Biosignatures: What can we measure now and in the near future?

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What can we measure?

- Which targets?

- What can be detected?
Known exoplanets

- ~2000 exoplanets known
- ~7000 planet candidates/validated
- Different types of planets:
  - hot-Jupiters
  - mini-Neptunes
  - super-Earths
Planet diversity

Super-Earths: \( R_p \leq 3 \text{ R}_{\text{Earth}}; M_p \leq 10 \text{ M}_{\text{Earth}} \)

→ Dashed lines: planets of different compositions.

Low-mass gas planets need to be disentangled from rocky planets. Indicators:
- Mean density (radius, mass)
- Atmosphere composition (\( \text{H}_2/\text{He}- \)dominated versus heavy elements)
- but: degeneracies remain.

→ Diversity of small planets is large and not well constrained.
Values for $\eta$-Earth

$\eta$ Earth: The fraction of stars hosting Earth-like planets in their habitable zone is not well known.

A non-comprehensive list from Kepler and radial velocity surveys:

<table>
<thead>
<tr>
<th>reference</th>
<th>planet frequency</th>
<th>host stellar type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaidos (2013) ApJ, 770, 90</td>
<td>31%-64% (46%)</td>
<td>dwarf stars</td>
</tr>
<tr>
<td>Bonfils et al. (2013) A&amp;A, 549, A109</td>
<td>28%-95% (41%)</td>
<td>M stars</td>
</tr>
<tr>
<td>Kopparapu (2013) ApJ, 767, 8</td>
<td>24%-60% (48%)</td>
<td>M stars</td>
</tr>
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</table>

Batalha et al., 2014 7 – 22% Sun-like stars

The fraction of (super)-Earths in the habitable zone of stars is not well known.
How many targets for biosignature spectroscopy?

Leger et al. (2015) (also: Stark et al. 2014)

Number of planets observable with a 2.4m coronograph (left) and a 4x0.75m interferometer (right) in a 5 year mission based on exposure time calculator.

→ The number of available targets for biosignature spectroscopy in the near future will be small → **need larger aperture**
→ M dwarf planets are less suited for coronographs, but good targets for interferometry
Target providers in near future

- RV searches
- high-resolution imaging
Planet Transits - detection status

Kepler:
- >~7000 KOIs --> radii
- ~1000 confirmed planets
- ~75 planets have RV masses

K2:
- >10 planets with RV masses

CoRoT:
- 32 planets with RV masses

Ground-based:
- >~240 planets with RV masses

Total: ~400 planets with radii & RV masses + planets with masses from TTVs

(numbers from spring 2016)
Targets from transit detection missions

- **K-2 (Kepler cont.)**
  - NASA
  - Fields in ecliptic plane for ~80 days/field
  - 95 cm aperture, Earth trailing
  - 7 – 17 mag

- **CHEOPS**
  - ESA, launch 2018
  - 30 cm aperture, Earth orbit
  - 6 - 12 mag

- **TESS**
  - NASA, launch 2017
  - Scan the whole sky, ~1 month/field,
  - ~2% of sky at poles for 1 year
  - 10 cm aperture, 4 telescopes, Earth-Moon orbit
  - 4 – 13 mag

- **PLATO**
  - ESA, launch 2025
  - 2 long fields (2-3 years/field)+ step-and-stare
  - 12 cm aperture, 28+2 telescopes, L2 orbit
Known small planets
super-Earths with known mean density

![Graph showing habitable zone](image-url)
super-Earths with known mean density

K2, TESS single transit detections, TESS continuous viewing zone
super-Earths with known mean density

TESS, CHEOPS, K2, ground-based

PLATO 2.0

PLATO: discover and characterize terrestrial planets around solar-like stars → including the habitable zone! (Rauer et al. 2014)
Targets from direct imaging

- Number increasing.

- Today: Focused on bright planets with relatively large separation to host star, young objects.

  → Gas giant planets, young planets, mini-Neptunes accessible today.

  → Future: coronography, interferometry for terrestrial planets in HZ.
How to select your target for biosignature search?

- **Point „blind“**: point at any star, assuming it will have a planet in the HZ \(\rightarrow\) needs combined search+characterization instrument; technique: direct imaging; difficult and costly, but probably needed for nearby Earth’s around Sun’s.

- **Point „semi-blind“**: point at any detected small (from transits) or light (from RV) or directly imaged planet in the HZ \(\rightarrow\) Not preferred if observing time „expensive“.

- **First characterize** detected planets to secure rocky nature (radius+mass), then detect main atmospheric species + molecules relevant for habitability (e.g. water, CO\(_2\)) \(\rightarrow\) prior characterization to biosignature search; carefully selected targets.

- **Techniques**: Transiting planets \(\rightarrow\) Direct imaging
# Time line for terrestrial planet characterization

<table>
<thead>
<tr>
<th>Time</th>
<th>Mission/Instrument</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to ~2025:</td>
<td>TESS: constrain ( \eta )-Earth for M dwarfs, provides bright targets for transit spectroscopy</td>
<td>mean density, albedo, phase curves</td>
</tr>
<tr>
<td></td>
<td>Ground-based: (e.g. Mearth (transit), CARMENES (RV) – target M dwarfs)</td>
<td>radii, or masses</td>
</tr>
<tr>
<td></td>
<td>Direct imaging: mini-Neptunes, large super-Earths, not HZ</td>
<td>Atmosphere spectroscopy</td>
</tr>
<tr>
<td></td>
<td>JWST</td>
<td>Atmosphere spectroscopy</td>
</tr>
<tr>
<td>2025 – 2035:</td>
<td>PLATO: constrain ( \eta )-Earth around solar-like stars, provides bright targets for transit spectroscopy</td>
<td>mean density, ages, albedo, phase curves</td>
</tr>
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<td></td>
<td>WFIRST, ELTs</td>
<td>Atmosphere spectroscopy</td>
</tr>
<tr>
<td>&gt; 2030:</td>
<td>large spectroscopy mission...</td>
<td>Atmosphere spectroscopy, biosignatures of HZ planets around solar-like stars</td>
</tr>
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</table>
What transit spectroscopy can provide today:

- **e.g.**: Atmospheres in gas giants

  - Rayleigh slopes → clouds
  - Na, K
  - H$_2$O, CO, CO$_2$, CH$_4$...
  - Hydrogen → indications of evaporating atmospheres

Sing et al. 2016
## What biosignatures to look for?

<table>
<thead>
<tr>
<th>Species</th>
<th>Biotic Source</th>
<th>Abiotic Source</th>
<th>Wavelengths</th>
</tr>
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<tbody>
<tr>
<td><strong>Indicators for potential habitability</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O</td>
<td>none; required for life</td>
<td>outgassing, impacts</td>
<td>near-IR – thermal IR</td>
</tr>
<tr>
<td>CO₂</td>
<td>outgassing</td>
<td></td>
<td>near-IR – 15µm</td>
</tr>
<tr>
<td><strong>biosignatures/bioindicator (non-exhaustive list)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen (O₂) (Ozone (O₃))</td>
<td>Cyanobacteria (Burial)</td>
<td>CO₂+hv H₂O+hv</td>
<td>0.78µm, 1.3µm (O₂)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.8 µm, 9.6µm (O₃)</td>
</tr>
<tr>
<td>Nitrous Oxide (N₂O)</td>
<td>(De)nitrifying Bacteria</td>
<td>Photochemistry</td>
<td>4.5µm, 7.8µm, 17µm</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>Methanogens</td>
<td>Outgassing</td>
<td>1.7µm, 2.3µm, 3.4µm, 7.8µm</td>
</tr>
<tr>
<td>Chloromethane (CH₃Cl)</td>
<td>Seaweed</td>
<td>Photochemistry</td>
<td>3.3µm, 13µm</td>
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Earth as an "exoplanet"

The spectrum of Earth observed during lunar eclipse:

Observed transmission spectrum:

Blue: reflection spectrum:

Absorption bands from:
- $O_2$ and $O_3$
- $H_2O$
- $CO_2$
- $CH_4$
- Rayleigh scattering

$\rightarrow$ This is what we would like to have for exoplanet XYZ!

Pallé et al. 2009
Detection of a planetary atmosphere during transit (transmission) with HST and JWST

→ Upcoming JWST mission provides an order of magnitude better detection capability.
An example: An „Earth“ orbiting a G2V star at 10pc

Hedelt et al. (2013)

Assumptions:
- 1D coupled climate-photochemical model.
- Modern Earth atmosphere.
- Cloud free atmosphere.
- 1 year orbital period.
- Only photon noise considered.

Filter bandpasses of JWST (MIRI (5-27.5 µm) and NIRCam (0.6-5 µm)) used for SNR calculations.
An example: An „Earth“ orbiting a G2V star at 10pc

Signal-to-Noise ratios for JWST and E-ELT

H2O, CO2
CH4
O3
CO2

Caution: assumes idealized conditions and a transiting planet around G type star at 10 pc
But: near-IR with JWST and E-ELT can provide detections for very nearby Earths (tbc).

SNR: integrated in NIRCam and MIRI filter bandpasses for JWST and same bandpasses for E-ELT for comparison of performances.

• Near-IR (and optical) wavelengths range more suitable for primary transit spectroscopy.

• But: For ground-based telescopes telluric lines are a problem.
The ground: E-ELT and high-resolution spectroscopy

3.8σ detection possible from 30 transits with HIRES@E-ELT.

With 3 transits/year and a typical site: O₂ can be detected in a decade for a terrestrial planet orbiting an M dwarf.

Oxygen from ground by high-resolution transit spectroscopy:

- Earth difficult (signal factor 2-3 lower than for hot Jupiter, transit occurrence)
- M dwarfs stars within reach!

HIRES: $R \approx 100,000$ 0.37-2.5 μm

(Maiolino et al. HIRES Science Case)

Snellen et al. 2013
Another example: An „Earth“ orbiting a star at 3pc
- Observations with 10m space telescope

Detections achievable for „Earth“ during primary transit.

Irwin et al. (2014)
A recent example

• The TRAPPIST 1b-d system (Gillon et al. 2016):

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<td>1.510 848 ± 0.000 019</td>
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<td>1c</td>
<td>1.049 ± 0.050</td>
<td>2.421 848 ± 0.000 028</td>
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<tr>
<td>1d</td>
<td>1.168 ± 0.068</td>
<td>4.551–72.820 (18.202 most likely)</td>
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• The host star:
  • Cool M dwarf (M8)
  • Distance: 12 pc

• Planetary mass unknown.

De Wit et al. 2016, HST observations
A recent example

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- Planetary mass unkown.

- The host star:
  - Cool M dwarf (M8)
  - Distance: 12 pc

- What if 1d were an „Earth“?
  - Assume Earth-like atmosphere
  - Compute spectra with JWST (NIRSPEC and MIRI) (Barstow&Irwin 2016)

$\Rightarrow$ $O_3$ could be detected around 1d in 30 transits
Planets orbiting M dwarf stars experience a different environment compared to solar-like stars:

- Stellar spectral energy distribution shifted to IR
- Depending on stellar activity:
  - higher UV flux
  - higher stellar cosmic ray flux

\[ \rightarrow \text{Can affect the detectability of atmospheric biosignatures} \]

Segura et al 2005
„Earth“ around different types of quiet M dwarfs

Place Earth in HZ, of M dwarfs calculate photochemical response and spectra.

- $N_2O$ can be a good biosignature for planets around M dwarfs (e.g. see also Segura et al. 2005).
- On Earth $N_2O$ destroyed by UV. On quiet M dwarfs, little UV and $N_2O$ builds up.
- Presence of absorption signals for M dwarf planets can strongly depend on stellar type and activity.

$\rightarrow$ Spectral ranges should cover also biosignatures which are weak for Earth.
$\rightarrow$ Modelling needed to understand response of biosignatures to the stellar environment.

See Seager et al. 2013 for a discussion of biosignatures in atmospheres of different composition.
Some more examples on the impact of stellar environment on biosignature signals:

Effect of varying stellar UV on the ozone biosignature for an Earth-like Planet in the HZ of a cool M-dwarf star (Grenfell et al. (2014), Ruegheimer et al. (2015)).

→ ozone signal increasing for enhanced UV (<180nm, O₂ photolysis increases).

Effect of Cosmic Rays on biosignatures for an Earth-like planet orbiting in HZ of M-dwarf (Segura et al. 2005; Grenfell et al. 2012), Griessmeier et al. (2016), Tabataba-Vakili et al. (2016))

→ Monitoring the host star and its activity is important.
Planes, planetary systems and their host stars evolve

→ Need to derive accurate planetary system age → asteroseismology

Stellar radiation, wind and magnetic field

Loss of primary, atmosphere

Formation in proto-planetary disk, migration

Cooling, differentiation

Secondary atmosphere

(plate)-tectonics

Cooling, differentiation

Life
Example: The Earth at different epochs (cloud free atmosphere)

→ Accurately known ages of planets will allow us to compare the evolution of atmospheres with time.

→ Place Earth evolution into a context of terrestrial planets in general.

→ Need to model early-Earth scenarios

Kaltenegger et al. (2007)
Example: The potential of phase curves, status today

55 Cancri e: Phase curve of hot super-Earths in IR

- Mass: 8.08 Mearth
- Radius: 1.91 Rearth
- Density: 6.4 g/cm^3
- Orbital period: 0.7 days

Demory et al. 2016

Temperature distribution:

- Very large temperature difference between day (2700 K) and night (1400 K)
  → Inefficient heat transport
- Hot spot located 41° East of substellar point
  → Efficient energy transport
- Interpretations:
  - Atmosphere with inefficient heat transport ?
  - Magma ocean on the day side ?
Optical phase curves allow in principle to detect the reflection of stellar light by the surface of an ocean.

Observationally challenging, but allows direct detection of liquid water

Need high SNR and large aperture
Summary I

Targets for transit spectroscopy:

• Planets in the HZ of M dwarf stars will be the main targets until mid-to end-2020 (TESS, ground). → need to better understand biosignatures for such planets.

• After 2025 targets for transit spectroscopy around bright solar-like stars from PLATO.

• Mean densities will be available for many transit spectroscopy targets.
• Ages (10%) for bright stars (from PLATO).

→ Targets for JWST, ELTs...
Summary II

• Spectroscopy of terrestrial planets in HZ of cool M dwarf stars is within reach of JWST and E-ELT.
  • Requires adding transits (up to several 10s)
  • Interpretation benefits from simultaneous monitoring of stellar activity.
• Terrestrial planets in HZ of solar-like stars needs future missions (direct imaging).

• Which parameters/species to observe? ⇒ We want them all!
  • Radii, masses, mean densities, ages, albedos, effective temperatures, Rayleigh slopes, range of atmospheric absorption bands, including at least O₂, O₃, H₂O, CO₂, CH₄, N₂O, +..., phase curves
  • Stellar activity monitoring