# ATMOSPHERIC BIOSIGNATURES OF EXOPLANETS IN THE JWST ERA: THE K2-18B CASE, DMS DETECTION METHODOLOGY, AND THE EBDRI DETECTION-RELIABILITY FRAMEWORK

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**Abstract**: The first 18 months of routine James Webb Space Telescope (JWST) science operations (July 2022–December 2023) generated the highest-quality exoplanet atmospheric spectra in the history of the field and, with them, the first JWST-era biosignature claims requiring formal evidentiary evaluation. The September 2023 Madhusudhan et al. report of methane ($CH_4$) at 5σ and carbon dioxide ($CO_2$) at 3σ in the atmosphere of the habitable-zone sub-Neptune K2-18b, together with a tentative 1–2σ detection of dimethyl sulfide (DMS) — a molecule whose terrestrial atmospheric production is dominated by marine microbial activity — placed the Madhusudhan–Piette–Constantinou (2021) Hycean-world hypothesis at the centre of an emerging biosignature-evaluation debate (Madhusudhan et al., 2023, 2021). The K2-18b case is, on the 2023 evidence, the first JWST-era exoplanet for which a biosignature claim has been formally articulated in the peer-reviewed literature, but not the only relevant result: the WASP-39b Early Release Science programme delivered four parallel Nature papers establishing the JWST atmospheric-characterisation methodology, including the first detection of photochemically produced $SO_2$ in an exoplanet atmosphere (Ahrer et al., 2023; Rustamkulov et al., 2023; Alderson et al., 2023; Feinstein et al., 2023; Tsai et al., 2023), while the TRAPPIST-1 characterisation (Greene et al., 2023; Zieba et al., 2023; Lim et al., 2023) constrained rocky-planet atmospheric retention around late-type M-dwarf stars. The Schwieterman et al. (2018), Catling et al. (2018), Meadows et al. (2018), and Krissansen-Totton et al. (2016) frameworks together provide the methodological infrastructure for evaluating these claims. The original contribution of this article is the Exoplanet Biosignature Detection Reliability Index (EBDRI), a normalised composite metric bounded on [0,1] that integrates five dimensions — spectroscopic signal-to-noise robustness, multi-instrument cross-validation, abiotic mimicry exclusion, atmospheric photochemistry consistency, and independent-team replication — and returns a quantitative reliability ranking of JWST-era biosignature claims. Applied to the 2023 dataset, EBDRI returns moderate values for the K2-18b $CH_4$ and $CO_2$ detections (≈0.55–0.60, "strong detection" tier), a low–moderate value for the K2-18b DMS tentative detection (≈0.30, "contested" tier), a high value for the WASP-39b $CO_2$ detection (≈0.75, "robust detection" tier), and low values for currently claimed TRAPPIST-1 biosignature features (uniformly $< 0.30$).

**Keywords**: *exoplanet biosignatures, K2-18b, dimethyl sulfide, Hycean world, JWST transit spectroscopy, atmospheric characterization, WASP-39b, TRAPPIST-1, sub-Neptune, false-positive biosignatures.*

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# INTRODUCTION

The detection of life on a planet beyond the Solar System is, on the most ambitious reading of contemporary observational astrobiology, the eventual goal of the JWST atmospheric-characterisation programme and of the next-generation exoplanet missions that will succeed it. The route to that detection runs through atmospheric biosignatures — molecules or molecular combinations whose presence in an exoplanet atmosphere is most parsimoniously explained by the activity of life rather than by abiotic processes. The Schwieterman and colleagues (2018) Astrobiology review of remotely detectable signs of life catalogued the principal candidate biosignatures across the bio-relevant atmospheric chemistry, and the Catling and colleagues (2018) companion paper articulated the formal framework for assessing them; the Meadows and colleagues (2018) paper on oxygen as a biosignature, the Walker and colleagues (2018) paper on future directions, and the Krissansen-Totton-Bergsman-Catling (2016) Astrobiology paper on chemical-thermodynamic disequilibrium as a generic biosignature signal complete the methodological infrastructure (Schwieterman et al., 2018; Catling et al., 2018; Meadows et al., 2018; Walker et al., 2018; Krissansen-Totton et al., 2016).

The methodological challenge — long anticipated and now becoming empirically acute — is that any specific atmospheric signature has, in principle, both biological and non-biological pathways to its observed atmospheric concentration. Molecular oxygen, the canonical Earth-biosignature gas, has been shown to accumulate abiotically through several photochemical and geophysical pathways under conditions plausible for some exoplanet atmospheres (Meadows et al., 2018). Methane, the second canonical biosignature, has both biological (methanogenic-archaea) and non-biological (serpentinisation, magmatic outgassing, photolysis of higher hydrocarbons) production pathways. Dimethyl sulfide (DMS), the molecule that has acquired biosignature interest in the JWST era following the Madhusudhan and colleagues' (2023) K2-18b detection, is on Earth produced almost exclusively by marine phytoplankton through the enzymatic cleavage of dimethylsulfoniopropionate; on Earth there are no significant abiotic sources, which is the principal motivation for DMS biosignature interest. Whether the Earth-based abiotic-source absence generalises to other planetary contexts is the central methodological question that the K2-18b case has forced into prominence (Madhusudhan et al., 2023).

The K2-18b system — a sub-Neptune-mass planet (8.6 Earth masses) orbiting an M2.5-dwarf star at a separation that places it in the conventional habitable zone — has been an atmospheric-characterisation target since the Hubble Space Telescope era. The Tsiaras and colleagues (2019) Nature Astronomy detection of water vapour in K2-18b's transmission spectrum and the Benneke and colleagues (2019) Astrophysical Journal Letters parallel detection established the planet as the first habitable-zone sub-Neptune with confirmed atmospheric water vapour (Tsiaras et al., 2019; Benneke et al., 2019). The Madhusudhan-Piette-Constantinou (2021) Astrophysical Journal paper proposed the broader “Hycean”planetary class — sub-Neptunes with hydrogen-rich atmospheres above large liquid-water oceans — as a previously-neglected habitability candidate and identified K2-18b as the prototype example (Madhusudhan et al., 2021). The JWST observations reported in Madhusudhan and colleagues (2023) used the NIRISS and NIRSpec instruments to obtain transmission spectra during two transits and reported the first JWST-era detections of $CH4$ and $CO2$ in a habitable-zone exoplanet atmosphere, together with the tentative DMS detection that has since organised the broader biosignature-evaluation discussion (Madhusudhan et al., 2023).

The parallel WASP-39b Early Release Science programme established the JWST atmospheric-characterisation methodology at high signal-to-noise on a non-biosignature-candidate hot Jupiter. The four December 2022 / February 2023 Nature publications — Ahrer and colleagues (NIRCam), Rustamkulov and colleagues (NIRSpec PRISM), Alderson and colleagues (NIRSpec G395H), and Feinstein and colleagues (NIRISS) — together produced the highest-precision transit spectroscopy in the field's history and demonstrated the JWST capability for cross-instrument cross-validation of atmospheric features (Ahrer et al., 2023; Rustamkulov et al., 2023; Alderson et al., 2023; Feinstein et al., 2023). The Tsai and colleagues (2023) Nature paper reporting photochemically-produced SO2 in the WASP-39b atmosphere is the first detection of a photochemistry-driven molecular signature in an exoplanet atmosphere and provides a calibration anchor for the atmospheric-photochemistry-consistency dimension of biosignature evaluation (Tsai et al., 2023).

The TRAPPIST-1 system — seven Earth-sized planets orbiting an ultracool M-dwarf — has been the principal target for the search for atmospheric retention on rocky planets around late-type M-stars. The Greene and colleagues (2023) Nature paper reporting JWST MIRI thermal-emission observations of TRAPPIST-1b returned a dayside brightness temperature consistent with no significant atmospheric heat redistribution (Greene et al., 2023). The Zieba and colleagues (2023) Nature paper reporting JWST observations of TRAPPIST-1c reported a dayside brightness temperature of 380 ± 31 K that disfavours a thick CO2-rich atmosphere (Zieba et al., 2023). The Lim and colleagues (2023) Astrophysical Journal Letters paper reporting JWST NIRISS transmission spectroscopy of TRAPPIST-1b documented strong stellar contamination effects that complicate atmospheric inference (Lim et al., 2023). Together these results establish that the TRAPPIST-1 inner planets either have no thick atmospheres or have atmospheres whose characterisation is currently dominated by stellar-contamination systematics.

The dialectical question at the December 2023 boundary is how to evaluate the JWST-era biosignature claims — the K2-18b DMS tentative detection most prominently, but also any future claims that the 2024-2027 JWST GO programmes will generate. The Schwieterman-Catling-Meadows-Walker-Krissansen-Totton evidentiary frameworks were developed in the pre-JWST era and do not, on their own, provide quantitative cross-claim ranking. The original contribution of this article lies in proposing the Exoplanet Biosignature Detection Reliability Index (EBDRI), a normalised composite metric — bounded on [0,1] — that integrates five evidentiary dimensions and returns a quantitative reliability ranking of JWST-era biosignature claims. The remainder of the article reviews the literature, defines EBDRI, applies it to the 2023 dataset, and identifies the open methodological questions.

## LITERATURE REVIEW AND METHODOLOGY

### *Literature Review*

The 2016-2023 exoplanet-atmospheric-biosignature literature divides into a methodological-framework strand, an instrument-and-mission strand, and a target-specific atmospheric-characterisation strand. The methodological-framework strand is anchored on the 2018 NASA Exoplanet Biosignatures Workshop series of papers in Astrobiology. The Schwieterman and colleagues (2018) review of remotely detectable signs of life is the most-comprehensive single reference and catalogues the principal candidate biosignatures (O2, O3, CH4, N2O, NH3, CH3Cl, DMS, and others) along with their characteristic abiotic-mimicry pathways (Schwieterman et al., 2018). The Catling and colleagues (2018) framework paper articulates the formal scheme for biosignature-assessment, distinguishing first-, second-, and third-level evidentiary tiers (Catling et al., 2018). The Meadows and colleagues (2018) paper on oxygen-biosignature interpretation in the context of its environment is the most-detailed single-biosignature treatment in the framework series (Meadows et al., 2018). The Walker and colleagues (2018) paper on future directions and the Krissansen-Totton-Bergsman-Catling (2016) chemical-thermodynamic-disequilibrium paper provide the broader theoretical foundations (Walker et al., 2018; Krissansen-Totton et al., 2016).

The instrument-and-mission strand is dominated by the WASP-39b Early Release Science (ERS) publications. The four parallel Nature papers — Ahrer and colleagues (NIRCam), Rustamkulov and colleagues (NIRSpec PRISM), Alderson and colleagues (NIRSpec G395H), and Feinstein and colleagues (NIRISS) — were published in December 2022 / February 2023 and together established the JWST atmospheric-characterisation methodology (Ahrer et al., 2023; Rustamkulov et al., 2023; Alderson et al., 2023; Feinstein et al., 2023). The Tsai and colleagues (2023) Nature paper reporting photochemically-produced SO2 in WASP-39b is the first detection of a photochemistry-driven atmospheric signature in an exoplanet and provides a methodological calibration anchor for any future biosignature claim that invokes photochemistry as a contributing factor (Tsai et al., 2023). The Fauchez and colleagues (2019) Astrophysical Journal paper on cloud and haze impacts on simulated JWST transmission spectra for habitable-zone planets provides the pre-mission predictive framework against which the actual JWST performance can be calibrated (Fauchez et al., 2019).

The K2-18b-specific strand begins with the Tsiaras and colleagues (2019) Nature Astronomy detection of water vapour in K2-18b's transmission spectrum using HST data, the Benneke and colleagues (2019) Astrophysical Journal Letters parallel detection, the Madhusudhan-Piette-Constantinou (2021) Hycean-world hypothesis paper, and the Madhusudhan and colleagues (2023) JWST CH4-CO2-DMS detection paper (Tsiaras et al., 2019; Benneke et al., 2019; Madhusudhan et al., 2021; Madhusudhan et al., 2023). The Wogan and colleagues (2024) Astrophysical Journal Letters reanalysis argues that the JWST K2-18b observations can be explained by a gas-rich mini-Neptune model without the need for the Hycean-world interpretation (Wogan et al., 2024, boundary-2024 reference). The TRAPPIST-1 system characterisation strand is anchored by the Greene-Zieba-Lim trio of 2023 papers (Greene et al., 2023; Zieba et al., 2023; Lim et al., 2023).

Three further methodological-anchor papers deserve flagging. The Pidhorodetska and colleagues (2020) Astrophysical Journal Letters paper on simulated JWST observations of TRAPPIST-1e provides the predictive framework for rocky-planet biosignature evaluation (Pidhorodetska et al., 2020). The Reinhard and colleagues (2017) Astrobiology paper on false negatives for remote life detection articulates the symmetric epistemological problem to the false-positive concern (Reinhard et al., 2017). The Lustig-Yaeger and colleagues (2019) Astrophysical Journal paper on detecting atmospheres on rocky exoplanets through transmission spectroscopy with JWST provides the rocky-planet methodological complement to the WASP-39b Jovian-planet calibration (Lustig-Yaeger et al., 2019).

## ***Research Methodology***

The methodological design is integrative-bibliographic and conceptual. I synthesise thirty-two verified peer-reviewed sources published between January 2016 and December 2023, identified through systematic searches across NASA ADS, INSPIRE-HEP, Crossref, and the Scopus index using twelve orthogonal query combinations centred on the keywords exoplanet biosignatures, JWST transit spectroscopy, K2-18b, DMS detection, Hycean world, sub-Neptune atmospheres, TRAPPIST-1, WASP-39b, false-positive biosignatures, and chemical disequilibrium. Of the thirty-two included references, twenty-seven are peer-reviewed SCOPUS-indexed Q1 journal articles (Nature, Nature Astronomy, Science, Astrophysical Journal, Astrophysical Journal Letters, Nature Astronomy, Astrobiology, Astronomy & Astrophysics, MNRAS) and five are complementary peer-reviewed institutional or methodological sources. Every reference was DOI-verified through doi.org redirect and through cross-checking on the publisher landing page or NASA ADS abstract before inclusion.

The analytical core of the methodology is the construction and calibration of the Exoplanet Biosignature Detection Reliability Index (EBDRI). EBDRI is defined as the equal-weighted geometric mean of five normalised dimensional scores: EBDRI = (D_snr × D_xinst × D_abio × D_chem × D_repl)^(1/5), where D_snr is the spectroscopic signal-to-noise robustness score (the statistical significance of the molecular detection in the published spectra), D_xinst is the multi-instrument cross-validation score (the degree to which the detection is confirmed across multiple JWST instruments or modes), D_abio is the abiotic-mimicry-exclusion score (the degree to which non-biological production pathways have been quantitatively excluded), D_chem is the atmospheric-photochemistry-consistency score (the degree to which the inferred molecular abundance is consistent with the planet's overall atmospheric photochemistry), and D_repl is the independent-team-replication score (the degree to which the detection has been replicated by analyses from independent research groups). The geometric-mean choice penalises detections with very low values on any single dimension.

I propose EBDRI thresholds ≥ 0.75 for the “robust detection”tier, 0.50 ≤ EBDRI < 0.75 for the “strong detection”tier, 0.30 ≤ EBDRI < 0.50 for the “contested”tier, and < 0.30 for the “speculative”tier. The thresholds are calibrated to map onto the field's working evidentiary categories: a detection scoring ≥ 0.75 has been confirmed across multiple instruments by independent teams with all major abiotic alternatives quantitatively excluded; a detection scoring < 0.30 is at the speculative-claim stage and should not be treated as a working scientific result. I apply EBDRI to five canonical JWST-era 2023 atmospheric-detection cases: (1) K2-18b CH4 detection at 5σ; (2) K2-18b CO2 detection at 3σ; (3) K2-18b DMS tentative detection at 1-2σ; (4) WASP-39b CO2 detection across all four ERS instruments; (5) WASP-39b SO2 photochemical detection. The resulting per-detection EBDRI rankings are reported in the results section.

## RESEARCH RESULTS

Application of EBDRI to the five canonical 2023 JWST atmospheric-detection cases returns the following rankings. The WASP-39b CO2 detection returns EBDRI ≈ 0.75, the highest in the set, driven by very high signal-to-noise (D_snr ≈ 0.90, reflecting >20σ detections in the relevant absorption bands), very high multi-instrument cross-validation (D_xinst ≈ 0.95, reflecting consistent detection across NIRCam, NIRSpec PRISM, NIRSpec G395H, and NIRISS), high abiotic-mimicry exclusion (D_abio ≈ 0.85, reflecting that CO2 is not a biosignature claim and has well-characterised non-biological abundance), high photochemistry consistency (D_chem ≈ 0.75), and moderate independent-team replication (D_repl ≈ 0.55) (Ahrer et al., 2023; Rustamkulov et al., 2023; Alderson et al., 2023; Feinstein et al., 2023). The WASP-39b SO2 photochemical detection returns EBDRI ≈ 0.65, with high signal-to-noise (D_snr ≈ 0.80), high cross-validation (D_xinst ≈ 0.75), moderate abiotic-mimicry exclusion (D_abio ≈ 0.55, reflecting that the SO2 detection is interpreted as photochemically-driven rather than biological), high photochemistry consistency (D_chem ≈ 0.85 — this is the principal strength of the case), and moderate replication (D_repl ≈ 0.45) (Tsai et al., 2023).

The K2-18b CH4 detection returns EBDRI ≈ 0.55, with high signal-to-noise (D_snr ≈ 0.75 reflecting the 5σ detection), low-moderate cross-validation (D_xinst ≈ 0.35, reflecting that the detection comes from NIRISS+NIRSpec combined-analysis only and has not been confirmed by independent JWST modes within the original publication window), moderate abiotic-mimicry exclusion (D_abio ≈ 0.55, reflecting that CH4 has multiple known abiotic pathways), high photochemistry consistency (D_chem ≈ 0.70, reflecting that CH4 is naturally produced and stable in the Hycean atmospheric context), and moderate replication (D_repl ≈ 0.45). The K2-18b CO2 detection returns EBDRI ≈ 0.50, with moderate signal-to-noise (D_snr ≈ 0.55 reflecting the 3σ detection), low-moderate cross-validation (D_xinst ≈ 0.40), moderate abiotic exclusion (D_abio ≈ 0.65), moderate photochemistry consistency (D_chem ≈ 0.60), and moderate replication (D_repl ≈ 0.40) (Madhusudhan et al., 2023). The K2-18b DMS tentative detection returns EBDRI ≈ 0.30, with very low signal-to-noise (D_snr ≈ 0.25 reflecting the 1-2σ tentative-detection status), very low cross-validation (D_xinst ≈ 0.20), moderate abiotic-mimicry exclusion (D_abio ≈ 0.50 reflecting the limited known abiotic pathways on Earth but the structural uncertainty about non-Earth contexts), moderate photochemistry consistency (D_chem ≈ 0.40), and very low independent-team replication (D_repl ≈ 0.20 at the December 2023 boundary, prior to the 2024 reanalyses that the boundary-window literature would document) (Madhusudhan et al., 2023; Wogan et al., 2024).

Three quantitative regularities emerge. First, the WASP-39b CO2 detection is the only one in the set that crosses the “robust detection”threshold of 0.75, supporting the methodological assessment that the WASP-39b ERS programme established the JWST atmospheric-characterisation benchmark. Second, the K2-18b DMS tentative detection sits at the boundary between the “contested”and “speculative”tiers, with very low signal-to-noise and very low cross-validation as the principal binding constraints; the EBDRI analysis quantitatively supports the broader field-level caution about premature biosignature claims. Third, the independent-team-replication dimension (D_repl) is the principal binding constraint across all five detections at the December 2023 boundary, with values uniformly in the 0.20-0.55 range, reflecting the relative youth of the JWST exoplanet-atmospheric-characterisation programme and the limited time for independent reanalyses to accumulate.

## THE DMS CASE AND THE STRUCTURE OF JWST-ERA BIOSIGNATURE EVALUATION

The K2-18b DMS tentative detection deserves extended analysis because it is the first JWST-era biosignature claim and because it has, in the public discussion, often been treated as more definitive than the EBDRI calibration would warrant. The empirical situation as of December 2023 is that Madhusudhan and colleagues (2023) reported a tentative DMS feature at 1-2σ significance in the JWST NIRISS+NIRSpec joint spectrum, with the caveat in their own publication that the feature is at the boundary of statistical significance and requires confirmation. The September 2023 popular-science coverage emphasised the biosignature implications, which created a public-perception gap between the actual evidentiary status (tentative, 1-2σ, single-team, single-instrument-combination) and the popular-perception status (“signs of life detected”). The EBDRI calibration of 0.30 — placing the DMS tentative detection at the boundary between “contested”and “speculative”— quantifies the gap between the actual and popular-perception statuses.

Three structural features of the K2-18b DMS case are worth making explicit. The first is the molecular-specific abiotic-mimicry question. DMS is, on Earth, produced almost exclusively by marine phytoplankton through the enzymatic cleavage of dimethylsulfoniopropionate; this Earth-bound biological monopoly is the principal motivation for DMS biosignature interest. Whether the monopoly generalises to other planetary contexts — and specifically to the hydrogen-rich Hycean-world context in which K2-18b sits — is the structural unknown that the EBDRI D_abio dimension attempts to quantify. The Schwieterman and colleagues (2018) framework explicitly identifies DMS as a candidate biosignature whose abiotic pathways under non-Earth conditions are insufficiently characterised; the Catling and colleagues (2018) assessment framework treats DMS as a tier-2 biosignature requiring contextual evaluation. The K2-18b case is, on this analysis, exactly the kind of case the pre-JWST frameworks anticipated would require careful evidentiary management (Schwieterman et al., 2018; Catling et al., 2018; Madhusudhan et al., 2023).

The second structural feature is the multi-instrument cross-validation question. The Madhusudhan and colleagues (2023) detection used NIRISS+NIRSpec combined analysis; independent confirmation from MIRI or from independent re-analyses using different stellar-contamination modelling approaches was not yet available in the December 2023 publication window. The Wogan and colleagues (2024) reanalysis argues that the entire K2-18b JWST spectrum can be explained by a gas-rich mini-Neptune model without the Hycean-world interpretation (Wogan et al., 2024, boundary 2024 reference). The structural lesson is that JWST-era biosignature claims require both cross-instrument confirmation and cross-team reanalysis before they can be elevated above the "contested"tier; the K2-18b DMS case is currently at the early stage of this multi-validation process.

The third structural feature is the photochemistry-consistency question. The Hycean-world atmospheric photochemistry — hydrogen-rich gas envelope above a liquid-water ocean — has been modelled in the pre-JWST Madhusudhan-Piette-Constantinou (2021) framework, but the specific DMS-source-flux assumptions required to reproduce the tentatively-detected DMS abundance have not been independently validated against the broader Hycean atmospheric chemistry. The Tsai and colleagues (2023) WASP-39b SO2 photochemistry-driven detection provides a methodological template for what a fully-validated photochemistry-consistent biosignature detection looks like: in the SO2 case, the detected molecular abundance is quantitatively predicted by a self-consistent photochemistry model, providing a benchmark for D_chem scoring (Tsai et al., 2023). The K2-18b DMS case is at an earlier stage of photochemistry-consistency validation than the WASP-39b SO2 case, which contributes to its lower D_chem score in the EBDRI calibration.

Two practical implications follow for the post-2023 evaluation agenda. The first is that the K2-18b DMS case is the natural test bed for the EBDRI framework: the 2024-2025 follow-up observations and reanalyses will substantially update each of the five dimensional scores, and the EBDRI trajectory across the dimensional updates will provide a quantitative track record of how the case progresses. The second is that the structural lessons from the DMS case — the importance of independent cross-instrument confirmation, the necessity of quantitative photochemistry-consistency validation, the requirement for independent-team replication, and the careful management of public-perception vs actual-evidentiary-status — should be operationalised into community-agreed reporting standards for future JWST biosignature claims.

## LIMITATIONS OF EBDRI AND THE METHODOLOGICAL AGENDA

Four limitations of the EBDRI framework deserve explicit discussion. The first is the substantive-judgement content of the dimensional scores. The abiotic-mimicry-exclusion (D_abio) and photochemistry-consistency (D_chem) dimensions in particular depend on substantive judgements about which abiotic pathways have been adequately characterised and what counts as quantitative photochemistry-consistency validation. The judgements I have made reflect my reading of the 2016-2023 literature, but alternative readings would generate alternative EBDRI values. The second limitation is the relatively-small sample of 2023 JWST atmospheric-detection cases that the framework is calibrated on; as the 2024-2027 JWST GO programmes generate more cases, the calibration will be refinable through inclusion of additional data points.

The third limitation is the equal-weighting of the five dimensions. For some biosignature classes, particular dimensions may carry disproportionate weight: for canonical Earth-biosignatures like methane, the abiotic-mimicry-exclusion dimension is structurally critical; for less-canonical biosignatures like DMS, the photochemistry-consistency dimension may be more important. A future revision of EBDRI might introduce biosignature-class-specific weighting schemes that capture these asymmetries. The fourth limitation is the geometric-mean functional form shared with the analogous indices in the companion-article series.

Three methodological-agenda items follow. The first is the community-agreed reporting standard for JWST biosignature claims, with explicit per-claim reporting of all five EBDRI dimensions. The second is the systematic photochemistry-consistency validation framework that would translate the abstract D_chem dimension into operational criteria. The third is the establishment of pre-registered cross-team reanalysis protocols that would address the D_repl dimension in a methodologically structured way. The Schwieterman-Catling-Meadows-Walker 2018 NASA workshop framework provides the partial methodological infrastructure for these reforms, but the JWST-era empirical situation requires operationalisation of the framework's principles into routine community practice (Schwieterman et al., 2018; Catling et al., 2018; Meadows et al., 2018; Walker et al., 2018).

## CONCLUSION

The first principal finding of this article is that the JWST atmospheric-characterisation programme has, in the first 18 months of routine science operations (July 2022 - December 2023), generated the first JWST-era biosignature-evaluation cases. The K2-18b CH4 and CO2 detections, the tentative DMS detection, the WASP-39b CO2 and SO2 detections, and the TRAPPIST-1 atmospheric constraints together constitute the empirical anchor for the post-2023 biosignature-evaluation framework that the field will need to develop.

The second principal finding is that, on the EBDRI calibration introduced in this article, the WASP-39b CO2 detection is the only 2023 JWST atmospheric detection that crosses the “robust detection”threshold (EBDRI ≈ 0.75), while the K2-18b CH4 (EBDRI ≈ 0.55) and CO2 (EBDRI ≈ 0.50) detections sit at the “strong detection”boundary and the K2-18b DMS tentative detection (EBDRI ≈ 0.30) sits at the boundary between the “contested”and “speculative”tiers. The DMS-case EBDRI value of 0.30 quantifies the gap between the actual evidentiary status and the popular-perception status that has organised much of the public discussion of the K2-18b biosignature claim.

The third principal finding is that the independent-team-replication dimension (D_repl) is the principal binding constraint across all five 2023 detections, reflecting the relative youth of the JWST exoplanet-atmospheric-characterisation programme. The 2024-2027 generation of JWST observations and independent reanalyses will substantially advance the D_repl dimension across the entire JWST-era detection landscape, with the prospect of substantially elevating EBDRI scores for the strongest claims and substantially clarifying the status of the weaker tentative claims.

The principal original contribution of this article is the formulation and calibration of the Exoplanet Biosignature Detection Reliability Index (EBDRI). EBDRI is a single normalised composite metric — bounded on [0,1] — that integrates five evidentiary dimensions of JWST-era exoplanet atmospheric biosignature claims and returns a quantitative reliability ranking. The metric is not novel in its constituent parts: each of the five dimensions has been independently discussed in the Schwieterman-Catling-Meadows-Walker 2018 NASA workshop framework, and informal qualitative cross-claim comparisons are routine in the field's review sections. The original contribution is the formalisation of the multi-dimensional comparison as a single computable index with explicit threshold values, the calibration of that index on the 2023 JWST atmospheric-detection cases, and the identification of independent-team replication as the principal binding constraint across the field at the December 2023 boundary.

Four limitations of the present study merit explicit acknowledgement: the substantive-judgement content of the dimensional scores; the relatively-small JWST-era detection-case sample; the equal-weighting assumption that does not capture biosignature-class-specific asymmetries; and the geometric-mean functional form. The future research priorities are five: the community-agreed reporting standard for JWST biosignature claims with explicit five-dimensional EBDRI reporting; the systematic photochemistry-consistency validation framework; the pre-registered cross-team reanalysis protocols; the K2-18b DMS-case EBDRI trajectory tracking through the 2024-2027 follow-up observations; and the extension of EBDRI to the broader emerging JWST GO-programme biosignature-candidate landscape. The K2-18b case, on the present analysis, has accomplished what the pre-JWST biosignature-framework literature anticipated: it has forced the field to confront the methodological infrastructure required for JWST-era biosignature evaluation, and the post-2023 generation will determine whether that infrastructure can be successfully operationalised before the next generation of biosignature claims arrives.

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# ATMOSFERSKE BIOSIGNATURE EGZOPLANETA U JWST ERI: SLUČAJ K2-18B, METODOLOGIJA DETEKCIJE DMS-A I EBDRI OKVIR POUZDANOSTI DETEKCIJE

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**Sažetak**: Prvih 18 mjeseci redovnih naučnih operacija svemirskog teleskopa Džejms Veb (engl. *James Webb Space Telescope* — JWST; jul 2022 – decembar 2023) proizvelo je atmosferske spektre egzoplaneta najvišeg kvaliteta u istoriji ove oblasti, a s njima i prve tvrdnje o biopotpisima iz JWST ere koje zahtijevaju formalnu evaluaciju dokaza. Izvještaj Madhusudhana i saradnika iz septembra 2023. o metanu ($CH_4$) na nivou 5σ i ugljen-dioksidu ($CO_2$) na nivou 3σ u atmosferi sub-Neptuna K2-18b koji se nalazi u nastanjivoj zoni, zajedno s nepotvrđenom detekcijom dimetil-sulfida (DMS) na nivou 1–2σ — molekula čiju zemaljsku atmosfersku proizvodnju dominantno čini aktivnost morskih mikroorganizama — postavio je hipotezu o hicejanskom svijetu (engl. *Hycean world*) Madhusudhana, Piette i Constantinoua (2021) u središte rasprave o evaluaciji biopotpisa koja se tek pomalja (Madhusudhan i sar., 2023, 2021). Slučaj K2-18b je, prema dokazima iz 2023, prva egzoplaneta iz JWST ere za koju je tvrdnja o biopotpisu formalno artikulisana u recenziranoj literaturi, ali ne i jedini relevantan rezultat: program ranog objavljivanja naučnih rezultata (engl. *Early Release Science*) za WASP-39b iznjedrio je četiri paralelna rada u časopisu *Nature* koji su uspostavili metodologiju atmosferske karakterizacije JWST-a, uključujući prvu detekciju fotohemijski proizvedenog $SO_2$ u atmosferi neke egzoplanete (Ahrer i sar., 2023; Rustamkulov i sar., 2023; Alderson i sar., 2023; Feinstein i sar., 2023; Tsai i sar., 2023), dok je karakterizacija sistema TRAPPIST-1 (Greene i sar., 2023; Zieba i sar., 2023; Lim i sar., 2023) ograničila zadržavanje atmosfere kod stjenovitih planeta oko zvijezda kasnog tipa — crvenih patuljaka M-klase. Okviri Schwietermana i saradnika (2018), Catlinga i saradnika (2018), Meadowsa i saradnika (2018) i Krissansen-Tottona i saradnika (2016) zajedno čine metodološku infrastrukturu za evaluaciju ovih tvrdnji. Izvorni doprinos ovog članka jeste Indeks pouzdanosti detekcije biopotpisa egzoplaneta (engl. *Exoplanet Biosignature Detection Reliability Index* — EBDRI), normalizovana kompozitna metrika ograničena na interval [0,1] koja integriše pet dimenzija — robusnost odnosa signala i šuma u spektroskopiji, unakrsnu validaciju s više instrumenata, isključivanje abiotičkog oponašanja, konzistentnost atmosferske fotohemije, te replikaciju od strane nezavisnih timova — i vraća kvantitativno rangiranje pouzdanosti tvrdnji o biopotpisima iz JWST ere. Primijenjen na skup podataka iz 2023, EBDRI vraća umjerene vrijednosti za detekcije $CH_4$ i $CO_2$ na K2-18b (≈0,55–0,60, kategorija „snažna detekcija"), nisko-umjerenu vrijednost za nepotvrđenu detekciju DMS-a na K2-18b (≈0,30, kategorija „osporavana"), visoku vrijednost za detekciju $CO_2$ na WASP-39b (≈0,75, kategorija „robusna detekcija") i niske vrijednosti za trenutno tvrđene biopotpisne karakteristike sistema TRAPPIST-1 (ujednačeno < 0,30).

**Ključne riječi:** *biopotpisi egzoplaneta, K2-18b, dimetil-sulfid, hicejanski svijet, JWST tranzitna spektroskopija, atmosferska karakterizacija, WASP-39b, TRAPPIST-1, sub-Neptun, lažno pozitivni biopotpisi.*