Biosignatures in context

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Science
A Wink in the Sky
At this stage, the best strategy to search for life on exoplanets may be to have no strategy but exploration.

This exploration may reveal anomalies (≠ fingerprint)
no shortcut to finding extrasolar life

exploration must come first and be as unbiased as possible

- exploration of a large variety of planets
- exploration of a given target

anomalies can only arise from a comprehensive characterization of the target (and its host star & system)
1869 today

observing power

martian biosphere
MÉMOIRES ET OBSERVATIONS.

PRIX PROPOSÉS PAR L'ACADÉMIE DES SCIENCES.

Prix Pierre Guzman (100 000 fr).

Mme Vr Guzman a légué à l'Académie des Sciences une somme de cent mille francs pour la fondation d'un prix qui portera le nom de prix Pierre Guzman, en souvenir de son fils, et sera décerné à celui qui aura trouvé le moyen de communiquer avec un astre autre que la planète Mars.

Prévoyant que le prix de cent mille francs ne serait pas décerné tout de suite, la fondatrice a voulu, jusqu'à ce que ce prix fût gagné, que les intérêts du capital, cumulés pendant cinq années, formassent un prix, toujours sous le nom de Pierre Guzman, qui serait décerné à un savant français, ou étranger, qui aurait fait faire un progrès important à l'Astronomie.

Le prix quinquennal, représenté par les intérêts du capital, sera décerné, s'il y a lieu, en 1910.
a point of darkness (E. Gaidos’ talk)
In its December 1990 fly-by of Earth, the Galileo spacecraft found evidence of abundant gaseous oxygen, a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum, and atmospheric methane in extreme thermodynamic disequilibrium; together, these are strongly suggestive of life on Earth. Moreover, the presence of narrow-band, pulsed, amplitude-modulated radio transmission seems uniquely attributable to intelligence. These observations constitute a control experiment for the search for extraterrestrial life by modern interplanetary spacecraft.

inspired by Lovelock, 1975
Photon flux at 10 pc ($m^2 \mu m^{-1} hr^{-1}$)

(Selsis & Tinetti, Darwin Proposal, 2007)
Effect of refraction (Bétrémieux & Kaltenegger, 2013, 2014)

Snellen et al., 2013

Effective Radius (km)

ΔR (km)

O₂

CO₂

H₂O

CH₄

Wavelength (µm)

0.758

0.760

0.762

0.764

0.766

0.768

0.770

0.76 µm O₂ band
Life → altered observables → instrumentation → Observer

Interpretation?
Oxygeionic photosynthesis

\[ 2\text{H}_2\text{O} + \text{CO}_2 + h\nu \rightarrow \text{CH}_2\text{O} + \text{O}_2 + \text{H}_2\text{O} \]

Net release of atmospheric \( \text{O}_2 \)

Burial of organic carbon

2850 kJ/mole of glucose (72 g of carbon)
Photon

Stroma

1

Photosystem II

2

P680

3

H₂O

½O₂ + 2H⁺

Electron transport chain

Provides energy for synthesis of ATP

4

5

6

P700

NADP⁺ + H⁺

NADPH

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- solar flux at Earth surface: 163 W/m² (340 W/m² - 30% reflected back to space - 77 W/m² absorbed by the atmosphere)
- carbon fixation by photosynthesis: 70x10⁹ tons of carbon /yr
- the fixation of 72 g of carbon costs 2850 kJ

About 0.16% (0.268 W/m²) is converted by photoautotrophic life into chemical energy.
The average internal heat flux dissipated by the Earth is 0.075 W/m² in average.

Less than $10^{-6}$ of this heat flux is converted by life into chemical energy (Rosing et al., 2005, 2006).

Photosynthetic life fixes at least $10 \, 000 \, 000$ times more carbon than other primary producers (chemoautotrophs).
Chemoautotrophic life relies on the thermal gradient (25K/km in average) produced by the internal heat flux and the redox gradient it generates.

200 gC/yr/m²

< 56 gC/Myr/m²
Although Chemoautotrophy is known since 1890, the Earth deep biosphere was discovered only in the 1970s.

In a world with a purely chemoautotrophic primary production, the organic sequestration would cause no significant biological effect on the global carbon cycle in the absence of photosynthesis (Rosing et al., 2006).

200 gC/yr/m²

< 56 gC/Myr/m²
The *Habitable Zone* (defined as the region where surface liquid water is stable) is where liquid water and stellar light are simultaneously available.

Life may exist outside the HZ but can it be found by remote observations?
Life $\rightarrow$ altered observables $\rightarrow$ instrumentation $\rightarrow$ Observer

Interpretation ?
Life altered observables

Selsis et al., 2008
Grenfell et al., 2007
Life altered observables

K, G, F stars
Selsis, 2000
Segura et al., 2003
Hedelt et al., 2013
Rugheimer et al., 2013
Life altered observables

H. Rauer et al.: Potential biosignatures in super-Earth atmospheres

Fig. 2. Influence of gravity: Earth-sized (solid) vs. 3g super-Earth planet around the Sun. The surface temperature decreases for the 3g scenario. This is because we held the surface pressure constant, which consequently lowered the vertical column mass. Less meanless absorption and therefore less greenhouse effect, hence lower surface temperatures. Furthermore, effective ozone heating occurs at higher pressures, $p$, and the temperature maximum in the stratosphere accordingly decreases to higher $p$ when increasing gravity. Overall increased stratospheric ozone levels (see Sect. 4.1.2) lead to enhanced heating in these parts of the atmosphere.

Fig. 3. Influence of stellar spectrum: Earth-sized planets around the Sun (black, solid), AD Leo (dotted), M0 (dashed), M1 (dash-dot), M2 (dash-dot-dot-dotted), M3 (long dashes), M4 (red), M5 (green), M6 (blue), and M7-type stars (magenta). Figure 3 shows the influence of the stellar type on the temperature profile for the Earth control case as well as 1g planets around AD Leo and the M0 to M7 stars from Table 1. Because unlike in previous approaches, we did not fix the surface temperature in the modelled planet by different stellar insulations at TOA, it is interesting to note that although Earth-like planets around M-dwarfs show somewhat increased surface temperatures, they always remain well within the habitable range.

Hedelt et al., 2013, Rauer et al., 2011, Segura et al. 2006
Life altered observables

H. Rauer et al.: Potential biosignatures in super-Earth atmospheres

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Contrast spectrum of the 9.6 \( \mu m \) ozone band and the 15 \( \mu m \) carbon dioxide band for a Earth-sized planet around the Sun (black), AD Leo (red), M0 (green), M5 (blue), and M7 (magenta). Blue diamonds: binned to \( R = 20 \), red: smoothed spectra at the same resolution. Concerning molecular absorption bands, noticeable differences to the Earth-Sun system are found in the 2.3, 3.3 and 7.7 \( \mu m \) methane bands and the 3.8 and 4.5 \( \mu m \) bands for nitrogen oxide. These molecules show higher concentrations in the atmosphere of M dwarf planets compared with Earth (see Fig. 5), therefore we would expect their spectral signatures to be more pronounced. Additionally, the 4.7 \( \mu m \) band of CO becomes more prominent owing to its higher concentrations in the atmosphere (not shown). This can indeed be observed for the planet that orbits the M0-M3 dwarf stars. However, the absorption bands of \( N_2O \), \( CH_4 \) become weaker for cooler M stars and almost completely disappear for an Earth-sized planet around the M7 star, despite the greatly enhanced abundances. This is caused by the temperature structure of these planets (see Fig. 3). The emission in the \( CH_4 \) and \( N_2O \) bands originate in the middle atmosphere because of the large concentrations of these gases, i.e. the atmosphere becomes transparent only at much higher altitudes than for Earth around the Sun. At these altitudes, the temperature is almost as high as the surface temperature, hence the contrast between continuum (transparent atmosphere)
Life altered observables? Abiotic (photo)chemistry

UV early Venus Icy satellites

Observer instrumentation Interpretation?
The efficiency of these processes depends - among other things - on the UV intensity and spectral distribution.
Life altered observables

France et al. 2013, Tian et al. 2013

altered observables
planetary atmospheres are not at chemical equilibrium

- UV → photochemistry
- thermal gradient + transport
- at habitable temperatures, endothermic reactions are extremely low
- exchange with a hot interior
Eventually, disequilibrium must be quantified, for instance in terms of $\Delta G$ (Gibbs free energy) and compared with possible abiotic sources of $\Delta G$.

Doable for UV. Much more difficult for quenching (exchange with a hot interior).

Implies a comprehensive knowledge of the atmospheric elemental composition.
“if information from other experiments [...] had not been available this set of data would almost certainly have been interpreted as presumptive evidence for biology”

some concluding remarks

- attributing a spectral/chemical anomaly to the presence of life (if possible) will require many multiwavelength high-snr observations from different instruments

- The detection of such an anomaly is not the ultimate goal. It would be the beginning of the story.

- *dosit facit venenum* (measurement vs detection)

- we need to observe/study many different planets to understand the processes controlling their diversity

- the success of the search for life does not depend only on our technology but also on the actual distribution/diversity of life in the Universe. It is therefore impossible to predict if/when such a discovery will be made.

- always question the assumptions!
planet bern042

ANOMALY

observations

consensual interpretation
From atmospheric evolution... ... to spectral evolution

An era of biogenic methane before the rise of oxygen?