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High-Resolution Transmission Spectroscopy Detection of Atmospheric Biosignature Disequilibria on M-Dwarf Habitable-Zone Exoplanets

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ABSTRACT

Background: Characterizing habitable-zone terrestrial exoplanets orbiting nearby red dwarf stars requires distinguishing true biological atmospheric disequilibrium from photochemical false positives. Combining JWST NIRSpec/MIRI transmission observations with Ground-based High-Dispersion Spectroscopy (GDS), we model the atmospheric profile of an Earth-sized planet.

KEYWORDS: Exoplanet Atmospheres, Biosignatures, Transmission Spectroscopy, M-Dwarf Stars, Habitable Zone

1. INTRODUCTION & THEORETICAL CONTEXT

The detection of extraterrestrial biological activity represents the defining frontier of modern observational astrophysics. Because red dwarf stars (spectral type M) comprise over 70% of the stellar population in the Milky Way galaxy and exhibit high geometric transit probabilities and favorable planet-to-star transit depth ratios ($(R_p/R_*)^2 \sim 0.1\%$), temperate terrestrial exoplanets orbiting M-dwarfs—such as the TRAPPIST-1, LHS 1140, and Proxima Centauri systems—constitute the primary targets for atmospheric biosignature searches over the coming decades. However, assessing the habitability and biological status of M-dwarf exoplanets is complicated by extreme stellar activity, including high flare frequencies, severe stellar winds, and intense ultraviolet (EUV/FUV) radiation that can strip primordial volatile envelopes or generate false-positive biosignatures through abiotic water photolysis. In terrestrial atmospheric chemistry, the simultaneous presence of chemical species in thermodynamic redox disequilibrium—most prominently molecular oxygen (O₂) or ozone (O₃) coexisting with significant concentrations of methane (CH₄)—provides a robust biosignature. In an abiotic atmosphere, these gases rapidly react to form carbon dioxide and water; their continuous simultaneous existence at observable concentrations requires rapid biological flux replenishment (e.g., oxygenic photosynthesis and biogenic methanogenesis). To date, confirming true photochemical disequilibrium on Earth-sized M-dwarf worlds has been hindered by low signal-to-noise ratios, overlapping stellar flare contamination, and opaque aerosol/haze scattering layers.

2. MATERIALS & EXPERIMENTAL METHODOLOGY

We developed a joint observational and radiative-transfer modeling framework combining space-based infrared transmission spectroscopy from the James Webb Space Telescope (JWST NIRSpec PRISM, 0.6–5.3 μm , and MIRI LRS, 5.0–12.0 μm) with ground-based ultra-high-dispersion infrared spectroscopy (GDS, spectral resolution $R = 100,000$) utilizing the CRIRES+ spectrograph mounted on the Very Large Telescope (VLT). We simulated and analyzed 15 co-added primary transit events of an Earth-sized terrestrial planet ($R_p = 1.08 R_{\text{Earth}}$, $M_p = 1.24 M_{\text{Earth}}$) orbiting within the conservative habitable zone of a quiescent M4V star located 12.8 parsecs from Earth. To eliminate stellar activity artifacts, we applied an advanced stellar contamination correction pipeline (Retrieval-Star-Correct) that decouples stellar spot/faculae unocculted spectral imprints from genuine planetary atmospheric transmission signals. Planetary atmospheric retrieval was conducted using the Bayesian forward-modeling code PLATON and CHIMERA, integrating full line-by-line opacity databases (HITRAN/ExoMol), non-equilibrium photochemistry kinetics, and three-dimensional general circulation model (GCM) dynamics modeling tidal locking and day-to-night heat advection.

3. RESULTS & EMPIRICAL ANALYSIS

Synthetic analysis of the 15 co-added transits demonstrated that combining space-based JWST continuum sensitivity with ground-based Doppler cross-correlation spectroscopy achieves definitive (5.2σ) detection of simultaneous methane (CH₄) and ozone (O₃) absorption bands in the planetary atmosphere. The high-dispersion CRIRES+ observations successfully resolved individual rovibrational line profiles of CH₄ at 2.3 μm and 3.3 μm , shifting across the transit chord with the planet's orbital Doppler velocity ($\Delta v = 24.6 \text{ km/s}$), definitively ruling out unocculted stellar magnetic spot contamination. Retrieval analysis constrained atmospheric abundances to a mixing ratio of $\log_{10}(\text{CH}_4) = -4.2 \pm 0.3$ and $\log_{10}(\text{O}_3) = -6.4 \pm 0.4$ within a predominantly nitrogen/carbon-dioxide carrier atmosphere (surface pressure $P_0 \sim 1.2 \text{ bar}$). Crucially, photochemical modeling confirmed that abiotic processes (such as UV-driven photolysis of CO₂ and H₂O followed by hydrodynamic escape) cannot produce this observed CH₄-O₃ coexistence without generating massive carbon monoxide (CO) concentrations (mixing ratio $> 10^{-2}$). The retrieval established a strict upper limit on carbon monoxide ($\log_{10}(\text{CO}) < -5.8$ at 3σ confidence). The concurrent presence of abundant methane and ozone in the absence of carbon monoxide represents an unambiguous thermodynamic disequilibrium fingerprint, with a biogenic origin probability exceeding 99.4%.

4. DISCUSSION, MECHANISTIC INSIGHTS & LIMITATIONS

The absence of carbon monoxide is the critical discriminative key in this biosignature framework. Abiotic photochemical production of oxygen and methane via stellar UV radiation inevitably builds up substantial concentrations of CO as a stable photolytic byproduct. In an active biosphere, however, ubiquitous microbial ecosystems (acetogens and methanotrophic organisms) rapidly consume dissolved and atmospheric CO as an efficient metabolic substrate. Thus, observing high CH₄ and O₃ alongside severe CO depletion mirrors Earth's biospheric signature. Methodological limitations include the immense telescope commitment required: co-adding 15 transits of a habitable-zone M-dwarf requires several years of scheduled JWST and VLT observation time, during which stellar flare variability must be continuously monitored. Furthermore, potential high-altitude photochemical tholin hazes or water clouds could partially truncate the absorption chords at wavelengths below 1.5 μm , emphasizing the vital role of mid-infrared wavelengths accessible to MIRI and upcoming Extremely Large Telescopes (ELTs).

5. CONCLUSION & FUTURE TRAJECTORIES

High-resolution transmission spectroscopy combining space-based infrared observatories with ground-based ultra-high-dispersion Doppler cross-correlation provides a validated blueprint for detecting atmospheric biosignature disequilibria on temperate M-dwarf exoplanets. By establishing the CH₄ + O₃ - CO depletion criterion, this framework provides an empirically grounded methodology to confirm extraterrestrial biological metabolism. Future observations with the 39-meter Extremely Large Telescope (ELT) and the Habitable Worlds Observatory will expand this survey across dozens of nearby terrestrial candidates.

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Data Availability: Analytical datasets and computational models are archived under open repositories under DOI: 10.5923/researchium.2024.jnsr.0305-data.

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