Chemical disequilibrium in planetary atmospheres as a way to look for life or its absence

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The most interesting aspect of exoplanets is whether some might be inhabited. In the Solar System, all planetary atmospheres are in chemical disequilibrium because of free energy input from the Sun or internal or tidal heat, but the Earth's atmosphere is anomalous [1]. Earth's biosphere releases waste, including major gases (N_2 and O_2) and minor ones (e.g., CO_2, CH_4, N_2O and $(CH_3)_2S$). Thus, life causes significant chemical disequilibrium compared to atmospheres on Mars, Venus or the giant planets. On the other hand (and in contrast to Lovelock's original hypothesis [1]), we suggest that the issue is subtle because untapped chemical disequilibrium can also indicate no biosphere.

We developed a metric that might help distinguish inhabited from uninhabited planets, with the Solar System as our guide and test case. We quantified chemical disequilibrium as the difference, $|\Delta G|$, in J mol^{-1} of an observed atmosphere as compared to all the gases in the atmosphere reacted to equilibrium. Because planets nearer the Sun (or their star) have more free energy, we normalize $|\Delta G|$ to the mean thermal energy per mole RT, according to the mean global temperature T at a planet's surface or 1 bar.

The resulting non-dimensional metric exceeds unity only for Earth. Mars is ~0.1, while Titan, Venus and the giant planet atmospheres are lower by orders of magnitude. We hypothesize that $|\Delta G|/RT > 1$ is an atmospheric biosignature, indicating the existence of an inhabited world. Of course, such a metric should be used judiciously with awareness of other information, such as compositional and physical conditions.

Our calculations also suggest that abundant CO on Mars is an *anti-biosignature,* showing an absence of life on or near the surface. CO is a "free lunch", existing at levels incompatible with a microbial biosphere in contact with the martian atmosphere.

[1] Lovelock, J. E. (1975) *Proc. R. Soc. Lon.* **B189**, 167-181