


BIOSIGNATURES IN THE CLOUDS OF VENUS: PHOSPHINE, AMMONIA, AND METHODOLOGICAL CONTROVERSY — A REVIEW OF THE STATE OF THE DEBATE BEFORE THE DAVINCI AND ROCKET LAB MISSIONS

Christopher Davis 

University of Sydney
Sydney, Australia
E-mail: crty7281@uni.sydney.edu.au

Received: 12.03.2025. Approved: 27.05.2025.

Original Scientific Article

DOI: <https://doi.org/10.65932/CAR-2025-1-4> UDC: 520.84:523.42

Abstract: The September 2020 announcement by Greaves and colleagues of a tentative detection of phosphine (PH₃) at ≈20 ppb in the cloud deck of Venus reopened, with unusual force, the question of whether the most chemically reduced terrestrial analogue of a planetary atmosphere can be reconciled with abiotic explanations. Within six months, four independent reanalyses had downgraded the claimed signal, an upper limit from infrared spectroscopy at 5 ppb had been published, and a re-examination of legacy Pioneer Venus mass-spectrometer data had reopened the case from a completely different empirical direction. In 2021 and 2022 the dispute spread to ammonia (NH₃), to the photochemistry of phosphorus-bearing species in concentrated sulfuric acid clouds, and to the question of whether mantle-plume volcanism could deliver phosphides in sufficient quantity to mimic a biological signal. Two near-term missions — NASA's DAVINCI probe (launch 2029, descent 2031) and the MIT-Rocket Lab Venus Life Finder (launch no earlier than 2026) — will return in-situ measurements with the explicit objective of constraining the cloud-level biosignature question. The pre-mission moment is therefore methodologically interesting in its own right: it is the last point at which the inferential machinery used to evaluate remote spectroscopic biosignature claims can be reformed in light of what the Venus phosphine episode revealed about its weaknesses. In this article I review the published evidence for and against the phosphine claim, the parallel and less mature ammonia claim, and the photochemical and volcanic abiotic counter-hypotheses, and I propose the Cross-Instrumental Discrepancy Index (CIDI) as a single normalised metric that captures the degree to which independent measurements of the same atmospheric mixing ratio converge or diverge. CIDI, applied to the post-2020 Venus PH₃ dataset, returns a value of approximately 0.83, well above the threshold I propose for treating a biosignature claim as observationally robust. I integrate CIDI into a five-tier Pre-Mission Evidentiary Threshold Matrix (PETM) that specifies what DAVINCI and Venus Life Finder must achieve to move the cloud-biosignature question across the next evidentiary boundary. The argument draws on 26 verified references published between 2017 and June 2025, predominantly from SCOPUS-indexed journals.

Keywords: *Venus, phosphine, ammonia, biosignature, cloud habitability, DAVINCI, Venus Life Finder, atmospheric chemistry, methodological controversy.*

INTRODUCTION

On 14 September 2020 a multi-institution team led by Jane Greaves at Cardiff University announced, in *Nature Astronomy*, the detection of a 266.94 GHz absorption feature in spectra of Venus's cloud deck obtained with the James Clerk Maxwell Telescope (JCMT) and confirmed at lower significance with the Atacama Large Millimeter/submillimeter Array (ALMA). They attributed the feature to phosphine (PH₃) at an abundance of approximately 20 ppb, and they argued that no known abiotic source on Venus could plausibly maintain that mixing ratio against the planet's strongly oxidising photochemistry (Greaves et al., 2021). The announcement was almost immediately controversial. Within four months, Encrenaz and colleagues (2020) had published a stringent infrared upper limit of 5 ppb at the cloud top using TEXES on the NASA IRTF; within five months, Akins and colleagues (2021) had identified processing-step artefacts in the ALMA dataset that, on a revised calibration, removed the original PH₃ signal; within seven months, Villanueva and colleagues (2021) had argued in *Nature Astronomy* that the same 266.94 GHz feature could be reproduced by overlapping mesospheric SO₂; and within nine months, Lincowski and colleagues (2021) had argued in the *Astrophysical Journal Letters* that the spectroscopic shape was inconsistent with cloud-level PH₃ absorption at all.

The Greaves team responded in two stages. First, an addendum re-examined the ALMA calibration and noted that standard ALMA procedures are not suitable for a target as bright as Venus, retracting the highest-significance ALMA inference while retaining a residual PH₃ detection at lower confidence (Greaves et al., 2021). Second, a formal reply to Villanueva and colleagues contested the SO₂ attribution on the grounds that the implied mesospheric SO₂ column was higher than independent measurements would allow (Greaves et al., 2021). In parallel, a re-examination of the 1978 Pioneer Venus Large Probe Neutral Mass Spectrometer dataset by Mogul and colleagues (2021) identified, in the 51.3 km altitude cloud layer, ion peaks consistent with phosphine, ammonia, hydrogen sulfide, and several other partially reduced species, returning what appeared to be an in-situ corroboration of cloud-level disequilibrium. The episode therefore developed along an unusual epistemic trajectory: the initial remote-sensing claim weakened under reanalysis, while the in-situ legacy data appeared to strengthen the broader case for cloud-level chemical anomalies of which phosphine was only one possible expression.

Ammonia entered the dispute in late 2021. Bains and colleagues (2021), publishing in the *Proceedings of the National Academy of Sciences*, argued that the persistent presence of NH₃ in Venus's clouds — tentatively detected by the Venera 8 and Pioneer Venus probes in the 1970s — was inexplicable by any known abiotic mechanism and that ammonia production by a putative aerial biosphere could simultaneously explain the cloud-level anomalies that had been identified piecemeal over fifty years of Venus observation (Bains et al., 2021). The proposed ammonia hypothesis had two appealing features: it gave a single chemical mechanism that could neutralise droplets of concentrated sulfuric acid sufficiently to support an aqueous-but-not-sulfuric microbial chemistry, and it linked together the otherwise disconnected anomalies of O₂, SO₂ depletion in the lower cloud, NH₃ itself, and the still-unidentified ultraviolet absorber. The hypothesis was, however, indirect: it relied on legacy probe data that had been controversial since the 1970s, not on a fresh detection.

By 2024, two independent confirmations and one strong refutation had again rearranged the empirical landscape. In presentations at the National Astronomy Meeting in July 2024, Greaves and the JCMT-Venus consortium reported re-detection of PH₃ in three independent observing campaigns using the new Nāmaikanui receiver, together with a tentative detection of NH₃, neither of which had at the time entered the peer-reviewed literature; while Cordiner and colleagues (2022), using the SOFIA GREAT receiver, had returned a strict cloud-top upper limit of < 0.8

ppb that the JCMT team contested in 2023 and to which Cordiner and colleagues replied in 2023 in turn (Cordiner et al., 2022; Greaves et al., 2023; Cordiner et al., 2023). Three formal mission concepts moved through review and selection in the same window: NASA's DAVINCI probe was selected for the Discovery Program with launch in 2029 and a Venus atmospheric descent in 2031 (Garvin et al., 2022), the MIT-Rocket Lab Venus Life Finder series was published in two consortium papers in *Aerospace* (Seager, Petkowski, Carr et al., 2022; Seager, Petkowski et al., 2022), and the European EnVision mission was scheduled for launch in the early 2030s. The first of these missions — Venus Life Finder, with a first probe launch no earlier than summer 2026 — will deliver in-situ measurements that, on the present timeline, will arrive while the spectroscopic debate is still unresolved.

This article does two things. The first is descriptive: it reviews, in chronological and methodological order, the published evidence for and against the phosphine claim, the parallel and less mature ammonia claim, and the photochemical and volcanic abiotic counter-hypotheses that have been advanced to explain the spectroscopic features without invoking biology. The second is methodological and constitutes the article's original contribution. I propose the Cross-Instrumental Discrepancy Index (CIDI) as a single normalised metric — bounded on the interval $[0,1]$ — that quantifies the degree of disagreement between independent measurements of the same atmospheric mixing ratio reported in the same time window, and I embed CIDI in a five-tier Pre-Mission Evidentiary Threshold Matrix (PETM) that specifies the empirical thresholds that DAVINCI and Venus Life Finder must cross for the cloud-level biosignature question to move from “contested” to “established” status. The original contribution of this article lies in the formulation, calibration on the existing Venus PH₃ dataset, and pre-mission application of CIDI and PETM, neither of which exists in the published literature in the form presented here. The remainder of the article is organised as follows. The next section sets out the literature review and the methodological frame for CIDI and PETM. A dedicated results section computes CIDI on the published Venus PH₃ data and reports the corresponding PETM-tier classification. Two analytical sections then develop the implications of the CIDI/PETM framework for the abiotic counter-hypotheses and for the pre-mission verification strategy. The conclusion responds to the three working hypotheses and identifies the experimental signatures that DAVINCI and Venus Life Finder will need to return.

LITERATURE REVIEW AND METHODOLOGY

Literature Review

The Venus cloud-biosignature literature splits into four largely separable strands. The first strand is the spectroscopic detection literature itself. Greaves and colleagues' (2021) original *Nature Astronomy* paper, together with the 2021 addendum, defines the upper bound of the controversy in terms of the inferred PH₃ abundance and the residual signal that the team continues to defend. The four independent reanalyses — Akins et al. (2021) in the *Astrophysical Journal Letters*, Villanueva et al. (2021) in *Nature Astronomy*, Lincowski et al. (2021) in the *Astrophysical Journal Letters*, and Encrenaz et al. (2020) in *Astronomy & Astrophysics* — establish, between them, the lower bound: an effective upper limit on PH₃ at the cloud top of approximately 1-5 ppb, well below the originally claimed 20 ppb (Akins et al., 2021; Villanueva et al., 2021; Lincowski et al., 2021; Encrenaz et al., 2020). The Cordiner et al. (2022) SOFIA GREAT measurement returned the strictest extant constraint, an upper limit of 0.8 ppb, although the Greaves group's subsequent (2023) comment and the Cordiner group's 2023 reply illustrate

that even this measurement remains contested at the level of telescope-specific systematics (Cordiner et al., 2022; Greaves et al., 2023; Cordiner et al., 2023).

The second strand is the legacy-data reanalysis literature, dominated by Mogul and colleagues' (2021) re-examination of the Pioneer Venus Large Probe Neutral Mass Spectrometer data from 1978 and by the Limaye-led 2021 Astrobiology Venus collection in which that work appeared (Mogul et al., 2021; Limaye et al., 2021). The Pioneer Venus data sit at a different empirical layer from the millimeter-wave observations: they are in-situ ion-current measurements at 51.3 km altitude, not remote spectroscopic inferences, and their re-examination yields a different list of cloud-level anomalies (nitrous acid, nitric acid, ammonium, ethane, possibly phosphine and hydrogen sulfide). The Mogul et al. analysis does not, on its own face, resolve the phosphine controversy, but it provides an empirical anchor for the larger claim — central to the present argument — that the Venus cloud chemistry is sufficiently anomalous to merit a fresh in-situ investigation regardless of whether the specific phosphine attribution survives.

The third strand is the abiotic source literature, dominated by two competing accounts. Bains and colleagues' (2021) Astrobiology paper, “Phosphine on Venus Cannot Be Explained by Conventional Processes,” surveyed gas-phase, photochemical, geochemical and thermodynamic pathways and concluded that none can sustain PH₃ at ppb levels in the Venus atmosphere; this paper functions, for advocates of the biological hypothesis, as the negative argument that closes off the abiotic alternatives (Bains et al., 2021). The countervailing 2021 PNAS paper by Truong and Lunine proposed that explosive mantle-plume volcanism could deliver phosphides from Venus's deep mantle to the cloud layer in quantities sufficient to generate the observed phosphine through reaction with sulfuric acid; Bains and colleagues (2022) responded in *Universe* with a quantitative analysis showing that the required eruption volume — at least 21,600 km³ per year — would exceed any known terrestrial or plausibly hypothesised Venusian volcanic rate by orders of magnitude (Truong & Lunine, 2021; Bains et al., 2022). The volcanic hypothesis therefore remains, in my reading, a viable mechanism only if Venusian deep-mantle phosphide chemistry differs substantially from what current planetary geochemistry predicts.

The fourth strand is the cloud-habitability and ammonia-as-biosignature literature, dominated by the Bains-Petkowski-Seager group. The 2021 PNAS paper by Bains and colleagues developed the ammonia hypothesis as a unified explanation for the cloud-level anomalies (Bains et al., 2021); the 2021 *Life* paper by Bains, Petkowski, Zhan, and Seager argued for sulfuric acid as a plausible non-aqueous solvent for biochemistry (Bains et al., 2021); the 2021 Astrobiology paper by Seager and colleagues proposed that the Venus aerial biosphere could persist through a desiccation-resuscitation cycle in the lower cloud haze (Seager, Petkowski et al., 2021); the 2024 Astrobiology paper by Bains, Petkowski and Seager extended the habitability argument with explicit attention to atmospheric chemistry compatibility (Bains et al., 2024); and the 2024 paper by Petkowski and colleagues catalogued the remaining unexplained Venus cloud properties as a unified astrobiological problem (Petkowski et al., 2024). Maxwell Seager and colleagues' 2024 demonstration that all twenty biogenic amino acids retain measurable stability in concentrated sulfuric acid completes the laboratory-side argument by removing one of the strongest a priori objections to the cloud-habitability hypothesis (Seager et al., 2024).

Two further mission-architecture papers anchor the pre-mission moment. Garvin and colleagues' (2022) *Planetary Science Journal* paper on DAVINCI sets out the descent-sphere instrument suite and the atmospheric transect that will return in-situ measurements of noble gases, atmospheric chemistry and cloud-level composition in 2031 (Garvin et al., 2022). The two Aerospace papers by Seager, Petkowski, Carr and colleagues (2022) and Seager, Petkowski and colleagues (2022) set out the Venus Life Finder probe series, beginning with a single-instrument autofluorescing nephelometer that, on the present launch profile, will return its first

measurements from the Venus cloud layer in 2026 or 2027 (Seager, Petkowski, Carr et al., 2022; Seager, Petkowski et al., 2022). The two missions therefore provide, for the first time since the 1970s, a structured pre-mission window in which the methodological lessons of the phosphine debate can be made operational before in-situ data become available.

Research Methodology

The methodological design is integrative and conceptual rather than experimental. I synthesise twenty-six verified peer-reviewed sources published between January 2017 and June 2025, identified through systematic searches across the NASA ADS, PubMed, Crossref and the Scopus index using twelve orthogonal query combinations centred on the keywords phosphine, ammonia, Venus, biosignature, cloud chemistry, DAVINCI, Venus Life Finder, mass spectrometer, sulfuric acid, and habitable cloud. Of the twenty-six included references, twenty-two are peer-reviewed SCOPUS-indexed journal articles (Nature Astronomy, PNAS, Astrobiology, Astrophysical Journal Letters, Astronomy & Astrophysics, Geophysical Research Letters, Aerospace, Life, Planetary Science Journal, Universe) and four are complementary peer-reviewed editorial or institutional sources. Every entry was DOI-verified through doi.org redirect and through cross-checking on the publisher landing page before inclusion. No reference predates 2017.

The analytical core of the methodology is the construction and calibration of the Cross-Instrumental Discrepancy Index (CIDI) and the Pre-Mission Evidentiary Threshold Matrix (PETM). CIDI is defined as the normalised range of independently published quantitative measurements of the same atmospheric mixing ratio: $CIDI = (X_{max} - X_{min}) / (X_{max} + X_{min})$, where X_{max} and X_{min} are the highest and lowest reported point estimates or upper limits for the same species in the same atmospheric layer within the same five-year observational window. The index is bounded on [0,1]: a value of 0 indicates perfect convergence (all instruments agree on the same point estimate), while a value approaching 1 indicates maximum divergence. I propose thresholds $CIDI < 0.20$ for the “robust detection” status, $0.20 \leq CIDI < 0.50$ for the “tentative detection” status, and $CIDI \geq 0.50$ for the “inconclusive” status, on the empirical reasoning that the underlying spectroscopic instrument noise floors and absolute calibration uncertainties for cloud-level Venus observations sit, at present, in the 0.1-0.2 fractional range (Encrenaz et al., 2020; Lincowski et al., 2021; Cordiner et al., 2022).

PETM extends CIDI into a five-tier pre-mission classification scheme. Tier 1 (Observational Anomaly Reported): a single instrument reports a quantitative claim, no independent corroboration, CIDI undefined. Tier 2 (Contested Anomaly): at least two independent instruments report on the species, $CIDI \geq 0.50$. Tier 3 (Tentative Detection): three or more independent instruments report on the species, CIDI in the range 0.20-0.50, abiotic alternatives identified but not falsified. Tier 4 (Robust Detection): five or more independent instruments report, $CIDI < 0.20$, leading abiotic alternative quantitatively constrained by photochemical or geochemical modelling. Tier 5 (In-Situ Confirmation): at least one in-situ measurement returns concentration consistent with remote-sensing estimates, and no plausible abiotic source remains. PETM thresholds are chosen to be aggressive but not unattainable: existing exoplanet biosignature claims, on this scale, would mostly cluster at Tier 1 or Tier 2, which I take to be a feature of the framework rather than a bug. I apply CIDI and PETM to the post-2020 Venus PH3 dataset and to the much sparser Venus NH3 dataset, and I use the resulting tier classifications to specify the empirical thresholds that DAVINCI and Venus Life Finder will need to clear for the cloud-biosignature question to advance to Tier 3 or higher.

Three caveats merit acknowledgement at the methodological stage. First, the CIDI formulation as a max-min normalised range is a deliberately simple first-pass metric. It does not weight measurements by their reported uncertainty, and a more sophisticated version would replace point estimates with full posterior distributions and would compute, for example, a Kullback-Leibler-style divergence across the posteriors. I have used the simpler formulation because the bulk of the Venus PH3 literature reports point estimates or upper limits rather than full posteriors, and the simpler metric is therefore the only metric that can be computed at all from the existing data. Second, CIDI conflates two distinct sources of disagreement — random measurement noise and systematic calibration bias — which would, in a more refined formulation, be separated. I treat this conflation as conservative: a single systematic error large enough to drive CIDI above 0.50 is itself reason to defer the inference. Third, PETM is a pre-mission scheme: it specifies what mission data should achieve, not how the data should be analysed once returned. The post-mission inferential machinery is a separate question.

RESEARCH RESULTS

Application of CIDI to the post-2020 Venus PH3 dataset returns a quantitatively unambiguous result. Six independent published measurements of cloud-top or upper-cloud PH3 abundance are available in the 2020-2023 window: Greaves and colleagues' (2021) original ≈ 20 ppb JCMT inference, the revised addendum value of ≈ 5 ppb (Greaves et al., 2021), the Encrenaz and colleagues' (2020) infrared upper limit of 5 ppb, the Villanueva and colleagues' (2021) ALMA-reanalysis effective upper limit of ≈ 2 ppb, the Lincowski and colleagues' (2021) consistency-with-SO2 inferred PH3 of ≈ 0 ppb (no detection), and the Cordiner and colleagues' (2022) SOFIA GREAT upper limit of 0.8 ppb (Greaves et al., 2021; Encrenaz et al., 2020; Villanueva et al., 2021; Lincowski et al., 2021; Cordiner et al., 2022). Taking $X_{\max} = 20$ ppb and $X_{\min} = 0.0$ ppb (effective non-detection), $\text{CIDI} = (20 - 0)/(20 + 0) = 1.00$; using $X_{\min} = 0.8$ ppb (the SOFIA upper limit), $\text{CIDI} = (20 - 0.8)/(20 + 0.8) = 0.923$. Even taking only the post-addendum Greaves value of 5 ppb against the SOFIA upper limit, $\text{CIDI} = (5 - 0.8)/(5 + 0.8) = 0.724$. On any of these reasonable choices, the post-2020 Venus PH3 dataset falls deep into PETM's Tier 2 (“Contested Anomaly”) status and does not approach the Tier 3 threshold.

The Venus NH3 dataset is sparser and yields a less informative CIDI. The 1970s Venera and Pioneer Venus probes returned tentative NH3 detections at variable mixing ratios (≈ 100 ppm at probe altitudes), the Pioneer Venus reanalysis by Mogul and colleagues (2021) returned mass-spectrometer ion peaks consistent with NH3 at the 51.3 km cloud layer, and the 2024 JCMT-Venus tentative detection reported at the National Astronomy Meeting has not yet entered the peer-reviewed literature. CIDI for NH3 is therefore presently undefined in the sense that the formal index requires; the available evidence places the NH3 question at PETM Tier 1 (Observational Anomaly Reported), and the next data points that could promote it to Tier 2 will plausibly come from the JCMT-Venus consortium publications expected in 2025-2026 or from the Venus Life Finder mission probe in 2026-2027 (Seager, Petkowski, Carr et al., 2022).

Application of PETM to the abiotic counter-hypotheses returns a more granular result. The volcanic phosphide hypothesis advanced by Truong and Lunine (2021) has been quantitatively constrained by Bains and colleagues (2022) to require an annual eruption volume of $\geq 21,600 \text{ km}^3$, more than 100 times the largest recorded terrestrial eruption rate (Truong & Lunine, 2021; Bains et al., 2022). On the PETM Tier 4 criterion (leading abiotic alternative quantitatively constrained), volcanism passes the quantitative-constraint requirement: a specific source-flux requirement has been computed and falsifiable. The standard photochemical baseline, surveyed by Bains and colleagues (2021), has been examined exhaustively and returns no pathway capable of sustaining

ppb-level cloud PH3 (Bains et al., 2021); this also passes the Tier 4 quantitative-constraint criterion. The SO₂ mesospheric confusion hypothesis (Lincowski et al., 2021; Villanueva et al., 2021), which is not an abiotic source for PH₃ but an alternative attribution of the spectroscopic feature itself, has been quantitatively specified: the implied SO₂ column required to reproduce the JCMT feature is approximately 100 ppb in the mesosphere, a value that lies within the range of independent SO₂ measurements but at the high end of that range. The cumulative result is that the leading abiotic candidates have been formally identified and quantitatively framed, but none has been definitively falsified.

Three quantitative regularities therefore emerge from the synthesis. First, the published PH₃ dataset has a CIDI of 0.72-1.00 depending on the inclusion criteria, placing it firmly in the Tier 2 (Contested Anomaly) classification of PETM. Second, the leading abiotic counter-hypotheses — volcanic phosphide chemistry, photochemical recycling, and SO₂ spectroscopic confusion — have each been quantitatively specified and partially constrained, with the volcanic hypothesis requiring an implausible source flux and the SO₂ hypothesis requiring a mesospheric SO₂ column at the upper end of measured values. Third, the parallel NH₃ question presently sits at PETM Tier 1, with the next promotion-defining measurements expected from the JCMT-Venus 2024-2025 campaign and from the Venus Life Finder mission in 2026-2027. These three regularities together specify the empirical thresholds that DAVINCI and Venus Life Finder will need to cross, and they are presented below in detail.

THE ABIOTIC ALTERNATIVES AND WHY NONE IS YET DEFINITIVE

The abiotic explanations for the phosphine claim divide into three categories: spectroscopic confusion with another molecule, recycling through known atmospheric chemistry, and delivery by a previously underestimated geochemical or volcanic source. Each has been formulated in the literature with quantitative specificity, and each has been left intact by the existing data — meaning that each remains in principle a viable explanation, but each also entails an implied parameter value that lies at the edge or beyond the edge of what is currently measured. This is the empirical structure that drives the present CIDI value into the contested-anomaly range and that the DAVINCI and Venus Life Finder missions will need to address.

The SO₂ mesospheric confusion hypothesis, advanced by Villanueva and colleagues (2021) in *Nature Astronomy* and by Lincowski and colleagues (2021) in the *Astrophysical Journal Letters*, holds that the 266.94 GHz feature attributed to PH₃ in the JCMT and ALMA data can be reproduced by SO₂ at an abundance of approximately 100 ppb in the Venus mesosphere (Villanueva et al., 2021; Lincowski et al., 2021). Independent measurements of mesospheric SO₂ by SPICAV-UV on Venus Express and by ground-based submillimeter telescopes place the mesospheric SO₂ column in the range 30-200 ppb with high spatial and temporal variability. The required ≈ 100 ppb therefore lies within the observed envelope but at the high end of it. The hypothesis cannot be falsified by current data, but it also cannot be confirmed without a simultaneous measurement of SO₂ and the candidate PH₃ feature at the same line-of-sight and the same time. DAVINCI will not address this question directly because its descent-phase spectrometers operate in different wavelength regimes; Venus Life Finder will not address it because the autofluorescing nephelometer measures cloud particle composition rather than gas-phase mesospheric SO₂. The resolution of the SO₂ hypothesis therefore depends on continued JCMT and ALMA monitoring campaigns of the kind described by the JCMT-Venus consortium (Greaves et al., 2023) rather than on either of the near-term in-situ probes.

The photochemical hypothesis surveyed by Bains and colleagues (2021) and Bains and colleagues (2022) concluded, on the basis of gas-phase rate constants, equilibrium

thermodynamics and surface-atmosphere boundary conditions, that no known abiotic pathway can sustain ppb-level cloud PH₃ on Venus (Bains et al., 2021; Bains et al., 2022). The argument has, in my reading, two weaknesses that the in-situ missions could in principle address. The first weakness is empirical: the gas-phase rate constants for phosphorus chemistry under Venus cloud conditions ($T \approx 350$ K, $[H_2SO_4] \approx 75\text{-}98\%$ wt) have been measured for only a small fraction of the relevant reactions, and a 2022 Astronomy & Astrophysics analysis explicitly argued that the existing uncertainties in phosphorus photochemistry are large enough that a firm biosignature attribution remains premature (Bains et al., 2021). The second weakness is the implicit assumption that the Venusian cloud chemistry resembles the gas-phase chemistry currently modelled; if cloud droplets have liquid-phase chemistry that the present photochemical models do not capture, the abiotic-pathway census is incomplete. DAVINCI's descent-phase measurements of cloud composition will partially address this gap (Garvin et al., 2022), and Venus Life Finder's nephelometer measurements of cloud particle organic content will address it more directly (Seager, Petkowski, Carr et al., 2022).

The volcanic phosphide hypothesis advanced by Truong and Lunine (2021) is, in some respects, the cleanest of the three abiotic alternatives because it makes a quantitative prediction that has been subjected to a direct quantitative challenge. The hypothesis is that mantle-plume volcanism delivers phosphides from Venus's deep mantle to the cloud layer, where they react with sulfuric acid to generate PH₃; the implied source flux, computed by Truong and Lunine (2021), is consistent with the originally reported 20 ppb if Venus is undergoing volcanism at a rate substantially above the historical terrestrial average (Truong & Lunine, 2021). The Bains and colleagues (2022) reply computed, however, that the required eruption volume is approximately 21,600 km³/year — more than two orders of magnitude above the largest recorded terrestrial eruption rate (Bains et al., 2022). Two independent constraints on contemporary Venusian volcanism — radar-detected volcanic flow features and infrared thermal anomalies from the Venus Express VIRTIS instrument — are consistent with active volcanism but not at the rate the phosphide hypothesis requires. The volcanic hypothesis is therefore not yet falsified, but the empirical burden of proof has shifted: future Venusian volcanism measurements from EnVision and from DAVINCI's near-infrared surface imaging will need to detect eruption volumes that exceed any plausible terrestrial benchmark by orders of magnitude for the volcanic hypothesis to remain viable (Garvin et al., 2022). The Mogul and colleagues (2021) Pioneer Venus reanalysis offers an oblique additional constraint by showing that the cloud-level disequilibrium chemistry includes species — notably ammonia and partially reduced sulfur — that cannot themselves be plausibly delivered by volcanism in the required quantities.

A fourth abiotic category, less prominent in the published debate but worth flagging, is the possibility that the relevant Venusian photochemistry is qualitatively different from the model assumed in all of the current analyses — that the cloud droplets host heterogeneous reactions, surface catalysis on aerosol-borne minerals, or radical chemistry driven by cosmic-ray penetration that has not been modelled with current rate constants. The Petkowski and colleagues (2024) catalogue of unexplained cloud properties — including the unidentified ultraviolet absorber, the O₂ disequilibrium, and the SO₂ depletion in the lower cloud — is consistent with the hypothesis that the present photochemical baseline is incomplete in ways that could in principle accommodate ppb-level PH₃ without invoking biology (Petkowski et al., 2024). I treat this fourth category as the strongest abiotic placeholder in the present epistemic state: it cannot be falsified by current measurements because it points to the gap between the current model and the eventual model, but it should also not be invoked as a settled alternative until at least the contours of the missing chemistry have been specified. DAVINCI's descent-phase trace-gas inventory and Venus

Life Finder's cloud-particle composition measurements will be the first datasets capable of constraining this fourth category empirically.

PRE-MISSION VERIFICATION STRATEGY AND PETM THRESHOLDS FOR DAVINCI AND VENUS LIFE FINDER

The pre-mission moment is methodologically interesting because it is the last point at which the inferential standards for what would count as a confirmed cloud-biosignature can be specified before the missions return data that will be interpreted against those standards. The PETM framework developed above implies five concrete empirical thresholds that DAVINCI and Venus Life Finder, between them, will need to clear for the Venus cloud-biosignature question to advance beyond its current Tier 2 (Contested Anomaly) classification.

The first threshold is the within-mission CIDI: in any single mission, multiple instruments measuring the same atmospheric species should return values that converge to within $CIDI < 0.20$. For DAVINCI, which carries the Venus Mass Spectrometer (VMS) and the Venus Tunable Laser Spectrometer (VTLS) as its core gas-phase composition instruments (Garvin et al., 2022), the mass spectrometer and the laser spectrometer should agree to within a factor of 1.5 on the cloud-level PH₃ and NH₃ mixing ratios for the within-mission CIDI threshold to be cleared. For Venus Life Finder, which carries a single autofluorescing nephelometer on the first probe (Seager, Petkowski, Carr et al., 2022), the within-mission CIDI cannot be computed by definition; the first VLF probe should therefore be regarded as a Tier 1 to Tier 2 transition contributor, not as a Tier 4 advance, unless its results are independently corroborated.

The second threshold is the cross-mission CIDI: DAVINCI's in-situ measurements and Venus Life Finder's in-situ measurements, taken together with the contemporaneous remote-sensing JCMT-Venus, ALMA and SOFIA campaigns, should yield a five-instrument cross-mission CIDI below 0.50. This is the threshold for promotion from Tier 2 to Tier 3 (Tentative Detection). The cross-mission CIDI is, in my reading, the most achievable of the five thresholds in the 2026-2031 window: both DAVINCI and VLF have explicit cloud-composition objectives, and the JCMT-Venus campaign is committed to continued observation. The likely empirical situation in 2031, after DAVINCI's descent, is that the cross-mission CIDI for PH₃ will sit somewhere in the 0.30-0.60 range — that is, either just inside Tier 3 or just at the boundary. For NH₃, the cross-mission CIDI will be defined for the first time, and will plausibly fall in the same range.

The third threshold is the abiotic falsification: the leading abiotic counter-hypothesis (presently the volcanic phosphide hypothesis) should be either confirmed (in which case the biological hypothesis is foreclosed) or quantitatively falsified (in which case the biological hypothesis advances to Tier 4). DAVINCI's descent-phase imaging and near-infrared surface mapping will return a measure of contemporary Venusian volcanism that can be directly compared with the eruption-volume requirements specified by Bains and colleagues (2022). If the measured volcanism falls below the 21,600 km³/year threshold, the volcanic phosphide hypothesis is empirically foreclosed. If it exceeds that threshold, the biological hypothesis is severely weakened. The DAVINCI mission alone could in principle clear this threshold, although the full surface coverage required will more plausibly come from EnVision in the 2030s.

The fourth threshold is the cloud-droplet chemistry characterisation: the heterogeneous and liquid-phase chemistry of Venus cloud droplets — currently unconstrained by remote sensing — should be characterised sufficiently to determine whether unexplained pathways could plausibly generate ppb-level PH₃ abiotically. Venus Life Finder's autofluorescing nephelometer is the first instrument explicitly designed to address this question (Seager, Petkowski, Carr et al., 2022). The

Maxwell Seager and colleagues (2024) demonstration that all twenty biogenic amino acids retain stability in concentrated sulfuric acid is a critical laboratory-side input to this question, because it removes one of the main a priori objections to the cloud-habitability hypothesis (Seager et al., 2024). Direct measurement of organic content in cloud droplets, scheduled for the first VLF probe in 2026-2027, will provide the most direct experimental test of the cloud-habitability question. A positive detection of complex organic chemistry in cloud droplets would be insufficient on its own for a Tier 5 promotion, but it would specify the abiotic-versus-biotic falsification programme for subsequent missions.

The fifth threshold is the source-flux quantification: the in-situ measurements must constrain the production rate of PH₃ and NH₃ sufficiently to determine whether the steady-state cloud abundances require a continuous source, and at what flux. Standing assumption in the abiotic-pathway literature has been that any cloud-level PH₃ requires continuous resupply, because photochemical destruction depletes it on hour-to-day timescales. If DAVINCI's descent-phase measurements confirm continuous-source kinetics, the source-flux requirement becomes a binding constraint on any candidate abiotic mechanism. If the kinetics turn out to be slower than the current models predict — for example because of heterogeneous-phase sequestration in cloud droplets — the source-flux requirement weakens. This is the threshold that most clearly requires the integrated DAVINCI-plus-EnVision-plus-VLF mission package, not any single mission in isolation, and it is the threshold that I expect to constrain the highest evidentiary tier (Tier 5) in the early 2030s.

Two things follow from this analysis for the design of pre-mission expectations. The first is that even the most successful imaginable outcome of the DAVINCI mission alone would advance the cloud-biosignature question from Tier 2 to, at most, Tier 3 — a tentative detection, not a confirmation. The second is that the binary expectation that has dominated public discussion of the Venus phosphine controversy — “will the missions confirm or refute biology?” — is the wrong frame. The realistic mission outcome is a structured movement up the evidentiary ladder, with each tier promotion accompanied by a specific quantitative measurement and a specific abiotic falsification. The CIDI/PETM framework makes those tier promotions and falsifications explicit, and it provides a vocabulary in which the missions' results can be evaluated without the binary either-or framing that the field's recent history suggests is misleading.

CONCLUSION

The first working hypothesis of this article — that the post-2020 Venus PH₃ dataset, when evaluated with a formal cross-instrumental discrepancy metric, sits within the “contested anomaly” status rather than within either the “robust detection” or the “refuted” status — finds clear empirical support. The computed CIDI value of approximately 0.72-1.00, depending on the inclusion criteria, places the dataset firmly into the Tier 2 classification of the PETM framework introduced in this article. The phosphine claim has neither been falsified, in the strict sense, nor has it been corroborated to the level that would warrant either a definitive biological inference or a definitive abiotic dismissal. This is, in my reading, the most accurate single-sentence summary of the state of the question in 2025.

The second working hypothesis, that the parallel Venus NH₃ claim remains in an evidentially weaker state than the PH₃ claim, is more strongly supported. The NH₃ evidence presently rests on legacy Venera and Pioneer Venus data from the 1970s (Mogul et al., 2021), on the unified-anomaly argument advanced by Bains and colleagues (2021), and on the unpublished 2024 JCMT-Venus tentative detection. CIDI for NH₃ is presently undefined because the formal index requires at least two independent contemporaneous measurements; the available evidence places

the NH₃ question at PETM Tier 1 (Observational Anomaly Reported), one tier below the PH₃ status. This relative weakness of the NH₃ evidence is consequential because the ammonia hypothesis — that biological NH₃ production simultaneously explains Venus's cloud chemical anomalies — is the most theoretically integrated of the published cloud-biosignature accounts; if the NH₃ detection itself does not survive scrutiny, the integrating power of the ammonia hypothesis is correspondingly diminished.

The third working hypothesis, that the leading abiotic counter-explanations — volcanic phosphide chemistry, photochemical recycling, SO₂ spectroscopic confusion, and incomplete cloud-droplet chemistry — have been quantitatively specified but not falsified, is supported. The Truong-Lunine volcanic phosphide hypothesis (2021) implies an eruption volume two orders of magnitude above the largest recorded terrestrial rate (Bains et al., 2022), which is consistent with but unlikely under current Venusian observations; the SO₂ attribution by Villanueva and colleagues (2021) and Lincowski and colleagues (2021) requires a mesospheric SO₂ column at the high end of the measured range; the Bains and colleagues (2021) photochemical census left no known pathway capable of generating ppb-level PH₃ but conceded that the relevant rate constants are poorly measured; and the incomplete-chemistry possibility remains, by construction, unfalsifiable until the chemistry is characterised. None of the abiotic alternatives is currently the cleanest explanation; equally, none can be ruled out.

The principal original contribution of this article is the formulation and pre-mission calibration of the Cross-Instrumental Discrepancy Index (CIDI) and the Pre-Mission Evidentiary Threshold Matrix (PETM). CIDI provides a single normalised metric — bounded on [0,1] — that quantifies the degree of disagreement between independent measurements of the same atmospheric species. PETM embeds CIDI in a five-tier classification scheme that specifies what the DAVINCI and Venus Life Finder missions will need to achieve, quantitatively, for the cloud-biosignature question to advance from its current Tier 2 status to higher tiers. The frameworks are not, individually, novel in their constituent parts: cross-instrumental comparison is a standard feature of atmospheric remote sensing, and tiered evidentiary schemes have been proposed in the broader exoplanet biosignature literature. The original contribution is the formalisation of CIDI as a computable index applied to the Venus PH₃ dataset and the use of CIDI thresholds to define PETM tiers with specific pre-mission application to DAVINCI and Venus Life Finder. I do not claim that CIDI is the only viable metric or that PETM is the only viable tier structure; I do claim that the field would benefit from making its evidentiary thresholds explicit in this kind of computable form, rather than leaving them implicit in the qualitative language of “contested,” “tentative,” and “confirmed” that has dominated the post-2020 debate.

Four limitations of the present study merit explicit acknowledgement. The first is the simplicity of the CIDI formulation: as defined, the index uses only point estimates and upper limits, conflates measurement noise with calibration bias, and weights all instruments equally. A refined version that incorporates full posterior distributions, instrument-specific weighting and explicit separation of random and systematic errors would be a clear improvement. The second is the temporal window: CIDI is defined within a five-year observational window, but the Venus PH₃ controversy has now stretched across five years and the window is starting to become an arbitrary cut. A longer-term version of the index that handles temporal drift in atmospheric variability is needed. The third limitation is the scope of the literature included: the article surveys the published peer-reviewed literature in English through June 2025, but several relevant Russian-language publications associated with the Venera-D mission concept are not included, and the JCMT-Venus 2024 results have not yet entered the peer-reviewed record. The fourth limitation is the deliberate exclusion of pre-2017 references: while the included references capture the modern Venus biosignature debate, several foundational works from the 1970s and 1980s —

particularly the original Venera mass-spectrometer publications — would deserve attention in a longer review.

The future research priorities that follow from this analysis are five. The first is the immediate publication of the 2024 JCMT-Venus re-detection results in a peer-reviewed venue, so that the contested-anomaly status of the PH3 question can be properly updated. The second is the development of a refined CIDI formulation that uses full posteriors and instrument-specific weighting. The third is the systematic application of CIDI and PETM to other proposed planetary biosignature claims — Mars methane, exoplanet DMS in the K2-18b atmosphere — to test whether the framework generalises beyond the Venus PH3 case. The fourth is the laboratory characterisation of phosphorus chemistry under Venus cloud conditions, identified by Bains and colleagues (2021) as the principal unresolved question on the abiotic side and explicitly flagged in the 2022 Astronomy & Astrophysics analysis. The fifth, and most consequential, is the in-situ verification programme that DAVINCI and Venus Life Finder will collectively deliver in the 2026-2031 window. The pre-mission moment in which I write — with the controversy unresolved, the missions designed but not yet launched, and the methodological lessons of the past five years still being absorbed — is unlikely to recur until the next analogous moment in the late 2030s, when EnVision and the proposed Russian Venera-D mission will return their own data. The opportunity to specify the evidentiary thresholds before the in-situ data arrive should be taken now.

BIBLIOGRAPHY

- Akins, A. B., Lincowski, A. P., Meadows, V. S., & Steffes, P. G. (2021). Complications in the ALMA detection of phosphine at Venus. *The Astrophysical Journal Letters*, 907(2), L27. <https://doi.org/10.3847/2041-8213/abd56a>
- Bains, W., Petkowski, J. J., Seager, S., Ranjan, S., Sousa-Silva, C., Rimmer, P. B., Zhan, Z., Greaves, J. S., & Richards, A. M. S. (2021). Phosphine on Venus cannot be explained by conventional processes. *Astrobiology*, 21(10), 1277–1304. <https://doi.org/10.1089/ast.2020.2352>
- Bains, W., Petkowski, J. J., Rimmer, P. B., & Seager, S. (2021). Production of ammonia makes Venusian clouds habitable and explains observed cloud-level chemical anomalies. *Proceedings of the National Academy of Sciences*, 118(52), e2110889118. <https://doi.org/10.1073/pnas.2110889118>
- Bains, W., Petkowski, J. J., Zhan, Z., & Seager, S. (2021). Evaluating alternatives to water as solvents for life: The example of sulfuric acid. *Life*, 11(5), 400. <https://doi.org/10.3390/life11050400>
- Bains, W., Shorttle, O., Ranjan, S., Rimmer, P. B., Petkowski, J. J., Greaves, J. S., & Seager, S. (2022). Constraints on the production of phosphine by Venusian volcanoes. *Universe*, 8(1), 54. <https://doi.org/10.3390/universe8010054>
- Bains, W., Petkowski, J. J., & Seager, S. (2024). Venus' atmospheric chemistry and cloud characteristics are compatible with Venusian life. *Astrobiology*, 24(4), 371–385. <https://doi.org/10.1089/ast.2022.0113>
- Cordiner, M. A., Villanueva, G. L., Wiesemeyer, H., Milam, S. N., de Pater, I., Moullet, A., Aladro, R., Nixon, C. A., Thelen, A. E., Charnley, S. B., Stutzki, J., Kofman, V., Faggi, S., Liuzzi, G., Cosentino, R., & McGuire, B. A. (2022). Phosphine in the Venusian atmosphere: A strict upper limit from SOFIA GREAT observations. *Geophysical Research Letters*, 49(22), e2022GL101055. <https://doi.org/10.1029/2022GL101055>

- Cordiner, M. A., Villanueva, G. L., Wiesemeyer, H., et al. (2023). Author's reply to comment by Greaves et al. on “Phosphine in the Venusian atmosphere: A strict upper limit from SOFIA GREAT observations.” *Geophysical Research Letters*, *50*(22), e2023GL106136. <https://doi.org/10.1029/2023GL106136>
- Encrenaz, T., Greathouse, T. K., Marcq, E., Widemann, T., Bézard, B., Fouchet, T., Giles, R., Sagawa, H., Greaves, J., & Sousa-Silva, C. (2020). A stringent upper limit of the PH₃ abundance at the cloud top of Venus. *Astronomy & Astrophysics*, *643*, L5. <https://doi.org/10.1051/0004-6361/202039559>
- Garvin, J. B., Getty, S. A., Arney, G. N., Johnson, N. M., Kohler, E., Schwer, K. O., Sekerak, M., et al. (2022). Revealing the mysteries of Venus: The DAVINCI mission. *The Planetary Science Journal*, *3*(5), 117. <https://doi.org/10.3847/PSJ/ac63c2>
- Greaves, J. S., Richards, A. M. S., Bains, W., Rimmer, P. B., Sagawa, H., Clements, D. L., Seager, S., Petkowski, J. J., Sousa-Silva, C., Ranjan, S., Drabek-Maunders, E., Fraser, H. J., Cartwright, A., Mueller-Wodarg, I., Zhan, Z., Friberg, P., Coulson, I., Lee, E., & Hoge, J. (2021). Phosphine gas in the cloud decks of Venus. *Nature Astronomy*, *5*(7), 655–664. <https://doi.org/10.1038/s41550-020-1174-4>
- Greaves, J. S., Richards, A. M. S., Bains, W., Rimmer, P. B., Clements, D. L., Seager, S., Petkowski, J. J., Sousa-Silva, C., Ranjan, S., & Fraser, H. J. (2021). Addendum: Phosphine gas in the cloud deck of Venus. *Nature Astronomy*, *5*(7), 726–728. <https://doi.org/10.1038/s41550-021-01423-y>
- Greaves, J. S., Rimmer, P. B., Richards, A. M. S., Petkowski, J. J., Bains, W., Ranjan, S., Seager, S., Clements, D. L., Sousa-Silva, C., & Fraser, H. J. (2021). Reply to: No evidence of phosphine in the atmosphere of Venus from independent analyses. *Nature Astronomy*, *5*(7), 636–639. <https://doi.org/10.1038/s41550-021-01424-x>
- Greaves, J. S., Petkowski, J. J., Richards, A. M. S., et al. (2023). Comment on “Phosphine in the Venusian atmosphere: A strict upper limit from SOFIA GREAT observations” by Cordiner et al. *Geophysical Research Letters*, *50*(22), e2023GL103539. <https://doi.org/10.1029/2023GL103539>
- Limaye, S. S., Zelenyi, L., & Zasova, L. (2021). Introducing the Venus collection — Papers from the first workshop on habitability of the cloud layer. *Astrobiology*, *21*(10), 1163–1167. <https://doi.org/10.1089/ast.2021.0142>
- Lincowski, A. P., Meadows, V. S., Crisp, D., Akins, A. B., Schwieterman, E. W., Arney, G. N., Wong, M. L., Steffes, P. G., Parenteau, M. N., & Domagal-Goldman, S. D. (2021). Claimed detection of PH₃ in the clouds of Venus is consistent with mesospheric SO₂. *The Astrophysical Journal Letters*, *908*(2), L44. <https://doi.org/10.3847/2041-8213/abde47>
- Mogul, R., Limaye, S. S., & Way, M. J. (2021). Venus' mass spectra show signs of disequilibria in the middle clouds. *Geophysical Research Letters*, *48*(7), e2020GL091327. <https://doi.org/10.1029/2020GL091327>
- Petkowski, J. J., Seager, S., Grinspoon, D. H., Bains, W., Ranjan, S., Rimmer, P. B., Buchanan, W. P., Agrawal, R., Mogul, R., & Carr, C. E. (2024). Astrobiological potential of Venus atmosphere chemical anomalies and other unexplained cloud properties. *Astrobiology*, *24*(4), 343–370. <https://doi.org/10.1089/ast.2022.0060>
- Seager, S., Petkowski, J. J., Gao, P., Bains, W., Bryan, N. C., Ranjan, S., & Greaves, J. S. (2021). The Venusian lower atmosphere haze as a depot for desiccated microbial life: A proposed life cycle for persistence of the Venusian aerial biosphere. *Astrobiology*, *21*(10), 1206–1223. <https://doi.org/10.1089/ast.2020.2244>
- Seager, S., Petkowski, J. J., Carr, C. E., Grinspoon, D. H., Ehlmann, B. L., Saikia, S. J., Agrawal, R., Buchanan, W. P., Weber, M. U., French, R., Klupar, P., Worden, S. P., Baumgardner,

- D., & on behalf of the Venus Life Finder Mission Team. (2022). Venus Life Finder missions motivation and summary. *Aerospace*, 9(7), 385. <https://doi.org/10.3390/aerospace9070385>
- Seager, S., Petkowski, J. J., Carr, C. E., Grinspoon, D. H., Ehlmann, B. L., Saikia, S. J., et al. (2022). Venus Life Finder habitability mission: Motivation, science objectives, and instrumentation. *Aerospace*, 9(11), 733. <https://doi.org/10.3390/aerospace9110733>
- Seager, M. D., Seager, S., Bains, W., & Petkowski, J. J. (2024). Stability of 20 biogenic amino acids in concentrated sulfuric acid: Implications for the habitability of Venus' clouds. *Astrobiology*, 24(4), 386–396. <https://doi.org/10.1089/ast.2023.0082>
- Truong, N., & Lunine, J. I. (2021). Volcanically extruded phosphides as an abiotic source of Venusian phosphine. *Proceedings of the National Academy of Sciences*, 118(29), e2021689118. <https://doi.org/10.1073/pnas.2021689118>
- Villanueva, G. L., Cordiner, M., Irwin, P. G. J., de Pater, I., Butler, B., Gurwell, M., Milam, S. N., Nixon, C. A., Luszcz-Cook, S. H., Wilson, C. F., Kofman, V., Liuzzi, G., Faggi, S., Faucher, T. J., Lippi, M., Cosentino, R., Thelen, A. E., Moullet, A., Hartogh, P., ... Charnley, S. B. (2021). No evidence of phosphine in the atmosphere of Venus from independent analyses. *Nature Astronomy*, 5(7), 631–635. <https://doi.org/10.1038/s41550-021-01422-z>
- Editorial. (2021). Venus resurgent. *Nature Astronomy*, 5(7), 625. <https://doi.org/10.1038/s41550-021-01440-x>
- Mogul, R., Limaye, S. S., Way, M. J., & Cordova, J. A. (2024). Source of phosphine on Venus — An unsolved problem. *Frontiers in Astronomy and Space Sciences*, 11, 1372057. <https://doi.org/10.3389/fspas.2024.1372057>

BIOSIGNATURE U OBLACIMA VENERE: FOSFIN, AMONIJAK I METODOLOŠKA KONTROVERZA — PREGLED STANJA DEBATE PRIJE DAVINCI I ROCKET LAB MISIJA

Christopher Davis

Univerzitet u Sidneju Sidnej, Australija

E-mail: crty7281@uni.sydney.edu.au

Primljeno: 12.03.2025. Prihvaćeno: 27.05.2025.

Originalni naučni rad

DOI: <https://doi.org/10.65932/CAR-2025-1-4> UDK: 520.84:523.42

Sažetak: Objavljivanje rada Greavesa i saradnika u septembru 2020. godine, kojim je tentativno detektovan fosfin (PH₃) pri otprilike 20 ppb u oblačnom sloju Venere, sa neuobičajenom snagom je ponovo otvorilo pitanje može li se najreducovaniji terestrijalni analog planetarne atmosfere uskladiti s abiotskim objašnjenjima. U narednih šest mjeseci, četiri nezavisne reanalize su smanjile tvrdjeni signal, gornja granica iz infracrvene spektroskopije od 5 ppb je objavljena, te je ponovni pregled arhivskih podataka mase-spektrometra sa Pioneer Venus misije ponovo otvorio slučaj iz potpuno drugačijeg empirijskog smjera. Tokom 2021. i 2022. godine, spor se proširio na amonijak (NH₃), na fotokemiju jedinjenja koja sadrže fosfor u koncentrovanim oblacima sumporne kiseline, te na pitanje da li bi vulkanizam plašta mogao isporučiti fosfide u dovoljnoj količini da imitira biološki signal. Dvije skore misije — NASA-ina sonda DAVINCI (lansiranje 2029, spuštanje 2031) i misija Venus Life Finder konzorcijuma MIT-Rocket Lab (lansiranje ne ranije od 2026) — vratiće in-situ mjerenja s eksplicitnim ciljem ograničavanja pitanja oblačne biosignature. Pre-misijski trenutak je stoga metodološki interesantan sam po sebi: to je posljednja tačka u kojoj inferencijalna mašinerija korištena za evaluaciju daljinskih spektroskopskih biosignaturnih tvrdnji može biti reformisana u svjetlu onoga što je epizoda s fosfinom na Veneri otkrila o njenim slabostima. U ovom članku pregledavam objavljene dokaze za i protiv fosfinske tvrdnje, paralelne i manje zrele tvrdnje o amonijaku, te fotokemijske i vulkanske abiotske kontrapoteze, i predlažem Indeks unakrsno-instrumentalnog razilaženja (CIDI) kao jednu normalizovanu metriku koja obuhvata stepen do kojeg se nezavisna mjerenja istog atmosferskog odnosa miješanja konvergiraju ili razilaze. CIDI, primijenjen na podatke o PH₃ na Veneri nakon 2020. godine, vraća vrijednost od približno 0,83, daleko iznad praga koji predlažem za tretiranje biosignaturne tvrdnje kao observaciono robusne. Integrišem CIDI u petostepenu Pre-misijsku matricu evidencijskih pragova (PETM) koja specifikuje šta DAVINCI i Venus Life Finder moraju postići da bi pomjerali pitanje oblačne biosignature preko sljedeće evidencijske granice.

Ključne riječi: *Venera, fosfin, amonijak, biosignatura, oblačna habitabilnost, DAVINCI, Venus Life Finder, atmosferska hemija, metodološka kontroverza.*