Disequilibrium biosignatures on the early Earth and their detectability with the James Webb Space Telescope

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Upcoming ground- and space-based telescopes will characterize habitable exoplanets and look for atmospheric gases produced by life. Oxygen is a promising biosignature gas, but several hypothetical scenarios have been proposed for producing abiotic oxygen or its surrogate, ozone. Furthermore, even if these scenarios can be ruled out by other observations, there is no guarantee that oxygenic photosynthesis is a common metabolism. Even on Earth, it took billions of years for oxygen to accumulate to detectable levels, and so oxygen biosignatures may be rare.

Atmospheric chemical disequilibrium is potentially a more general biosignature. We have developed a quantitative metric for atmospheric disequilibrium and applied it to the Solar System planets and the Earth through time [1]. The biogenic disequilibrium in Earth's atmosphere in both the Phanerozoic and Proterozoic is mostly attributable to the coexistence of O_2, N_2, and liquid water, and far exceeds the photochemically-produced disequilibria of the other Solar System atmospheres. We also applied our disequilibrium metric to the anoxic Archean Earth, and found that life maintained a predominant disequilibrium between CO_2, CH_4, N_2, and liquid water. Such a combination of gases would not persist without significant replenishment of CH_4 from the surface, which we have shown to be difficult to explain without life. This leads us to propose that the coexistence of CO_2 and CH_4 in the atmosphere of an ostensibly habitable exoplanet as a potential biosignature. The inference to life would be strengthened by the absence of atmospheric CO, which would be present if abiotic CH_4 were outgassed and if no life were consuming CO.

Finally, we performed simulated Bayesian retrievals to show that this new biosignature is potentially detectable with the James Webb Space Telescope for nearby transiting planets such as the TRAPPIST-1 system.

[1] Krissansen-Totton et al. (2018) *Sci. Adv.* 4, eaao5747.