Towards a Statistical Framework for HWO Biosignature Assessment

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"No single effect, experiment, or paper provides definitive evidence about its claims. **Innovation** identifies possibilities. **Verification** interrogates credibility. Progress depends on both.....it helps to separate what we know from what we think we know."
- Errington et al., (2021).

Motivation

Given the importance of life detection to the field of astrobiology, the increasing number of life detection claims, and the expanding suite of current and future missions with astrobiological goals, there is a clear need for the astrobiology community to develop best practices and a framework for the scientific assessment of claims of biosignature detection.

Not Just Looking for Life, Looking for "not-Planet"

A biosignature assessment framework must take into account the context of the environment in which a potential biosignature is found.

- Contextual clues can then be used to carefully weigh the likelihood that the possible biosignature has a biological or abiotic origin.
- Targeted biosignatures (atmosphere, surface or temporal features) from a specific metabolism, e.g. photosynthesis, or methanogenesis can be sought.
- To enhance confidence that these potential biosignatures are due to life, known planetary processes that could produce the biosignatures should be successively ruled out.
- To search for "life as we don't know it" via agnostic biosignatures, we need to understand terrestrial planetary processes and characterize the planetary environment sufficiently well that we can confidently identify processes that are likely "not-planet".

Five Very Important Questions

In a July 2021 workshop, co-organized by the NExSS and NfoLD Research Coordination networks, the astrobiology community discussed and developed a series of 5 questions that form the basis for a biosignature assessment framework (Meadows, Graham et al., 2022).

THE BIOSIGNATURE ASSESSMENT FRAMEWORK

DETECTION

Question 1: Have you detected an authentic signal?

Question 2: Have you adequately identified the signal?

INTERPRETATION

Question 3: Are there abiotic sources for your detection?

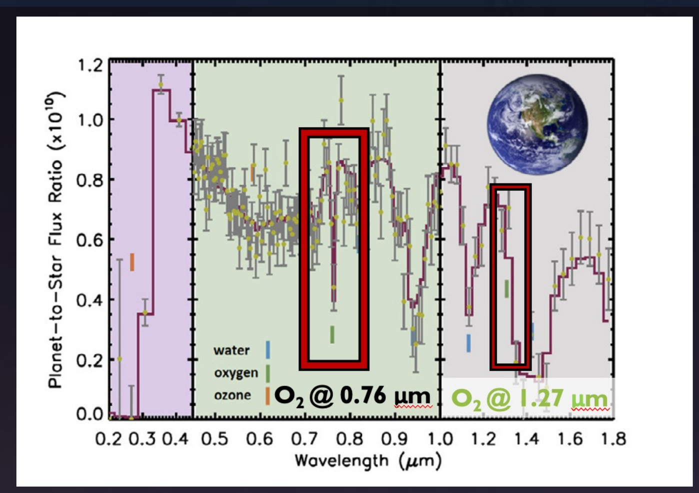
Question 4: Is it likely that life would produce this expression in this environment?

Question 5: Are there independent lines of evidence to support a biological (or non-biological) explanation?

Meadows, Graham et al., 2021, Community Report from the Biosignatures Standards of Evidence Workshop https://arxiv.org/abs/2210.14293

Applying the Framework to HWO's Mission Lifecyle, and the Search for O_2

Q1: Have you detected an authentic signal?

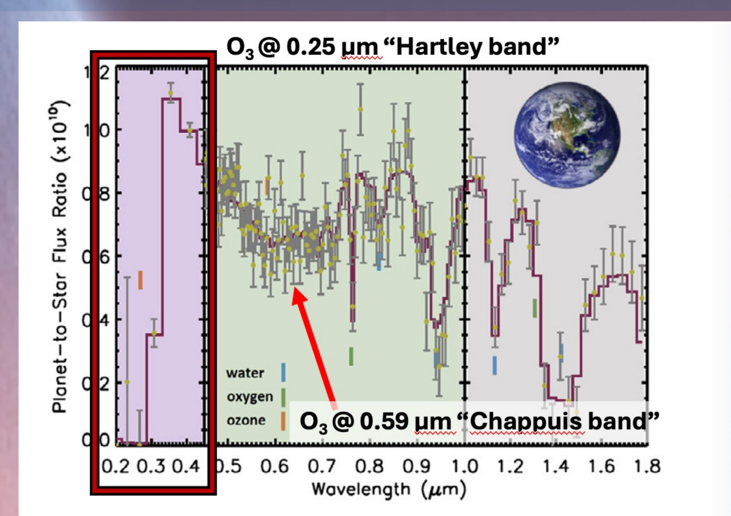


Picture Credit: Robinson, Schwieterman

Confirmation of a detected signal requires planning and knowledge of calibration, background noise sensitivities, resolution, operations and instrument behavior.

- Is the Signal-to-noise adequate (e.g., SNR > 5)?
- Have instrument systematics been excluded?
- Has stellar noise been sufficiently characterized?
- Detection at multiple wavelengths or at multiple epochs?

Q2: Have you adequately identified the signal?



Picture Credit: Robinson, Schwieterman

Signal identification requires understanding instrument and observing parameters that could impact data interpretation such as adequate spectral resolution.

- Detection of multiple bands at multiple wavelengths
- Detection of photochemical/lytic byproducts e.g. O_3

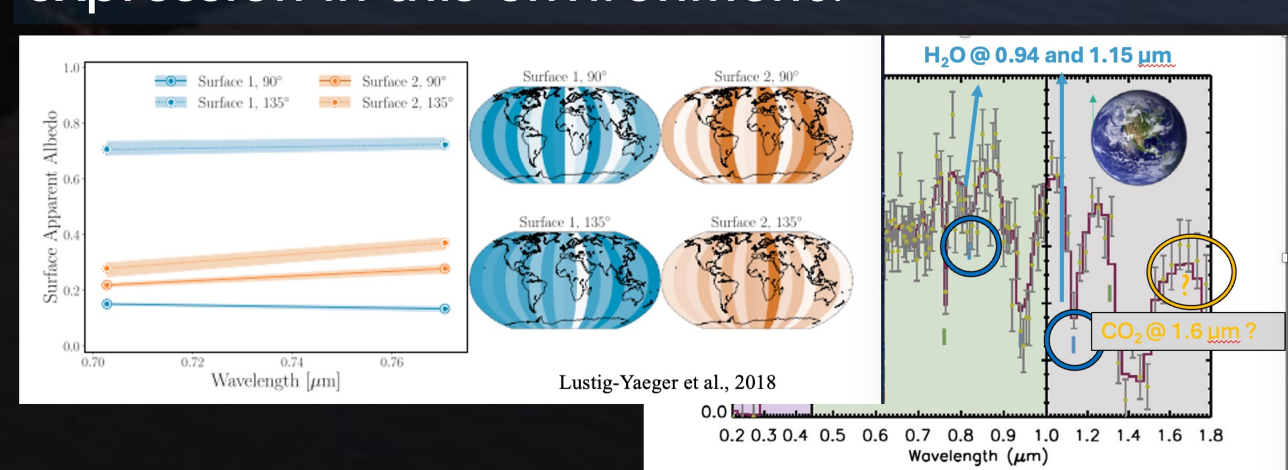
Q3: Are there abiotic sources for your detection?

Meadows et al., 2017

False positive recognition can be enhanced by:

- pre-flight laboratory, field and theoretical work to identify false positives and their discriminants
- Ensuring instruments have the wavelength range, resolution and sensitivity to detect false positives
- For the O_2 example, O_2-O_2 CIA (O_4) from past ocean loss, or CO from CO_2 photolysis, would confirm an abiotic source for the O_2. Detecting H_2O, CH_4, and/or the Rayleigh slope ($\propto \lambda^{-4}$) can support biological O_2.

Q4: Is it likely that life would produce this expression in this environment?



Picture Credit: Robinson, Schwieterman

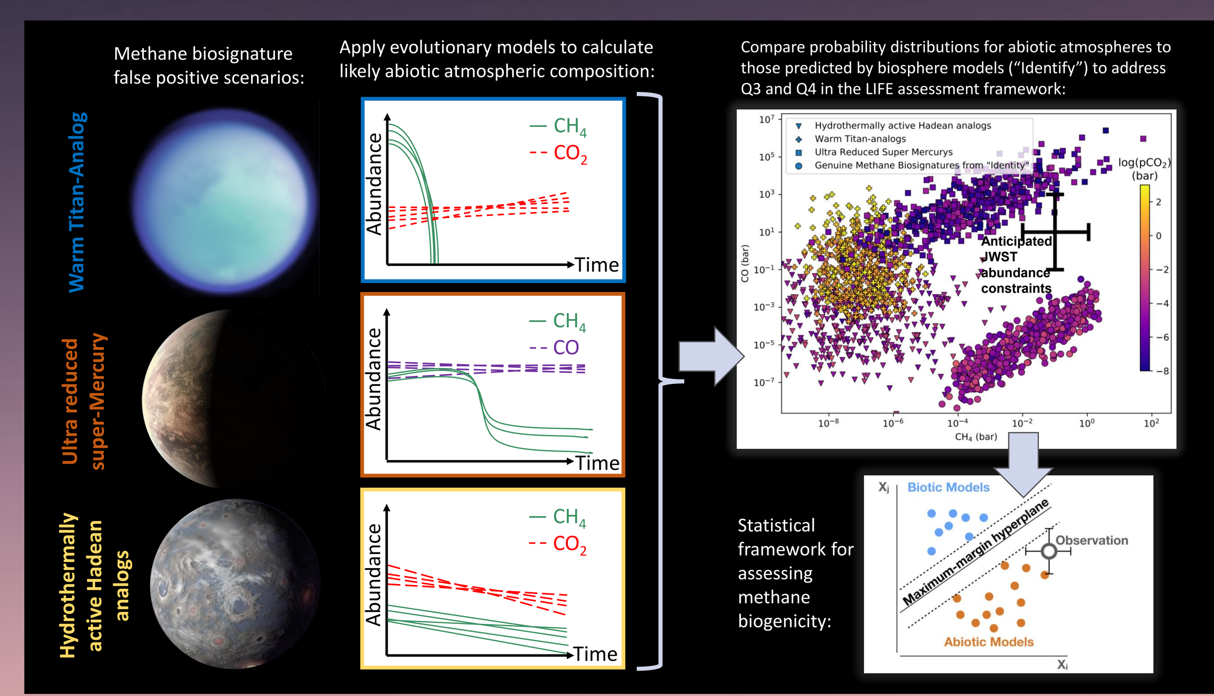
The likelihood of biogenicity for the signal could be enhanced by finding it in a habitable environment, and assessing chemical plausibility, given other environmental parameters.

- Water band or cloud detection supports but does not confirm the presence of an ocean, multiphase mapping to detect phase dependent effects and glint would confirm a surface ocean.
- Detection of substrates for photosynthesis (H_2O and CO_2)

Q5: Are there independent lines of evidence that support a biological (or non-biological) explanation?

Question 5 places an emphasis on ensuring that the STM and the instrument suite supports accessibility of multiple independent lines of evidence to assess whether biological or abiotic formation is more likely. The Science Traceability Matrix could include measurements to assess key aspects of habitability and environmental context—to search for additional, corroborating biosignatures (e.g. surface and seasonal), and to rule out false positives and unrealistic metabolisms/biomass.

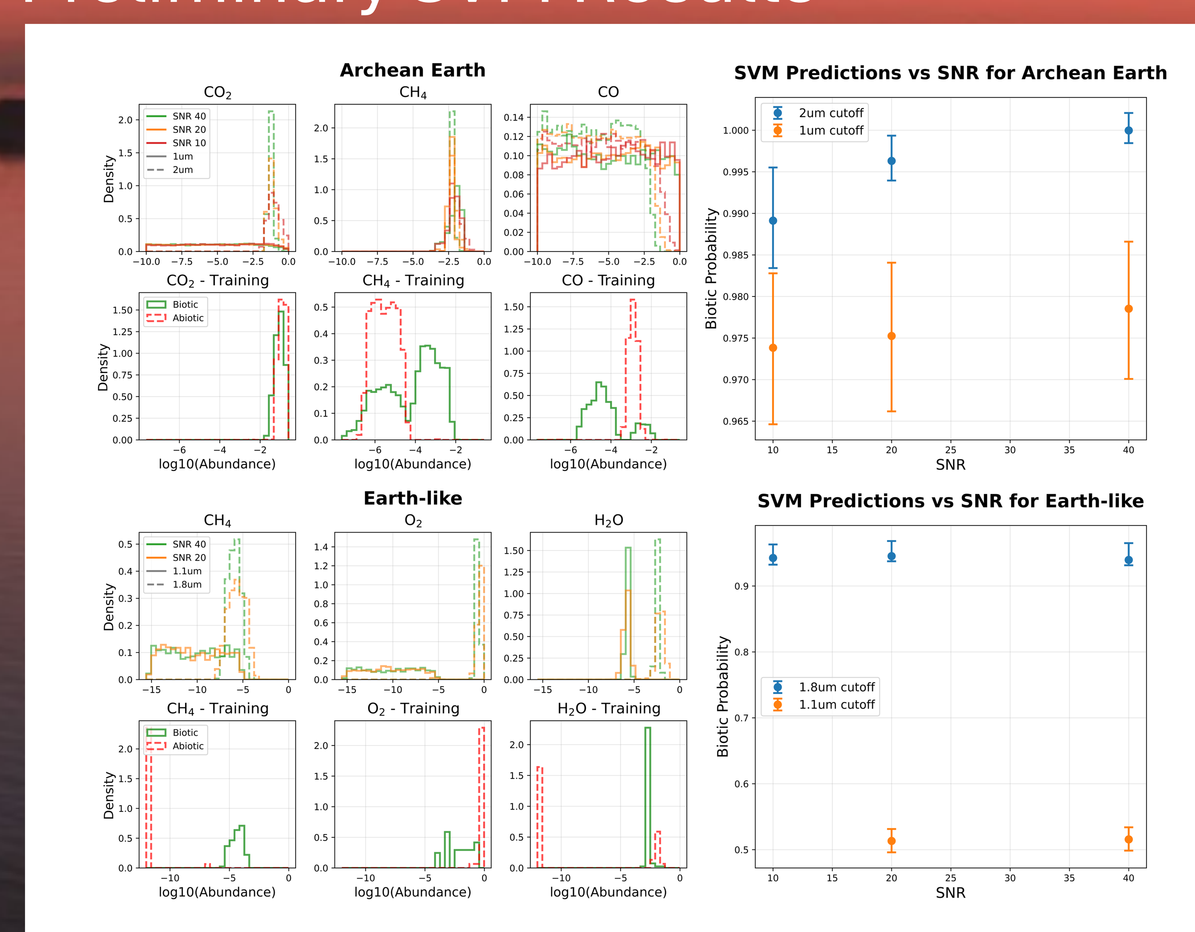
Developing a Statistical Framework for Biosignature Assessment



Picture Credit: Krissansen-Totton

But how do we turn a sense that life is more or less likely on a planet, given its spectrum, into something more quantifiable? The Virtual Planetary Laboratory Team is working on a statistical biosignature assessment framework that uses a Support Vector Machine (SVM), trained on both inhabited and abiotic (false positive) environmental parameter suites, to quantify the likelihood that retrieved parameters from a given spectrum are due to life.

Preliminary SVM Results



McCarty et al., in prep

McCarty, Papesh, Ulses

The above plot shows preliminary results for the SVM trained on abiotic and inhabited Archean Earth environments (top set of 7) and on photosynthetic and abiotic O_2-dominated environments (bottom set of 7). Each set of six plots show retrieved posteriors for molecular abundance on the top, and the SVM training dataset distributions (biotic vs abiotic) for that molecule on the bottom. The SVM was applied to retrieved molecular abundance results from two sets of simulated spectra: a shorter maximum wavelength (1 or 1.1µm), and a longer 1.8 or 2µm wavelength cutoff.

These preliminary results show SVM confidence in life detection increasing strongly for observations taken with the longer wavelength range cutoff, and a weaker increase in biotic probability with increased S/N > 10.