainty $< \pm 0.5$ dex)

The abundances of Earth's main atmospheric gases N_2 and O_2 are not retrieved due to them a lacking MIR spectral features. However, we can infer the presence of a ≈ 1 bar atmosphere, of which the bulk is transparent in the MIR. For trace gases (see Figure 3), we observe the following:

1. **For most gases:** our results show no strong dependence on the spectral quality.
2. **For CH_4:** our results improve significantly with increasing spectral quality.

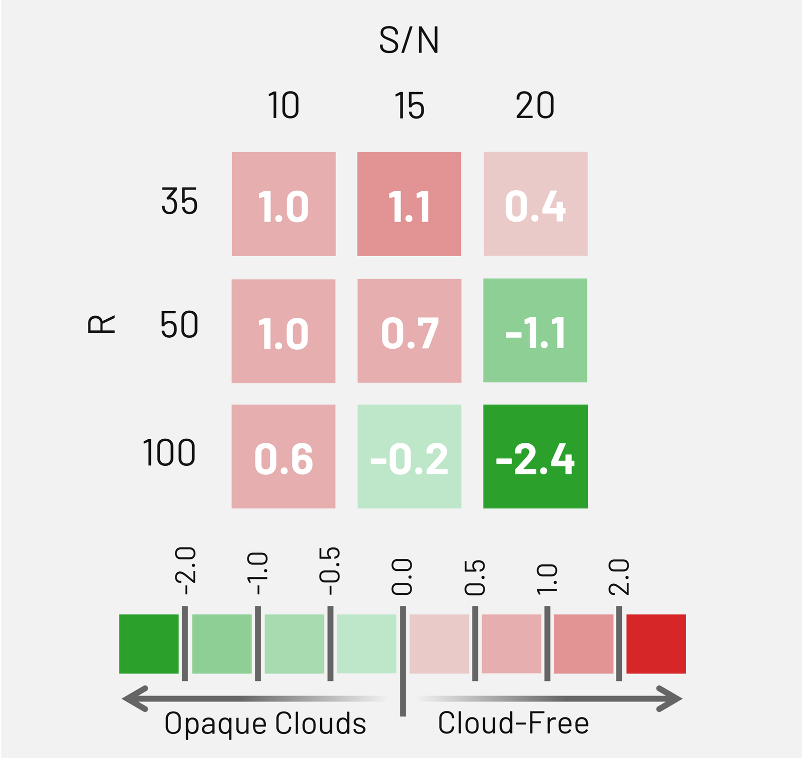
Figure 3: Retrieval results for trace gases at different R and S/N LIFE mock observations. ✅: Constrained abundance (uncertainty $< \pm 1.0$ dex); 🟠: constrained but cannot exclude lower abundances; ❌: unconstrained abundance.



A more detailed analysis of our results reveals that an **R of at least 50** and **an S/N of at least 10** is required to detect CH_4 in the atmosphere of an Earth-twin exoplanet.

Venus-Twin Results

Figure 4: Retrieval performance of atmosphere models (opaque H_2SO_4 clouds & cloud-free) Venus' MIR spectrum. For positive values (red) the cloud-free model performed better. Negative values (green) favour the cloudy model.



Our results for planet parameters and atmospheric gas abundances do not depend on the spectral quality. This is true for both retrievals using the cloud-free and cloudy models:

- ✅ Planet radius (uncertainty $< \pm 0.1 R_\oplus$)
- ✅ CO_2 (uncertainty $< \pm 1.0$ dex)
- ✅ Bond albedo
- ❌ Surface temperature/pressure (cloud-free: retrieved values correspond to the cloud top), H_2O, CO

Since both models fit the observation well, we test if the cloudy model is preferred by our retrieval via the Bayes' factor. In Figure 4, we plot the Bayes' factor for different input qualities. We identify two regimes:

1. **Low quality spectra:** Both models fit equally well. The cloud-free model is preferred, because it has less parameters. The information content of these spectra is too low to justify the additional parameters of the cloudy model. Thus, we **cannot infer clouds**.
2. **High quality spectra:** The cloudy model fits better. Thus, we **can infer clouds**.

Background – Atmospheric Retrieval Routine

An atmospheric retrieval fits a parametric model for the exoplanet's emission spectrum to the observed spectrum. Our Bayesian retrieval routine is based on two subroutines:

1. **petitRADTRANS [3]:** 1D radiative transfer code to calculate the emission spectrum corresponding to an atmosphere described by a set of parameters.
2. **pyMultiNest [4]:** Bayesian parameter estimation with MultiNest [5], an implementation of Nested Sampling [6]. Searches parameter space to find the combination of parameters that best models the observed spectrum and provides Bayesian uncertainties for these parameter values.

In **both studies** our atmospheric model assumes:

- atmosphere consisting of 100 layers,
- each layer in radiative equilibrium,
- temperature and pressure of each layer are defined via a pressure-temperature profile (fourth order polynomial),
- constant vertical mixing ratio for all gases.

In the **Venus-twin study** our cloud model assumes:

- a single cloud layer defined by the cloud-top pressure and the cloud thickness,
- cloud opacity approximation via Mie scattering by a 84% H_2SO_4, 16% H_2O solution,
- the particles follow a log-normal size distribution defined by the mean particle size and the standard deviation.

Background – LIFE (Large Interferometer For Exoplanets)

We aim to characterize the atmospheres of terrestrial exoplanets, assess their habitability, and search for signs of life in their spectra. To achieve this goal, large direct-imaging space-missions are required. The LUVOIR [7] and HabEx [8] mission concepts were proposed to NASA. Both missions aim to directly measure the stellar light reflected by the exoplanet in the visible (VIS) and near-infrared (NIR) range.

The LIFE interferometer [see talk by Sascha P. Quanz; 9] aims to directly measure the thermal emission of a large sample of terrestrial exoplanets in the MIR. Such measurements can only be realized with a large, space-based nulling interferometer. The LIFE initiative is working toward the launch of such an instrument [see additional LIFE-related poster contributions: Alei+, Dannert+, Kammerer+].

LIFE will probe the MIR wavelength range instead of the NIR/VIS range because more atmospheric gases have strong absorption features in the MIR. This allows for a better assessment of the atmospheric structure and composition [10, 11]. Further, emission spectra provide a stronger constraint on the planetary radius. Finally, the MIR provides access to a large variety of biosignatures (detectable spectral features produced by biotic processes). An example of a biosignature is the simultaneous presence of large amounts of O_3 and CH_4 [12], which are both detectable in the MIR.

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