Abiotic Oxygen and the Limits of Earth Analogy in Exoplanet Biosignature Interpretation

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Abstract

The detection of atmospheric oxygen on a rocky exoplanet is widely regarded as a strong indicator of biological activity. This expectation derives from a single observational precedent: Earth. We argue that this extrapolation conflates two epistemologically distinct categories of knowledge — universal physical laws, which apply to any rocky planet under any conditions, and contingent terrestrial chemistry, which reflects the specific geochemical boundary conditions of one planet around one star. Through a process-by-process flux analysis of four independently documented abiotic O_2 production mechanisms on Archean Earth — UV-C photolysis coupled to hydrodynamic H_2 escape, SO_2 photodissociation (directly evidenced by the sulfur mass-independent fractionation record), silicate mechanochemistry, and terrestrial plasma electrolysis — we demonstrate that their combined production (~6×10^{11}–6×10^{12} mol O_2 yr^{-1}) is of comparable magnitude to the total Archean reductive sink capacity (~5.1×10^{12} mol O_2-eq. yr^{-1}). This near-equivalence means that the boundary between abiotic and biological oxygen cannot be resolved from Earth's own geochemical record with current data — an epistemological result with direct consequences for exoplanet life detection. We propose a formal framework distinguishing physically universal constraints from geochemically contingent parameters, and argue that biosignature interpretation must be grounded in the former before observational data from JWST and future missions can be evaluated without circular reasoning.

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1. Introduction

The modern biosignature framework rests on a sample of one. Every molecule proposed as a potential indicator of life beyond Earth — O_2, O_3, CH_4, N_2O, dimethyl sulfide — derives its status from its role in Earth's biosphere. This is a necessary starting point, but it carries an implicit epistemological commitment that is rarely examined: the assumption that what biology does on Earth, it

does in qualitatively similar ways elsewhere, under conditions that may differ by orders of magnitude in temperature, pressure, stellar flux, atmospheric composition, and geological history.

This paper examines that assumption through the specific case of atmospheric oxygen. O_2 has long been considered among the most compelling potential biosignatures, on the grounds that no known abiotic process produces it in quantities sufficient to dominate a planetary atmosphere. Recent work has significantly eroded this position: (Wordsworth & Pierrehumbert, 2014) demonstrated abiotic O_2 accumulation in CO_2-rich atmospheres; (Krissansen-Totton et al., 2021) showed that waterworld planets can develop Earth-like O_2 inventories through hydrodynamic H_2 escape alone; and a growing body of experimental work documents abiotic O_2 production through mineral chemistry (Stone et al., 2022), (He et al., 2023) and SO_2 photodissociation (Farquhar et al., 2000), (Wogelius & Walther, 2022).

The response of the biosignature community to these findings has been to identify and catalog abiotic false-positive scenarios, then to propose contextual discriminants intended to rule them out. This approach represents significant scientific progress. However, it implicitly accepts terrestrial geochemical parameters as the reference baseline — not because this choice has been defended epistemologically, but because no alternative baseline has been formally established. The present paper proposes that alternative.

We propose a more fundamental critique: the terrestrial chemical framework is not universal. It is the product of a specific set of geochemical boundary conditions that obtained on one planet, around one star, with one particular tectonic regime, atmospheric composition, and oceanic chemistry. Applying its quantitative results to other planetary systems is not an extrapolation of physical laws — it is an extrapolation of contingent geochemical outcomes. The distinction matters enormously for the interpretation of atmospheric data from JWST and future observatories.

This paper does not apply the proposed framework to a specific exoplanet target. This is deliberate. The quantitative parameters required to establish a physically universal abiotic baseline for any given planet — stellar UV flux, planetary mass, atmospheric composition, tectonic state — are not derivable from terrestrial analogy. They must be observed directly for each target. The present contribution establishes the analytical framework and its epistemological grounding; its application awaits observational data of sufficient quality from JWST and future missions.

This paper is organized as follows. Section 2 presents a rigorous quantitative analysis of abiotic O_2 production on Archean Earth, with explicit uncertainty bounds. Section 3 formalizes the distinction between universal physical constraints and contingent terrestrial chemistry. Section 4 develops the implications for exoplanet biosignature interpretation and proposes falsifiable predictions.

2. Abiotic O_2 Production on Archean Earth: A Constrained Flux Analysis

We analyze four abiotic O_2 production mechanisms with independent geochemical or experimental support, and present quantified flux ranges with explicit uncertainty bounds. Where a mechanism cannot be quantitatively constrained with current data, it is identified as such and excluded from the numerical balance, with the specific experimental gap noted.

2.1 Archean Boundary Conditions

A qualitative distinction from the modern system governs all flux estimates. In the modern atmosphere (21% O_2), any O* radical produced by photochemistry immediately encounters abundant ambient O_2 and recombines — the net yield is negligible. In the Archean anoxic atmosphere (<10^{-6} PAL O_2), O* has no recombination partner. The sign of the net O_2 flux from any dissociative process is therefore a function of ambient O_2 concentration — a qualitative difference in mechanism, not merely a quantitative scaling. Table 1 summarizes the boundary conditions that determine the magnitude of each production flux.

Table 1. Key Archean boundary conditions relevant to abiotic O_2 production (~3.0 Ga). PAL = present atmospheric level.

Parameter	Archean (~3.0 Ga)	Modern	Primary consequence for O_2 yield
Atmospheric O_2	<10^{-6} PAL	0.21 atm	No O* recombination with ambient O_2
Atmospheric CO_2	~0.1–0.3 bar	4×10^{-4} bar	Enhanced photodissociation substrate
Volcanic SO_2	~10–100 ppmv	<1 ppbv	Continuous SO_2 photolysis source
UV-C flux (100–280 nm)	~10× modern (no O_3 shield)	~0 at surface	Direct photolysis of H_2O and SO_2
EUV/X flux	3–10× modern (young Sun)	1×	Enhanced H_2 ionization and escape
Tectonic activity	3–5× modern	1×	Continuous silicate fracturing
H_2 escape rate	~10^{12}–10^{13} mol yr^{-1}	~4×10^{10} mol yr^{-1}	Irreversible O_2 accumulation ratchet

2.2 Mechanism P1: UV-C Photolysis of H_2O and Hydrodynamic H_2 Escape

In the absence of an ozone shield, UV-C radiation (100–280 nm) from the young Sun photodissociated atmospheric water vapor and CO_2 continuously. The governing reactions are:

$$2H_2O + h\nu(UV\text{-}C) \rightarrow 2H_2\uparrow + O_2$$
(2.1)

$$CO_2 + h\nu(VUV) \rightarrow CO + O(^1D) \rightarrow \tfrac{1}{2}O_2$$
(2.2)

UV photolysis and hydrodynamic H_2 escape are treated as a single integrated flux. The H_2 escape rate provides the most direct and best-constrained quantitative handle on net irreversible O_2 production: each mole of H_2 lost to space renders ½ mol of O_2 permanently non-recombinant (Eq. 2.3). (Catling et al., 2001) estimated the pre-GOE H_2 escape flux at ~10^{12}–10^{13} mol H_2 yr^{-1} — a value independently supported by xenon isotope fractionation records, which document a sustained Archean H_2 escape rate 2–3 orders of magnitude above the post-GOE value of ~4×10^{10} mol H_2 yr^{-1} (Zahnle et al., 2019):

$$P_1 = \tfrac{1}{2} \cdot F(H_2)\ [\text{mol } O_2\ yr^{-1}]$$
(2.3)

$$\text{Lower bound: } F(H_2)_{escape} = 10^{12}\ \text{mol yr}^{-1} \rightarrow P_1 = 5\times10^{11}\ \text{mol } O_2\ yr^{-1}$$

$$\text{Upper bound: } F(H_2)_{escape} = 10^{13}\ \text{mol yr}^{-1} \rightarrow P_1 = 5\times10^{12}\ \text{mol } O_2\ yr^{-1}$$

P_1 estimate: ~5×10^{11}–5×10^{12} mol O_2 yr^{-1}. This is the best-constrained single production mechanism, anchored to independent isotopic evidence. Cumulative total: ~5×10^{11}–5×10^{12} mol O_2 yr^{-1}.

2.3 Mechanism P2: SO_2 Photodissociation — The MIF-S Constraint

This mechanism holds a unique evidential status: it is the only abiotic O_2 production pathway with a direct, continuously preserved geochemical signature in the rock record. The sulfur mass-independent fractionation (MIF-S) signal — anomalous $\Delta^{33}S$ and $\Delta^{36}S$ values in sediments older than ~2.4 Ga — was established by (Farquhar et al., 2000) as the product of UV photolysis of volcanic SO_2 in an anoxic, ozone-free atmosphere. (Pavlov & Kasting, 2002) constrained atmospheric O_2 at $<10^{-5}$ PAL from MIF-S preservation requirements, simultaneously confirming the anoxic condition and the continuous SO_2 photolysis flux. The disappearance of MIF-S at ~2.4 Ga marks the GOE with sub-million-year precision.

$$SO_2 + h\nu(<217\ nm) \rightarrow SO + O$$
(2.4)

$$SO + h\nu(<231\ nm) \rightarrow S^0 + O$$
(2.5)

$$S^0 \rightarrow S_8\ \text{(aerosol polymerization and deposition)}$$
(2.6)

$$2O \rightarrow O_2\ \text{(net, in anoxic atmosphere)}$$
(2.7)

The elemental sulfur produced (Eqs. 2.5–2.6) polymerizes into S_8 aerosols and deposits — it exits the cycle permanently. The O produced by Eqs. 2.4–2.5 has no ambient O_2 to recombine with, yielding a net positive O_2 flux per mole of SO_2 photolyzed. An ionic pathway for direct O_2 production from SO_2 double

photoionization has been additionally documented (Wogelius & Walther, 2022). The volcanic SO_2 flux to the Archean atmosphere is estimated at ~1–10 Tmol SO_2 yr^{-1} (Catling & Kasting, 2017). Applying a photolysis efficiency ε of 1–10% — consistent with Archean UV-C flux and SO_2 column density estimates — yields:

$$P_2 = \varepsilon \cdot F(SO_2) \text{ [mol } O_2 \text{ yr}^{-1}\text{]}$$
(2.8)

Lower bound: $\varepsilon = 0.01$, $F(SO_2) = 10^{12}$ mol $yr^{-1} \rightarrow P_2 = 10^{10}$ mol O_2 yr^{-1}

Upper bound: $\varepsilon = 0.10$, $F(SO_2) = 10^{13}$ mol $yr^{-1} \rightarrow P_2 = 10^{12}$ mol O_2 yr^{-1}

P_2 estimate: ~10^{10}–10^{12} mol O_2 yr^{-1}. The MIF-S record provides direct observational evidence that this mechanism operated continuously throughout the Archean. The primary uncertainty is the photolysis efficiency ε, which requires experimental determination under Archean UV-C intensity and SO_2 column density conditions.

The upper bound efficiency of 10% may appear optimistic given recombination reactions such as O + SO → SO_2 that partially suppress net yield. However, the central argument of this paper does not require the upper bound. At the conservative lower bound alone (ε = 0.01), the mechanism yields ~10^{10} mol O_2 yr^{-1} — a quantifiable, geochemically non-negligible flux sufficient to establish the mechanism's relevance independently of any optimistic efficiency assumption.

A potential objection concerns photon competition between SO_2 and the dominant CO_2 in the Archean atmosphere. This objection implicitly assumes homogeneous gas mixing. In a dynamic planetary atmosphere under hydrostatic equilibrium, each gas component follows an independent pressure scale height H = RT/Mg, where M is molar mass. The higher molar mass of SO_2 (64 g/mol) relative to CO_2 (44 g/mol) produces a proportionally shorter scale height, concentrating SO_2 at lower altitudes in circumferential bands rather than distributing it uniformly. High-altitude UV photochemistry driving H_2 escape and lower-altitude SO_2 photolysis therefore operate in spatially distinct atmospheric domains, without mutual photon competition.

Cumulative total: ~5×10^{11}–6×10^{12} mol O_2 yr^{-1}.

2.4 Mechanism P3: Silicate Mechanochemistry

(Stone et al., 2022) demonstrated experimentally that fault movements in hot underground fractures produce H_2O_2 and molecular O_2 under entirely anoxic conditions. (He et al., 2023) confirmed this mineral-based pathway through systematic quartz abrasion experiments. The governing reactions are:

$$\equiv Si\text{–}O\text{–}Si\equiv + \text{friction} \rightarrow \equiv Si\bullet + \equiv SiO\bullet$$
(2.9)

$$2(\equiv SiO\bullet) + H_2O \rightarrow 2(\equiv SiOH) + H_2O_2$$
(2.10)

$$H_2O_2 \rightarrow H_2O + \tfrac{1}{2}O_2 \quad (\Delta H = -101\ \text{kJ mol}^{-1}) \qquad (2.11)$$

(Zhang et al., 2023) estimated a global Mesoarchean ROS production flux of ~3.9–6.7×10^8 mol oxidants yr^{-1} from continental silicate weathering. Extending to the oceanic ultramafic crust — which represents 3–5× the continental surface area and was continuously renewed at 3–5× modern tectonic rates — and applying the stoichiometric conversion of Eq. 2.11, assuming comparable ROS yield per unit friction energy across felsic and mafic mineralogies, a simplification that remains to be experimentally validated (see Section 5):

Lower bound: Continental estimate alone (Zhang et al., 2023): ~10^8 mol O_2 yr^{-1}

Upper bound: Extended to oceanic crust at 5× tectonic activity: ~10^{10} mol O_2 yr^{-1}

P_3 estimate: ~10^8–10^{10} mol O_2 yr^{-1}. This mechanism is individually minor in total flux but carries a distinct biological significance: the H_2O_2 produced in turbulent subaqueous environments was directly available to proto-photosynthetic microorganisms, a point developed in Section 3.3. Cumulative total: ~6×10^{11}–6×10^{12} mol O_2 yr^{-1}.

2.5 Mechanism P4: Terrestrial Lightning — An Unresolved Contribution

Electrical discharges in an anoxic CO_2/H_2O atmosphere constitute a physically plausible additional source of O*. We exclude this mechanism from the quantitative analysis for two reasons.

First, the available yield data do not apply to natural lightning. The most widely cited NO^x yield per flash (Schumann & Huntrieser, 2007) derives from controlled laboratory plasma discharge experiments. The kinetics of a natural lightning channel — involving a return stroke at ~30,000 K followed by millisecond-timescale cooling and complex channel chemistry — are not reproduced in laboratory plasma chambers. Laboratory yields cannot be directly applied to natural lightning.

Second, lightning in a nitrogen-bearing atmosphere functions primarily as a nitric acid generator. Electrical discharges dissociate N_2 and O_2 to produce NO, which is rapidly oxidized to NO_2 and then to HNO_3 via reaction with H_2O. The net O_2 yield per flash is effectively zero. In an Archean atmosphere dominated by CO_2 and H_2O, the nitrogen fixation pathway is absent, but the plasma kinetics of CO_2/H_2O dissociation under natural lightning discharge conditions have not been experimentally characterized. The O* yield per flash cannot be estimated by analogy without introducing an unquantified systematic error.

The net contribution of terrestrial lightning to Archean O_2 production is therefore currently unresolvable. Its quantitative characterization — specifically, laboratory measurement of O_2 yield per joule of discharge energy in CO_2/H_2O mixtures at Archean atmospheric pressures — is identified as a research priority.

2.6 Reductive Sink Capacity and Net Flux Balance

Table 2 presents the principal Archean reductive sink fluxes. A critical methodological point governs the dominant sink: the oceanic Fe^{2+} system was not a static depleting reservoir but a dynamically renewed flux, sustained by continuous hydrothermal input from mid-ocean ridge and off-axis vent systems. (Thompson et al., 2019) calculated that hydrothermal and weathering Fe^{2+} inputs were sufficient to sustain peak banded iron formation (BIF) deposition at ~4.5 Tmol Fe yr^{-1}. The O_2 demand of this dynamic sink is calculated from stoichiometry:

$$4Fe^{2+} + O_2 + 10H_2O \rightarrow 4Fe(OH)_3\downarrow + 8H^+ \quad (2.12)$$

$$2Fe(OH)_3 \rightarrow Fe_2O_3 + 3H_2O \text{ (BIF formation)} \quad (2.13)$$

Applying Eq. 2.12 to the peak Fe^{2+} flux of 4.5 Tmol Fe yr^{-1} yields an O_2 demand of ~1.1×10^{12} mol O_2 yr^{-1}.

Table 2. Archean reductive sink fluxes and O_2-equivalent demand (~3.0–2.4 Ga).

Sink mechanism	Governing equation	O_2-eq. flux (mol yr^{-1})	Source
Fe^{2+} oceanic oxidation (dynamic BIF flux)	Equations 2.12–2.13	~1.1×10^{12}	(Thompson et al., 2019)
Serpentinization of komatiites	$Fe^{2+} + H_2O \rightarrow Fe^{3+} + H_2$	~2.0×10^{12}	(Meier et al., 2021)
Volcanic reductant gases (H_2S, SO_2, H_2)	$H_2S + ¾\ O_2 \rightarrow SO_2 + H_2O$	~1.0×10^{12}	(Kump, 2001)
Crustal FeS_2 weathering	$FeS_2 + ⅞\ O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-}$	~0.5×10^{12}	(Kasting, 2013)
Atmospheric CH_4 oxidation	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	~0.5×10^{12}	(Kharecha et al., 2005)
Total sink capacity		**~5.1×10^{12}**	

Table 3. Abiotic O_2 production fluxes by mechanism.

Mechanism	Lower bound (mol O_2 yr^{-1})	Upper bound (mol O_2 yr^{-1})	Evidential basis
P1 — UV photolysis + H_2 escape	~5×10^{11}	~5×10^{12}	Xe isotope fractionation; H_2 escape models
P2 — SO_2 photodissociation (MIF-S)	~10^{10}	~10^{12}	Archean sedimentary MIF-S record

P3 — Silicate mechanochemistry	~10^{8}	~10^{10}	Experimental (Stone et al., 2022)
P4 — Terrestrial lightning	—	—	Unresolved — plasma kinetics uncharacterized
Total abiotic (P1+P2+P3)	**~6×10^{11}**	**~6×10^{12}**	
Total sink capacity	**~5.1×10^{12}**	**~5.1×10^{12}**	
Net O_2 flux	**-4.5×10^{12} (deficit)**	**$+9\times10^{11}$ (marginal surplus)**	

The result of Table 3 must be stated with precision: the combined abiotic O_2 production from three quantitatively constrained mechanisms brackets the total Archean reductive sink capacity. The lower bound yields a deficit; the upper bound yields a marginal surplus. Neither is demonstrably correct with current data. This near-equivalence is the central empirical finding of this paper — not a quantitative failure, but an epistemological result whose implications are developed in Section 3.

3. Universal Physical Laws versus Contingent Geochemistry: A Necessary Distinction

3.1 A Category Error in the Biosignature Literature

The result of Section 2 — that abiotic O_2 production on Earth cannot be cleanly distinguished from biological production using currently available geochemical data — reveals a structural problem in the biosignature literature. Current frameworks implicitly treat two distinct categories of knowledge as equivalent:

Physically universal constraints are statements that follow from physical laws applicable to any rocky planet: the Hoyle resonance ($^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma$, E^{rrs} = 7.65 MeV) guarantees oxygen-rich lithospheres wherever stars produce heavy elements; UV photolysis of H_2O is thermodynamically inevitable on any water-bearing planet orbiting a UV-active star without an ozone shield; hydrodynamic H_2 escape is a function of planetary mass and temperature, independent of atmospheric composition. These constraints apply universally — to any rocky planet we observe.

Contingent geochemical parameters are quantities that reflect the specific combination of boundary conditions that obtained on Earth: a particular atmospheric CO_2 and SO_2 content, a particular tectonic renewal rate, a particular oceanic Fe^{2+} concentration, a particular volcanic reductant flux. The quantitative flux estimates of Section 2 — both production rates and sink capacities — belong to this category. They are not derivable from physical laws

alone; they require the specific Archean boundary conditions of Table 1, themselves only partially constrained.

This is not a critique of planet-specific photochemical modeling, which has advanced considerably. It is an observation that the interpretive threshold separating abiotic from biological oxygen signals — implicitly grounded in Earth's Archean reductive sink balance — has not yet been formally examined as a contingent parameter rather than a universal one. The present paper proposes that examination.

This distinction is not terminological. The quantitative result of Section 2 — that abiotic and biological O_2 fluxes bracket the same order of magnitude on the only inhabited planet accessible to direct study — makes the distinction empirically consequential. If the boundary cannot be resolved on Earth with Earth's own data, it cannot be resolved on a planet observed at interstellar distances by inference from Earth's geochemical parameters. The category error consists in applying contingent geochemical parameters — derived from one planet under one set of historical conditions — to other planetary systems as though they constituted universal physical law.

3.2 The n = 1 Problem and Its Epistemological Consequences

Exobiology operates with a sample of one inhabited planet. The implications of this constraint have not been drawn fully. From Earth alone, we cannot distinguish between:

(a) Universal properties of life: biology, wherever it exists, produces O_2 as a thermodynamic consequence of oxygenic photosynthesis, in quantities that systematically exceed abiotic production under any planetary boundary conditions.

(b) Contingent properties of life on Earth: Earth biology produces O_2 in the observed quantities because of the specific evolutionary trajectory of cyanobacteria under Archean geochemical conditions — conditions that may not be replicated on any other known planet.

The analysis of Section 2 demonstrates that this distinction cannot be resolved from Earth's geochemical record: abiotic and biological contributions to Archean O_2 are of comparable magnitude and cannot be cleanly separated with current data. If we cannot resolve this on the only inhabited planet accessible to direct study, we cannot resolve it on a planet observed at interstellar distances through a telescope.

3.3 A Causal Implication: Abiotic Oxidants as Selective Pressure

There is a further consequence of this analysis that deserves recognition. If abiotic O_2 and H_2O_2 production is a physically universal consequence of UV irradiation and silicate chemistry on wet rocky planets, it may also constitute a universal selective pressure driving the evolution of oxidant-utilizing metabolisms. Hao et al. (2021, Nature Communications) demonstrated experimentally that abiotic H_2O_2 and O_2 from silicate abrasion in turbulent subaqueous environments created the oxidant gradients that selectively

disadvantaged anaerobic microorganisms — concluding that this abiotic supply created an evolutionary impetus for the origin of oxygenic photosynthesis. Under this interpretation, cyanobacteria did not invent O_2 production from scratch in a fully reduced environment; they evolved to exploit an oxidant gradient that already existed.

This reframes the relationship between abiotic geochemistry and biology. Rather than treating biological O_2 production as a discrete event that superseded an abiotic baseline, the evidence suggests a continuum: abiotic oxidants → selective pressure → biological amplification → atmospheric oxygenation. The GOE, under this framework, represents not the origin of O_2 production but the point at which the combined abiotic and biological flux permanently exceeded the renewal capacity of geochemical reductive sinks.

4. Implications for Exoplanet Biosignature Interpretation

4.1 Rebuilding the Framework on Universal Constraints

A biosignature framework grounded in physically universal constraints rather than contingent terrestrial chemistry would have the following properties:

Universal baseline first. For any target planet, the first step in atmospheric interpretation is to establish what O_2 and related gases would be expected from photolysis, escape, and mineral chemistry alone — given the directly observable parameters of that planet: stellar UV flux, planetary mass and escape velocity, atmospheric composition, and estimated tectonic state. This baseline will differ for every target and cannot be assumed from terrestrial analogy.

Biological signal as departure from universal baseline. The diagnostic signature of biology is not O_2 above an absolute threshold derived from Earth, but an atmospheric state that cannot be explained by the universal baseline alone — a departure that requires an additional source. The classical CH_4 + O_2 disequilibrium biosignature (Krissansen-Totton, Olson & Catling, 2018) approximates this principle, though its application requires that the universal baseline be established individually for each target planet.

Observational context as prerequisite, not supplement. Stellar UV flux, planetary mass, tectonic indicators, and atmospheric composition are not optional contextual supplements to biosignature detection; they are the inputs required to compute the universal baseline. A detection without this context is not a weak detection — it is an uninterpretable signal.

4.2 Testable Predictions

Prediction 1. Any tectonically active rocky planet with liquid water, a CO_2/SO_2-bearing atmosphere, and a host star with sufficient UV-C output will develop a measurable abiotic O_2 signal, independently of biological activity. The magnitude of this signal will scale with planetary age, tectonic rate, stellar UV flux, and atmospheric composition. This prediction is falsifiable with sufficient spectral sensitivity from JWST or its successors.

Note on quantitative thresholds: *The absence of precise numerical thresholds in Prediction 1 is not a weakness of the framework — it is a direct consequence of its central argument. The scaling parameters governing abiotic O_2 production (stellar UV flux, tectonic rate, atmospheric SO_2 abundance, planetary escape velocity) are not derivable from terrestrial analogy; they must be measured directly for each target planet. Assigning a universal threshold derived from Earth's boundary conditions would reproduce the category error this framework is designed to correct. The prediction is falsifiable in principle; its quantitative form requires planet-specific observational inputs that are unavailable prior to observation.*

Prediction 2. The presence of sulfur mass-independent fractionation (MIF-S) in a planetary atmosphere — detectable in principle through S isotopologue spectroscopy — would constitute direct evidence of ongoing SO_2 photolysis in an anoxic environment. Its co-detection with O_2 would confirm abiotic O_2 production without biological amplification. Its disappearance from a planet's spectral record would mark an analog of the GOE — the onset of sustained atmospheric oxygenation.

Prediction 3 (falsification). A rocky, water-bearing planet with confirmed active tectonics, a CO_2/SO_2 atmosphere, a UV-active host star, and an age exceeding 3 Ga that shows no detectable O_2 or O_3 would require revision of the universal physical baseline presented here. Such an observation would imply either an unexpectedly efficient sink system or boundary conditions outside the range of current models.

5. Limitations and Research Priorities

Flux uncertainty. The flux estimates of Section 2 span one to two orders of magnitude. This uncertainty is genuine and reflects the incomplete constraint of Archean boundary conditions. Narrowing these bounds — particularly the SO_2 photolysis efficiency ε and the tectonic scaling of P_3 — requires targeted experimental work under Archean UV and pressure conditions.

Lightning plasma kinetics. The O* yield of natural lightning discharge in CO_2/H_2O mixtures at Archean atmospheric pressures has not been experimentally measured. Laboratory determination of this parameter would directly constrain P_4 and potentially alter the quantitative balance of Table 3.

Mafic mineralogy yield validation. The extension of continental ROS yield estimates to oceanic ultramafic crust (Section 2.4) assumes comparable mechanochemical efficiency across felsic and mafic mineralogies. Experimental characterization of H_2O_2 yield per unit friction energy in basaltic and komatiitic substrates under high hydrostatic pressure is required to constrain this extrapolation.

Operational classification of universal vs. contingent parameters. The distinction introduced in Section 3 requires a systematic classification of existing biosignature components — identifying which are grounded in physically universal constraints and which in contingent terrestrial chemistry.

This classification exercise is beyond the scope of the present paper and constitutes a necessary foundational contribution to the field.

Selective pressure hypothesis. (Hao et al., 2021) demonstrate that abiotic oxidants could have created selective pressure for the evolution of oxygenic photosynthesis; they do not demonstrate that this pressure was necessary. Whether oxygenic photosynthesis could have evolved in a fully anoxic environment remains an open question.

These limitations do not invalidate the central argument. They define the research agenda required to place it on a fully quantitative foundation.

6. Conclusion

Atmospheric oxygen has long been treated as a strong indicator of biological activity on exoplanets, on the grounds that no abiotic process produces it in sufficient quantities to dominate a planetary atmosphere. This paper has challenged that position on two counts.

First, a mechanism-by-mechanism flux analysis of three quantitatively constrained abiotic O_2 production mechanisms on Archean Earth — UV-C photolysis coupled to hydrodynamic H_2 escape, SO_2 photodissociation directly evidenced by the sulfur mass-independent fractionation record, and silicate mechanochemistry — yields a combined production of ~6×10^{11}–6×10^{12} mol O_2 yr^{-1}. This brackets the total documented Archean reductive sink capacity of ~5.1×10^{12} mol O_2-eq. yr^{-1}. The mathematical result is:

$$\Sigma_i P_i \sim 6\times10^{11}–6\times10^{12} \text{ mol } O_2 \text{ yr}^{-1} \quad \Sigma_j S_j \sim 5.1\times10^{12} \text{ mol } O_2\text{-eq. yr}^{-1} \quad (6.1)$$

The near-equivalence of Eq. 6.1 means that the boundary between abiotic and biological oxygen cannot be resolved from Earth's own geochemical record with current data. This is not a quantitative failure — it is an epistemological result. It demonstrates that even for the only inhabited planet accessible to direct study, we cannot cleanly separate the abiotic and biological contributions to atmospheric O_2.

Second, this result exposes a structural category error in current biosignature frameworks: the conflation of physically universal constraints — which follow from physical laws applicable to any rocky planet — with contingent geochemical parameters, which reflect the specific boundary conditions of one planet under one set of historical conditions. Applying the quantitative outputs of terrestrial geochemistry to other planetary systems as though they constituted universal physical law introduces an unquantified systematic bias into life detection.

The implication for exoplanet observation is direct: the interpretation of any atmospheric signal as a biosignature requires that a physically universal abiotic baseline be established first — derived from the directly observable parameters of the target planet, not assumed from terrestrial analogy. Before that baseline is established, a detection is not evidence of life. It is an unresolved signal.

Exobiology and paleoclimatology are historical and observational sciences operating on vast timescales and, currently, a sample size of one. This paper does not seek to replace the terrestrial geochemical model with a new rigid framework, nor does it claim absolute precision in quantifying Archean fluxes. Rather, it demonstrates that because abiotic O_2 production is driven by universal physicochemical processes, the irreducible uncertainty in distinguishing abiotic from biological oxygen must be formally integrated into interpretive frameworks — not treated as a problem to be solved by additional terrestrial analogy.

This paper does not claim that life is rare or that O_2 is uninformative. It claims that the framework currently used to interpret O_2 as a biosignature has been built on a foundation that conflates the universal and the contingent — and that correcting this conflation is a necessary condition for meaningful life detection in the era of JWST and beyond.

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