Draft version October 4, 2023
Typeset using LaTeX **modern** style in AASTeX631

Bioverse: Origins of Life

Martin Schlecker[1] and et al.

[1] *Steward Observatory, The University of Arizona, Tucson, AZ 85721, USA; schlecker@arizona.edu*

ABSTRACT

tbd.

1. INTRODUCTION

Introduce OOL, the importance of planetary contexts

2. ORIGINS OF LIFE SCENARIOS AND THEIR PREDICTIONS

Present widely discussed OOL scenarios and their predictions on exoplanet observables; derive testable hypotheses.

In this section, we present some of the most prominent origins of life scenarios and their observational predictions. We focus on the necessary environmental conditions for the processes and reactions inherent to each scenario, and aim to identify distinct observables that are accessible via present and near-future remote sensing techniques.

2.1. *Hydrothermal vents*

e.g., Russell+2010 ... The hydrothermal vents scenario requires a direct contact of an ocean and the planetary mantle/crust. This requirement is not met on an ocean world with large amounts of water, where the water pressure on the ocean floor is high enough to form high-pressure ices (Noack+2016).

see discussion in Kite & Ford 2018 Sect. 6.4

SR: The sealing away of the planetary interior from the ocean due to high-pressure ice layers is a common assumption for water world exoplanets (in addition to the references above, see e.g. Hu et al. 2021). I'm not convinced it is correct, because of relatively recent evidence showing the possibility of molecular assimitation into such ices and subsequent transport, e.g., https://iopscience.iop.org/article/10.1088/0004-637X/769/1/29/meta, https://iopscience.iop.org/article/10.3847/1538-4357/acb49a/meta, https://iopscience.iop.org/article/10.3847/1538-4357/aa5cfe/meta (I'm sure there are other workers in this area, this is just the group with which I am familiar). Exoplaneteers mostly uniformly accept this proposition, so it's not an unreasonable assumption if you want to run with it so long as its acknowledged and caveated reasonably; I'm just highlighting this for your attention so that you can make an informed decision.

Prediction: Planets with high-pressure ices do not show biosignatures.

2.2. *Subaerial ponds*

... By its nature, the subaerial ponds scenario relies on rock surfaces exposed to the planetary atmosphere. Water worlds that have their entire planetary surface covered with water contradict this requirement and do not allow for the wet-dry cycling inherent to this origin of life scenario. The competition of tectonic stress with gravitational crustal spreading (Melosh 2011) sets the maximum possible height of mountains, which in the solar system does not exceed $\sim 20\,\mathrm{km}$. Such mountains will be permanently under water on water worlds. Another impediment to wet-dry cycles is tidal locking of the planet as it stalls stellar tide-induced water movement and diurnal irradiation variability.

Prediction: Biosignatures occur outside the tidal locking zone and at bulk densities consistent with exposed rock..

SR: I'm not a priori sold that tidal locking means that no wet-dry cycles occur. you can still have cycling driven by transient changes in instellation due to flares, for example (e.g., https://iopscience.iop.org/article/10.3847/1538-4357/aadfd1/meta). Similarly, I wonder if 3D effects might not give rise to variability (https://iopscience.iop.org/article/10.3847/PSJ/acc9c4/meta). I argue that it is more robust to establish a correlation between biosignatures and planets which show evidence of continents/land. I think that Ty Robinson in our department has done some work in this area, his papers might be a good starting point. Other papers which look relevant (but with which I am not familiar, as this is not my area): https://academic.oup.com/mnras/article/511/1/440/6501216, https://academic.oup.com/mnras/article/495/1/1/5733176, https://iopscience.iop.org/article/10.3847/1538-3881/aad775/meta, https://iopscience.iop.org/article/10.3847/1538-3881/aaed3a/meta, https://iopscience.iop.org/article/10.3847/1538-3881/ab2df3/meta

2.3. *UV flux*

A major hypothesis in the origin of life is that UV light played a constructive role in getting life started on Earth (see Ranjan et al. 2016, 2017c; Rimmer et al. 2018; Rapf & Vaida 2016; Pascal et al. 2012; Green et al. 2021; and sources therein).

If UV light is required to get life started, then there is a minimum planetary UV flux requirement to have an inhabited world. This requirement is set by competitor thermal processes; if the photo-reaction does not move forward at a rate faster than the competitor thermal process(es), then the abiogenesis scenario cannot function. On the other hand, abundant UV light vastly in excess of this threshold does not increase the probability of abiogenesis, since once the UV photochemistry is no longer limiting, some other thermal process in the reaction network will be rate-limiting process instead. Therefore, a putative dependence of life on UV light is best encoded as a step function (see, e.g., Ranjan et al. 2017c; Rimmer et al. 2018; Rimmer, Ranjan & Rugheimer 2021).

One origin-of-life scenario has been refined to the point where the threshold flux has been measured. The cyanosulfidic scenario has been shown to require a mean flux of at least $F_{\mathrm{NUV,min}} = (6.8 \pm 3.6) \times 10^{10}\,\mathrm{photons\,cm^{-2}\,s^{-1}\,nm^{-1}}$ integrated from 200–280 nm at the surface in order to function (Rimmer et al. 2018; Rimmer et al. 2021 Astrobiology; Rimmer et al. 2023).

SR: This is an interesting number, because it is below what was available on early Earth (so this scenario could have worked on early Earth) but until recently it was below what was thought to be available on habitable zone M-dwarf exoplanets. So it was thought that identification of biosignatures on M-dwarf planets could therefore falsify the cyanosulfidic scenario, with a potential caveat for transient UV from flares. Two recent developments have complicated the picture. First, Rimmer et al. 2018 had an error in their radiative transfer routines. Correcting for this error, early M-dwarfs and highly active M-dwarfs emit enough UV to meet the Rimmer et al. 2018 criterion (Ranjan et al. 2023). Second, a recent publication argues that /all/ estimates of M-dwarf UV are underestimates, and that late M-dwarf stars have similar emission to Sunlike stars (Rekhi et al. 2023). I suspect this is incorrect, because it contradicts a lot of work from e.g. the MUSCLES collaboration and the HAZMAT project, but it's worth keeping an eye on in case it is correct after all.

We use this threshold value as our baseline case.

TL: this scenario, the impact trigger, and the redox state are all interrelated and not easily to disentangle (UV scenarios depend on the right redox range at the surface, as do impact scenarios); however we can try to build this into the general debate. instead of having an "other scnearios" seciton i would suggest discussing/introducing the redox constraints in the introdcution together iwht planet formation and primordial differentiation processes.

Prediction: Past UV flux and the occurrence of biosignatures are correlated.

2.4. *Other Processes related to the Origins of Life*

2.4.1. *Planetary redox state and evolution*

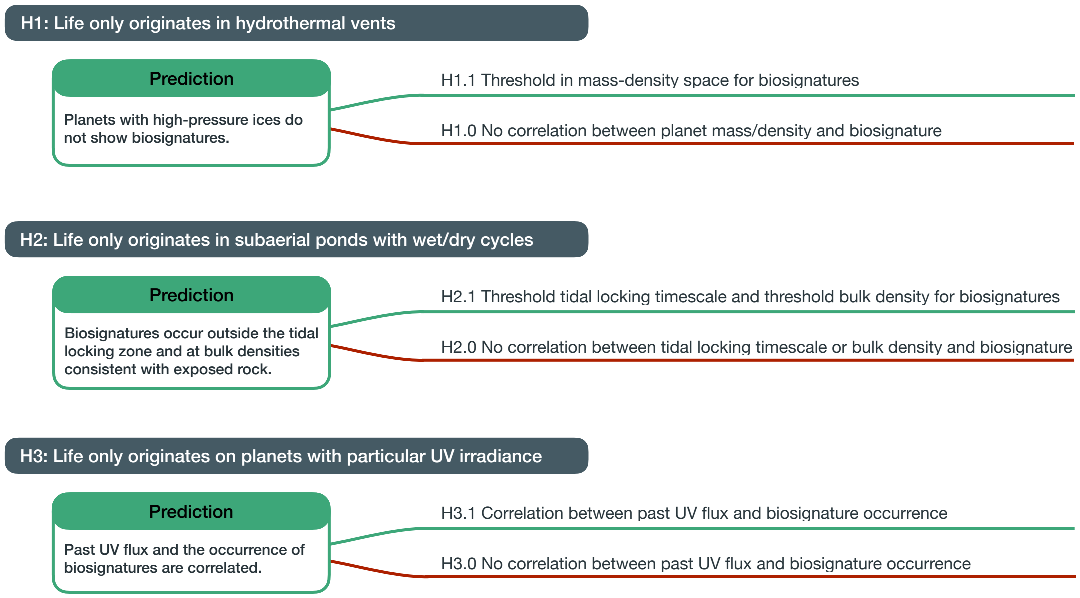

Figure 1. Origins of Life scenarios, their predictions on exoplanet observables, and derived population-level hypotheses.

The synthesis of prebiotic compounds requires moderately to highly reduced chemical environments (Kitadai & Maruyama 2018, Benner+2020, Sasselov+2020, Lichtenberg & Clement 2022). ... Surficial origins of life chemistries are dependent on the redox state of a planet being ∼neutral (not too reduced or oxidized) to allow the presence of precursor molecules like HCN. The planetary redox state leaves an imprint on its atmospheric composition and thus planet size (very reduced atmospheres are large) and spectral signatures. Connected to the cyanosulfidic scenario, the pond scenario, and the impact trigger.

2.4.2. *Impact trigger*

Iron-rich impactors have been suggested to intermittently provide the reduced environments favored by prebiotic chemistry (e.g., Sekine+2003, Hashimoto+2007, Kuwahara & Sugita 2015, Genda+2017, Wogan+2023). ... Prebiotic synthesis triggered through reduced impactors that stochastically create transiently reducing or neutral atmospheres requires a certain composition of the impactors, the planet to not be in a magma ocean state (???) (Lichtenberg & Clement 2022), and, related to this requirement, occurrence of impact events during early planetary evolution. Suggested observables are stochastic increases in brightness temperature, transient increases of planet size, and change of planet composition (decreasing with decreasing impact rate, i.e., stellar age).

2.5. *Origins of Life Hypotheses*

... Figure 1 lists the hypotheses derived from the predictions of each OOL scenario.

...

3. HYPOTHESIS TESTS

Briefly introduce Bayesian model comparison, then present the particular hypotheses in their mathematical form.

3.1. *Considered planets and their orbits*

All Origins of Life scenarios considered here require water as a solvent; we thus consider only rocky planets that may sustain liquid water on their surface. Different formulations of habitable zones as regions around a star where a planet with Earth's atmospheric composition can maintain liquid water on its surface exist (e.g., Mol Lous et al. 2022; Spinelli et al. 2023; Tuchow & Wright 2023). CITE! Ramirez & Kaltenegger 2017, 2018 Here, we adopt the popular estimates of Kasting et al. (1993) and Kopparapu et al. (2013, 2014) that define a temperate zone between the runaway greenhouse transition CITE! and the maximum greenhouse limit CITE!. We use the parametrization in Kopparapu et al. (2014) to derive luminosity and planetary mass-dependent edges of the habitable zone a_{inner} and a_{outer}. We further follow Bixel & Apai (2021) and classify as "exo-Earth candidates" all planets with radii $0.8S^{0.25} < R < 1.4$ that orbit within the above boundaries. The lower limit was suggested as a minimum planet size to retain an atmosphere (Zahnle & Catling 2017).

3.2. *Bayesian hypothesis testing with `Bioverse`*

3.3. *Fraction of inhabited planets with detectable biosignatures*

Presumably, not all habitable worlds are inhabited and not all inhabited worlds develop detectable biosignatures. The fraction of exo-Earth candidates that are both inhabited and harbor detectable biomarkers at the time when we observe them remains speculative; we aggregate them in the unitless parameter f_{life}.

3.4. *H1: Life only originates in hydrothermal vents*

The hydrothermal vent scenario does not allow oceans deep enough to form an impenetrable layer of high-pressure ice on its floor. The resulting allowed parameter space is described by a lower limit on the bulk density.

+ exclude atmospheric signature for water worlds?

...

3.5. *H2: Life only originates in subaerial ponds with wet/dry cycles*

We parametrize the required exposed land surface in this scenario as a lower limit in bulk density that is higher than for H1. Further, the tidal locking timescale of the planet may not be smaller than the age of the system. ...

3.6. *H3: Life only originates on planets with particular UV irradiance*

Our third theoretical experiment is to test the UV irradiance requirement (Sect. 2.3) by relating the occurrence of life on a planet with a minimum past UV flux. Here, we focus on the prebiotically interesting 200–280 nm range CITE and the quiescent stellar flux. Our concrete hypothesis shall be that life only occurs on planets that at some point in their history have received UV radiation in this wavelength range that exceeded a minimum NUV flux $F_{\mathrm{NUV,min}}$. We further require this flux to have lasted for $\geq 100\,\mathrm{Myr}$ to allow for a sufficient "origins timescale" (Rimmer 2023). We then have

$$H_3 = f_{\mathrm{life}}(\theta, F_{\mathrm{NUV}}) = \begin{cases} 0, & F_{\mathrm{NUV}} < F_{\mathrm{NUV,min}} \\ f_{\mathrm{life}}, & F_{\mathrm{NUV}} \geq F_{\mathrm{NUV,min}} \text{ for } \Delta t \geq 100\,\mathrm{Myr} \end{cases} \tag{1}$$

and the corresponding null hypothesis $H_{3,null} = f_{\mathrm{life}}(\theta)$, i.e., no correlation with UV flux.

3.6.1. *past UV flux*

? relate U-band energy to bolometric flux.

OPTIONAL: "We further test the scenario of a linear correlation of past UV flux and biosignature occurrence rate. This test requires the detection of multiple biosignatures."
Test for negative correlations as well?

4. EXOPLANET SURVEY SIMULATIONS

biomarkers: Focus on molecular Oxygen? Excess Methane? (e.g., Seeburger et al. 2023)

A commonly discussed biomarker is molecular Oxygen (O_2), which on Earth emerged as a byproduct of photosynthesis during the Proterozoic era. While not the only atmospheric species discussed as a signature for planetary life CITE, we focused on O_2 as a representative biomarker for our spectroscopic survey simulations.

4.1. *Habitable Worlds Observatory*

4.1.1. *target list*

Provisional stellar target List for the habitable Worlds Observatory: (Mamajek & Stapelfeldt 2023)

4.2. *Nautilus*

4.3. *LIFE*

TL: please not optional... :) happy to help support this section

5. RESULTS

5.1. *Information content in mass-density space*

5.2. *Information content in tidal locking timescale-density space*

5.3. *Correlation of past UV flux and biosignature occurrence*

6. DISCUSSION AND CONCLUSIONS

6.1. *What do we learn from a single biosignature detection?*

discuss constraining power on OOL of a convincing biosignature detection on a single planet, depending on the position of the planet in the parameter space we explored.

6.2. *Constraining power for the origins of life as a function of biosignature location*

How does the location of biosignature detections impact the credibility of OOL scenarios?

biosignature on M dwarf planet vs. FGK: Impact on UV flux requirement?

6.3. *Caveats*

6.3.1. *Planetary composition*

TL: the three scenarios are very specific in terms of planet composition (== redox state :-) and thermal state, we need to discuss this here

6.3.2. *Atmosphere transmission*

Theoretical work suggests that the atmosphere of prebiotic Earth was largely transparent at near-UV wavelengths with the only known source of attenuation being Rayleigh scattering (Ranjan & Sasselov 2017; Ranjan et al. 2017). We thus approximated surface UV flux using top-of-atmosphere fluxes. This represents a conservative approach, since any planet that fails to meet the irradiance criterion receives even lower near-UV radiation at its surface.

SUKRIT please specify as neccessary

6.3.3. *Stellar flares*

Our assumptions on past UV flux neglect the contribution of stellar flares, which may be hypothesized as an alternative source of UV light (Ranjan & Sasselov 2017). This concerns mainly ultracool dwarfs, due to their low quiescent emission and high pre-main sequence stellar activity (**??**). Recent work indicates that the majority of stars show inadequate activity levels for a sufficient contribution through flares (Glazier et al. 2020; Ducrot et al. 2020; Günther et al. 2020). The biosignature surveys we simulated here may test the hypothesis of sufficient UV radiation via stellar flares.

6.4. *Conclusions and future work*

REPRODUCIBILITY

REFERENCES

Bixel, A., & Apai, D. 2021, The Astronomical Journal, 161, 228, doi: 10.3847/1538-3881/abe042

Ducrot, E., Gillon, M., Delrez, L., et al. 2020, A&A, 640, A112, doi: 10.1051/0004-6361/201937392

Glazier, A. L., Howard, W. S., Corbett, H., et al. 2020, ApJ, 900, 27, doi: 10.3847/1538-4357/aba4a6

Günther, M. N., Zhan, Z., Seager, S., et al. 2020, AJ, 159, 60, doi: 10.3847/1538-3881/ab5d3a

Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108, doi: 10.1006/icar.1993.1010

Kopparapu, R. K., Ramirez, R. M., SchottelKotte, J., et al. 2014, ApJL, 787, L29, doi: 10.1088/2041-8205/787/2/L29

Kopparapu, R. K., Ramirez, R., Kasting, J. F., et al. 2013, ApJ, 765, 131, doi: 10.1088/0004-637X/765/2/131

Mamajek, E., & Stapelfeldt, K. 2023, 55, 116.07

Mol Lous, M., Helled, R., & Mordasini, C. 2022, Nat Astron, 6, 819, doi: 10.1038/s41550-022-01699-8

Ranjan, S., & Sasselov, D. D. 2017, Astrobiology, 17, 169, doi: 10.1089/ast.2016.1519

Ranjan, S., Wordsworth, R., & Sasselov, D. D. 2017, Astrobiology, 17, 687, doi: 10.1089/ast.2016.1596

Rimmer, P. B. 2023, in Conflicting Models for the Origin of Life (John Wiley & Sons, Ltd), 407–424, doi: 10.1002/9781119555568.ch16

Seeburger, R., Higgins, P. M., Whiteford, N. P., & Cockell, C. S. 2023, Astrobiology, 23, 415, doi: 10.1089/ast.2022.0127

Spinelli, R., Borsa, F., Ghirlanda, G., Ghisellini, G., & Haardt, F. 2023, The Ultraviolet Habitable Zone of Exoplanets, doi: 10.48550/arXiv.2303.16229

Tuchow, N. W., & Wright, J. T. 2023, ApJ, 944, 71, doi: 10.3847/1538-4357/acb054

Zahnle, K. J., & Catling, D. C. 2017, ApJ, 843, 122, doi: 10.3847/1538-4357/aa7846